A Hybrid Denitrification—Alternate Cycles Reactor To Enhance the Nitrogen Biological Removal in a Real Wastewater Treatment Plant

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ABSTRACT: This paper involves the retrofitting of a real municipal wastewater treatment plant (WWTP) of 6600 population equivalent (PE), from a traditional biological process to a predenitrification—alternating cycles (PreD-AC) technology, defining a hybrid reactor. The application was investigated for 11 months, from the upgrading in October 2009 to September 2010. The process optimization allowed to reach high standards of effluent’s quality, with total nitrogen (TN) and ammonia (NH₄-N) concentrations lower than 15 and 1 mg L⁻¹, respectively. Moreover, the flexibility and automatic control of the process guaranteed an energy consumption decrease of 17%, with a specific energy consumption of 0.18 kW h PE TN⁻¹ d⁻¹ as an average value. A reduction of 20% was reached by comparing the sludge amounts disposed in landfills in 2009 and 2010.

INTRODUCTION

The activated sludge process, which is one of the biological treatment methods, is commonly used in domestic wastewater treatment, to obtain the colloidal and dissolved carbonaceous organic matter removal. If nitrogen decrement is also considered, anoxic denitrification is maintained in a separate zone, or carousel-type ditches are used for this purpose. An efficiency evaluation of the traditional biological treatments was carried out for most of the small wastewater treatment plants (WWTPs) in the country of Italy, characterized by denitrification—nitrification (DN), total oxidation, or membrane bioreactor (MBR) processes. Among these technologies, the DN process, despite its simple implementation, requires elevated maintenance costs, mainly because of continuous aeration and high internal recycle ratios (in the range of 2—6). However, an on/off strategy applied to the aeration devices makes it possible to maintain nitrification and denitrification in a single aeration reactor, so the nitrogen removal can also be achieved. In this system, which is called the alternating cycles process, the dissolved oxygen (DO) concentration is always changing, whereas the conventional system is generally operated under a stable DO level. The alternating process model and its optimization is currently reported in limited works in the current literature,⁵⁶ based upon Activated Sludge Model No. 1, and more simulation results to determine the optimum operation profile were published using distributed parameter models described by partial differential equations in Activated Sludge Model No. 3.⁵ As full-scale applications, more than 40 WWTPs with a design capacity of 700—400 000 PE (where PE represents population equivalent) are working in the Italian territory, by applying the AC process in the biological reactor to treat urban or industrial wastewaters. Some of the results obtained from the real cases are presented in the literature,⁶—⁹ showing the AC capacity to achieve high-quality standards of the effluent¹⁰ and to contain operating costs. This paper presents the application of the AC process in the Castrezzato urban WWTP. Particularly, the possibilities to reclaim the existing structures in order to evaluate the performances of a hybrid reactor, constituted

Figure 1. Scheme of the level control of the alternating cycles process.

by a predenitrification phase and a following alternating-cycles unit, are discussed. Moreover, the results, in terms of pollutant removal, automatic control of the process, energy savings, and sludge reduction, are reported.

MATERIALS AND METHODS

Process Development and Automatic Control. The biological process was entirely managed on the basis of dissolved oxygen (DO) and oxidation reduction potential (ORP) signals.¹¹ The aeration was guaranteed by an automatic control of the DO and ORP signals, while the anoxic phase, carried out by organic compounds, was guaranteed based on the ORP scale. By analyzing the typical signal profiles, it was possible to identify the end of the ammonia and of the nitrates. By noticing these points, the automatic control device defined the ignition and switching off of mixers and blowers to determine anoxic andoxic phases.
respectively. The time length of those periods influenced the nitrogen removal. In some situations (influent overloads or underloads), the DO and ORP profiles are not reliable or overaeration can occur. In these cases, a maximum time safety control permits one to save the energy consumption by stopping the oxic phase or by increasing the anoxic one. Moreover, the application of a statistic processes the signal data, giving information about the oxic and anoxic durations and the end reasons of each phase. In this way, by suggesting the parameter modifications, the process optimization was effectively reached. The data-processing software was purposely engineered to evaluate the reliability of the control system. The software processed the database of the analogical and digital online signals giving basically two types of information: (i) the time length of the aerobic and anoxic phases; and (ii) the end-reason that led the automatic control device to switch from aerobic phase to anoxic phase and vice versa (set point maximum time, maximum DO and/or ORP, optimal condition (CO)) (see Figure 1).

