Comprehensive Review of Control and Operational Strategies for Partial Nitrification/ANAMMOX System

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ABSTRACT: This study examines control strategies developed for wastewater treatment via partial nitrification and the anaerobic ammonium oxidation process with the objective of enhancing nitrogen removal efficiency. The implementation of different control strategies were analyzed and explained with the help of pictorial representations. The benefits of the different control strategies were also briefly discussed. The biological process of nitrogen removal requires appropriate pairing between control and manipulated variables. Furthermore, the approach to follow when selecting suitable candidates and determining the pairing criterion was discussed. Although the conventional feedback–feedforward control logic is easy to implement, incorporation of the nonlinearity and complexity associated with the processes requires the design of advanced control systems.

1. INTRODUCTION

The ongoing study on the anaerobic ammonium oxidation (ANAMMOX) process has extremely improved the process over the past 20 years, but there are still many unexplored areas of the process implementation and performance. The control process is a technological advancement in wastewater treatment and has resulted in new opportunities for development of feasible nitrogen removal systems. Owing to the significant adverse effects of ammonia on the environment, nitrogen (ammonium) removal from wastewater is a crucial step. It is conventionally accomplished by combining nitrification and denitrification processes. Nitrification in conventional nitrogen removal systems involves high energy consumption, whereas an external organic carbon source is required for denitrification. An alternate and more sustainable solution to the problem is the application of the ANAMMOX process. The popularity of the method lies in the numerous advantages it offers, such as reduced energy consumption, oxygen usage, and organic carbon cost and amount of sludge production. It also helps in reducing plant operational cost. The drawback of the ANAMMOX process is low bacterial growth rate, leading to long start-up periods varying from 2 to 40 months. The ANAMMOX process can be applied in treating different types of wastewater containing ammonia in varying concentrations. Due to the advantages the process offers, it has resulted in an emerging research field in theory and application.

With proper control, the process could be optimized to plant operation at maximum efficiency. Most of the studies developed control strategies involving supervisory, feedback, feedforward, and advanced control techniques, such as model-predictive control (MPC) and fuzzy control, to facilitate regulation of aeration volume, dissolved oxygen (DO) concentration, and nutrient removal rates. Several applications and research studies for high-rate ANAMMOX processes were reported. The selection of control and manipulated variables, along with the design of the control configuration for the activated sludge system, is reviewed in ref. A number of control systems were analyzed with the help of mathematical models and soft sensors. Future trends in real-time control systems were predicted, and the report implied that sensors are not a cause of major concern during plant operation. A fuzzy logic-based supervisory control system for optimization and control of DO concentration was evaluated in the studies. Decentralized proportional integral derivative (PID) controllers and state-space models, involving noise disturbance and disturbance modeling principles, a supervisory control system, a scheduled PI control scheme, and decentralized PI control have been devised in order to control biological processes. Furthermore, rule-based real-time control strategies have been developed to meet the quality requirements of effluent water. The real-time implementation of the control system for performing DO optimal control was conducted. Works on model predictive control (MPC) and cascade control schemes are reported in the literature. A PID controller was designed for DO level and ammonia control. Beraud et al. developed a multiobjective genetic algorithm for evaluating and optimizing the various control laws. A model-based set point optimization and an enhanced