Plant Description and Upgrading. To demonstrate the efficiency of the alternating cycles (AC) process, this paper concerns the monitoring period from October 2009 to September 2010. The Castrezato municipal WWTP, located in Brescia Province, was initially designed to remove nitrogen and carbon via a predenitrification/C0 nitrification biological process, assuming a volume ratio (D/N%) equal to 30%. (See Figure 2.)

A general description of operation units of the WWTP is reported in Table 1. The pretreatment unit of the water line is provided with fine screening and degritting units. The biological reactor characteristics defined a total volume of 781 m³, with a specific design volumes (Vsp) of 118 L PE⁻¹ and a hydraulic retention time (HRT) of 14.4 h at an average flow rate of 1300 m³ d⁻¹. To avoid structural modifications and guarantee the process elasticity contrary to a long-shaped reactor, the upgrading of the plant was achieved by performing a hybrid process into the circular biological tank, defining a PreD-AC reactor. The AC technology was applied in the nitrification tank, with a Vsp value equal to 91 L PE⁻¹, which defined a sufficient value to retrofit the previous process to the new one. The AC process is an affirmed technology that is based on the automatic alternation of oxic and anoxic phases into the same reactor. The aerobic period enables complete ammonia oxidation, whereas the anoxic one allows nitrates denitrification. With specific reference to the biological process, the automatic control was ensured by checking signals of two couples of DO and ORP probes. The aeration was ensured by an existing volumetric compressor and the biomass suspension by three submerged mixers, which were installed for the upgrading. Moreover, the AC reactor was provided with a total suspended solids (TSS) probe to measure the biomass concentration, while an ORP was installed in the predenitrification tank. The wastewater plant management was facilitated through the installation of a device for the waste sludge flow rate, in order to maintain a constant sludge retention time (SRT) value (10 d) and to guarantee complete ammonia nitrification. Finally, a disinfection unit precedes the treated water discharge. The sludge line is actually equipped with an aerobic stabilization tank, a thickening basin, and a dewatering unit.

Process Monitoring the Lab-Analyzed Parameters. The physicochemical composition of the wastewater was evaluated by weekly laboratory analysis on averaged samples according to standards methods. Moreover, influent loads and removal efficiencies of chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) were estimated to determine the effective reliability of the biological treatment.
**Table 1. Flow Scheme and Unit Dimensions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
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<tr>
<td><strong>Water Line</strong></td>
<td></td>
</tr>
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<td>design data</td>
<td></td>
</tr>
<tr>
<td>population equivalent</td>
<td>6600 PE</td>
</tr>
<tr>
<td>Q&lt;sub&gt;min&lt;/sub&gt;</td>
<td>54 m&lt;sup&gt;3&lt;/sup&gt; h&lt;sup&gt;−1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Q&lt;sub&gt;peak&lt;/sub&gt;</td>
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<tr>
<td>Q&lt;sub&gt;max&lt;/sub&gt;</td>
<td>1623 m&lt;sup&gt;3&lt;/sup&gt; h&lt;sup&gt;−1&lt;/sup&gt;</td>
</tr>
<tr>
<td>screening</td>
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<td>number of units</td>
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<tr>
<td>spacing</td>
<td>30 mm</td>
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<tr>
<td>pumping station</td>
<td></td>
</tr>
<tr>
<td>number of units</td>
<td>3</td>
</tr>
<tr>
<td>volume</td>
<td>23 m&lt;sup&gt;3&lt;/sup&gt;</td>
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<tr>
<td>dewatering</td>
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</tr>
<tr>
<td>number of units</td>
<td>1</td>
</tr>
<tr>
<td>spacing</td>
<td>2 mm</td>
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<td>volume</td>
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<tr>
<td>biological unit</td>
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<tr>
<td>predenitrification volume</td>
<td>181 m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>AC volume</td>
<td>600 m&lt;sup&gt;3&lt;/sup&gt;</td>
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<tr>
<td>nominal V&lt;sub&gt;p&lt;/sub&gt;</td>
<td>118 PE&lt;sup&gt;−1&lt;/sup&gt;</td>
</tr>
<tr>
<td>V&lt;sub&gt;p&lt;/sub&gt;, COD-based</td>
<td>190 PE&lt;sup&gt;−2&lt;/sup&gt;</td>
</tr>
<tr>
<td>V&lt;sub&gt;p&lt;/sub&gt;, TN-based</td>
<td>150 PE&lt;sup&gt;−3&lt;/sup&gt;</td>
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<tr>
<td>HRT Q&lt;sub&gt;mean&lt;/sub&gt;</td>
<td>14.4 h</td>
</tr>
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<td>aerobic stabilization</td>
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<td>number of units</td>
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<tr>
<td>volume</td>
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<td>dewatering</td>
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<td>number of units</td>
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</table>

**RESULTS AND DISCUSSION**

**Influent Characterization.** By investigating the period from April 2009 to September 2010, it was possible to evaluate the influent characteristics and the mass loads. The effective treatment capacity, which is always lower than the design one (6600 PE), increased after the AC process application (see Figure 3) from an average value of 2839 PE<sub>TN</sub> (April 2009—September 2009) to 5669 PE<sub>TN</sub> (October 2009—May 2010). The influent characterization of the entire period highlighted the elevated variability of the flow and of the incoming mass loads (Table 2). In fact, although the complete reliability of the flow rate measurement device was evaluated from May 2010, an increment of influent flow rate (Q<sub>in</sub>, given in units of m<sup>3</sup> d<sup>−1</sup>) was defined before and after the AC application with a general increase from 485 m<sup>3</sup> d<sup>−1</sup> (March 2009) up to 2796 m<sup>3</sup> d<sup>−1</sup> (August 2010) (see Table 2). Instead, the concentrations were noticed during all the winter seasons of 2009 and 2010, when the values of COD = 118%, TSS = 60%, and TN = 100% were achieved up to 536 mg<sub>L</sub> COD<sup>−1</sup> (October 2009, see Table 2) and 57 mg<sub>L</sub> TN<sup>−1</sup> (May 2010, Table 2). These conditions determine a reduction of the mass loads, despite the flow rate increase, during the summer seasons (July and August in 2009 and 2010), establishing an average effective treatment capacity of 3868 PE<sub>TN</sub> for the months of June 2010—August 2010 during the AC application (Figure 3). It is possible to affirm that the increase in PE was, probably, due to augmentation of macro pollutant concentrations of industrial or agricultural origin and to the periodic infiltration in the drainage system of the water-bearing stratum. Concerning the physicochemical composition of incoming wastewater, it is possible to note, as in all the experimental and monitoring periods, that the COD/TN ratio was always <7 and only occasionally increased up to 8.7 during the monitoring phase and up to 10.4 during the experimental period (Table 2). Particularly, the percentile analysis of COD/TN (Figure 4) (October 2009 to September 2010) reflected a value of <7 until the 65th percentile. The statistical analysis that was conducted defined a general limiting COD/TN condition (Figure 4), showing values that were, respectively, <7 for the 65% (65th percentile) of the influent samples and <5 for the 50% (50th percentile) of the influent samples.

**Effluent Quality and Process Efficiency.** Despite the variation of the influent mass loads after the PreD-AC application and the increment of the nitrogen loading rate (NLR, given in units of kg<sub>N</sub> m<sup>−3</sup> d<sup>−1</sup>, expressed as the TN load on each m<sup>3</sup> of reactor volume) from 0.05 kg m<sup>−3</sup> d<sup>−1</sup> during the monitoring period to 0.10 kg m<sup>−3</sup> d<sup>−1</sup> of the experimental one; adequate denitrification phases and elevated TN performances were ensured from April 2010 (Figure 5). Until March 2010, the PreD-AC process did not guarantee an evident efficiency, in terms of effluent quality, with ammonia concentrations up to 43 mg L<sup>−1</sup>. In fact, because of blowers blockage, the nitrogen removal was not fully completed. From April 2010, when air diffusers were substituted, the process was enabled to contain the ammonia and TN concentrations within, respectively, average effluent values of 0.7 mg<sub>N</sub><sub>INH4</sub> L<sup>−1</sup> and 7.9 mg<sub>L</sub> m<sup>−1</sup> TN<sup>−1</sup> (see Figures 5 and 6), with a removal efficiency of >75%. The permanent anoxic condition in the PreD tank determined, through fermentation phenomena, an increase of rapidly biodegradable substrate, ensuring a partial nitrates reduction and favoring the elevated removal performances in the AC reactor, despite the increment of influent TN concentration being, on average, equal to 37 mg<sub>L</sub> m<sup>−1</sup> TN<sup>−1</sup> (Figure 5). This aspect was developed by Activated Sludge Model No. 3. The influent characterization used as simulation input was calibrated on the basis of the real data in the nonlimiting denitrification condition with COD/TN equal to 12 (Simulation 1) and in the limiting denitrification ratio of COD/TN equal to 6 (Simulation 2) at 20 °C and 10 d of sludge retention time (SRT) (Table 3). The SRT imposed was equal to the real one. In fact, in the full-scale plant, a control device ensured the constant SRT value of 10 d and a stable biomass concentration (average value of 3 g MLSS L<sup>−1</sup>), also to obtain a complete nitrification phase. The influent reported in Table 3 represents the flow incomes in the AC reactor after the PreD basin. In both cases, the PreD unit, by developing the hydrolysis conditions, determined an increment of the of volatile fatty acids (VFA) equal to 8 and 1 mg<sub>VFA</sub> L<sup>−1</sup> for Simulations 1 and 2, respectively. This amount of biodegradable carbon determined an optimization of the anoxic performances for the following AC process and the simulated results as final nitrates effluent defined concentrations of 7 mg<sub>L</sub> m<sup>−1</sup> NO<sub>3N</sub> L<sup>−1</sup> for Simulation 1 and 8 mg<sub>L</sub> m<sup>−1</sup> NO<sub>3N</sub> L<sup>−1</sup> for Simulation 2. The comparison with the real results obtained during the experimental phase shows, as in the limiting COD/TN ratio (Table 2), that the final effluent NO<sub>3N</sub> characterization highlighted an average of 4.8 mg L<sup>−1</sup> (Oct and Nov 2009, as well as Feb, May, Aug, and Sep 2010; see Table 4).
lower than the average value (8 mgNO$_x$-N L$^{-1}$) obtained in Simulation 2. This better behavior could be related using the contribution of energy decoupling during the AC process for the continuous change of the environmental aerobic and anoxic conditions. This mechanism, coupled with a lower COD use for the anoxic biomass growth,$^{14}$ defined a higher carbon amount available for the nitrate reduction.$^{15}$ As demonstrated, the AC process assured the denitrification process, despite the low COD/TN value, via the automatic alternation of oxic and anoxic phases, the elevated control level, and the best exploitation of nitrogen-bound oxygen. Concerning the average COD, TSS, and nutrient values in the effluent, all the parameters were lower than

Table 2. Influent Characterization

<table>
<thead>
<tr>
<th>month</th>
<th>$Q_{in}$ (m$^3$ d$^{-1}$)</th>
<th>COD (mg L$^{-1}$)</th>
<th>TSS (mg L$^{-1}$)</th>
<th>TN (mg L$^{-1}$)</th>
<th>NH$_4$-N (mg L$^{-1}$)</th>
<th>COD/TN</th>
<th>TP (mg L$^{-1}$)</th>
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<tr>
<td>Monitoring Phase</td>
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<tr>
<td>Jan-2009</td>
<td>810</td>
<td>229</td>
<td>35.0</td>
<td>26.3</td>
<td>2.9</td>
<td>4.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Feb-2009</td>
<td>1354</td>
<td>229</td>
<td>76</td>
<td>1.2</td>
<td>1.6</td>
<td>3.0</td>
<td>3.7</td>
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<tr>
<td>Mar-2009</td>
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<td>128</td>
<td>3.7</td>
<td>8.7</td>
<td>3.6</td>
<td>3.7</td>
<td>2.3</td>
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<tr>
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<td>286</td>
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<td>3.0</td>
<td>2.0</td>
<td>2.0</td>
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<tr>
<td>May-2009</td>
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<td>312</td>
<td>121</td>
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<td>6.3</td>
<td>3.7</td>
<td>1.6</td>
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<td>108</td>
<td>22.5</td>
<td>13.6</td>
<td>3.7</td>
<td>2.3</td>
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<td>Jul-2009</td>
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<td>106</td>
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<td>3.6</td>
<td>2.0</td>
<td>2.0</td>
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<td>18.8</td>
<td>4.5</td>
<td>3.4</td>
<td>1.9</td>
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<tr>
<td>Sep-2009</td>
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<td>Oct-2009</td>
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<td>3.1</td>
<td>3.0</td>
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<td>4.4</td>
<td>3.3</td>
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<tr>
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<td>53.4</td>
<td>6.1</td>
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<td>244</td>
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<td>Aug-2010</td>
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<td>42</td>
<td>21.5</td>
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<td>6.2</td>
<td>1.9</td>
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</table>
the law limits: between March and June 2010, the COD average removal percentage was estimated to be 80%, whereas that of the TSS was 82%. All of the effluent concentration values are summarized in Table 4.

To evaluate the global efficiency of the process and to verify the periodic changing of the configuration parameters, more than 2500 cycles were studied using the statistical analysis device. The end of the oxic phase was reached for optimal conditions (OCs) in more than 50% of the cases (Figure 7), while overloads caused the remaining end conditions of cycles for maximum time. As shown in Figures 7 and 8, the process guaranteed constant and elevated percentages of optimal conditions in the anoxic phase, despite the COD/TN variation.

### Table 3. ASM3 Influent Data of Simulations

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<tr>
<th>Parameter</th>
<th>Simulation 1</th>
<th>Simulation 2</th>
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<tr>
<td>Q</td>
<td>1300 m³ d⁻¹</td>
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<tr>
<td>T</td>
<td>20 °C</td>
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<tr>
<td>SRT</td>
<td>10 d</td>
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<tr>
<td>COD/TN</td>
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<td>6</td>
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<tr>
<td>VFA₅₀ (%)</td>
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<td>1 mg/L</td>
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<td>COD</td>
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<td>208 mg/L</td>
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<td>RBCOD</td>
<td>54 mg/L</td>
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<tr>
<td>VFA</td>
<td>0 mg/L</td>
<td>0 mg/L</td>
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<tr>
<td>VFA₅₀ (in + out PreD)</td>
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<td>1 mg/L</td>
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<tr>
<td>NBCODs</td>
<td>81 mg/L</td>
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<td>NBCODp</td>
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<td>N-N₂O₅</td>
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<td>P₅₀</td>
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<td>P-PO₄</td>
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<td>TSS</td>
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### Table 4. Effluent Concentrations

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<thead>
<tr>
<th>Month</th>
<th>COD (mg L⁻¹)</th>
<th>TSS (mg L⁻¹)</th>
<th>TN (mg L⁻¹)</th>
<th>NH₄-N (mg L⁻¹)</th>
<th>NO₃-N (mg L⁻¹)</th>
<th>TP (mg L⁻¹)</th>
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In addition, a partial increment of anoxic OCs was registered with NLR greater than 0.07 kg_TN m⁻³ d⁻¹. Considering the signals elaboration, it is possible to affirm that the general conditions of the process are stable, with percentages of time
lengths of aerobic and anoxic phases of ~65% and ~35%, respectively.

Energy Consumption. The alternation of aerobic and anoxic phases into the same reactor permitted the nitrogen removal with the absence of internal recycle: this aspect, together with the intermittent aeration, allowed an increment in energy savings. By referring to the total energy, the annual reduction was 17%, considering a daily average consumption of 880 kWhe d⁻¹ and 730 kWhe d⁻¹ in 2009 and 2010, respectively (see Figure 9). The most significant savings was obtained by calculating the energy specific consumptions, summarized in Table 5: in fact, during the periods from January to July in 2009 and 2010, the rate reduced from a value of 0.31 kWhe PE₄TN⁻¹ d⁻¹ to 0.16 kWhe PE₄TN⁻¹ d⁻¹. This significant reduction, which is greater than the literature values,¹⁶ can be related to the increment of the treatment capacity of the plant (PE₄TN).

Produced Sludge Reduction. From the literature studies, both theoretically and experimentally, there is evidence that the value for the heterotroph anoxic yield is reduced, compared to the aerobic yield value changing from 0.67 mg COD/mg COD to 0.53 mg COD/mg COD.¹⁷ The reduction in anoxic yield determines effects on the net sludge production, since, in most conventional nitrogen removal activated sludge systems, the mass of sludge produced under anoxic conditions is small, compared to that produced under aerobic conditions.¹⁷ Furthermore, a reduced anoxic endogenous respiration rate may compensate for the reduced anoxic yield. Moreover, the change in the environmental

| Table 5. Specific Energy Values |
|-------------------------------|------------------|
| Specific Energy               | 2009             | 2010             |
| month                         | (kWhe PE₄COD⁻¹ d⁻¹) | (kWhe PE₄TN⁻¹ d⁻¹) |
| Jan-09                        | 0.34             |                  |
| Feb-09                        |                  |                  |
| Mar-09                        |                  |                  |
| Apr-09                        | 0.31             | 0.31             |
| May-09                        | 0.29             | 0.21             |
| Jun-09                        | 0.57             | 0.31             |
| Jul-09                        | 0.61             | 0.39             |
| Aug-09                        | 0.43             | 0.24             |
| Sep-09                        | 0.64             | 0.35             |
| Oct-09                        | 0.13             | 0.51             |
| Nov-09                        | 0.48             | 0.32             |
| Dec-09                        |                  |                  |
| Jan-10                        | 0.16             | 0.14             |
| Feb-10                        | 0.22             | 0.13             |
| Mar-10                        | 0.11             | 0.13             |
| Apr-10                        | 0.19             | 0.13             |
| May-10                        | 0.18             | 0.12             |
| Jun-10                        | 0.22             | 0.20             |
| Jul-10                        | 0.22             | 0.20             |
| Aug-10                        | 0.36             | 0.19             |

| Table 6. Sludge Production     |
|-------------------------------|------------------|
| Production (ton/month)         | 2009             | 2010             |
| January                       | 47.5             | 22.1             |
| February                      | 22.0             | 38.7             |
| March                         | 49.9             | 37.0             |
| April                         | 25.6             | 20.7             |
| May                           | 36.1             | 25.4             |
| June                          | 22.7             | 24.1             |
| July                          | 25.0             | 20.7             |
| August                        | 30.2             | 21.2             |
conditions of the reactor, between the aerobic and the anoxic ones, defines the mechanisms of sludge lysis and energy decoupling, in favor of excess sludge reduction.\(^{(18)}\) In this real case, by comparing the sludge amounts disposed in landfill in 2009 and 2010, it is possible to affirm that during the PreD-AC application, the sludge production reduced of \(~22\%\). The monthly production of sludge is reported in Table 6. A monitoring of the total solids percentage (TS%) contents in the disposed sludge could allow further investigations on the \(Y_{\text{obs}}\) values (kg TSS produced/kg COD transformed).

\section*{CONCLUSION}

The paper has investigated the application of the predenitrification—alternating cycles (PreD-AC) process in a Castrezzato urban wastewater treatment plant (WWTP) of 6600 PE, for a period of 11 months from the upgrading in October 2009, in terms of nutrients removal, energy savings, and sludge reduction. The design volumes permitted the retrofitting of the existing biological process into the hybrid PreD-AC process obtaining, even in the case of overloading, and effluent conforming to the law limits \((<15 \text{ mg L}^{-1} \text{ for total nitrogen (TN) and } <1 \text{ mg L}^{-1} \text{ for ammonia (NH}_4-N))\). The automatic control ensured the monitoring of the process by checking the dissolved oxygen (DO) and oxidation reduction potential (ORP) signals and statistical analysis, determining optimal conditions (OCs) of \(>75\%\) in anoxic phases and \(>50\%\) in oxic phases. The hybrid PreD-AC reactor was confirmed to be a good solution to entirely reclaim the existing structures and support the denitrification phase. A \(17\%\) reduction in the total energy consumption was attained, and the total sludge production decreased by \(~22\%\).

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(1) APAT. Guida per l’adeguamento, miglioramento e razionalizzazione del servizio di depurazione delle acque di scarico urbane, Sept. 26, 2005.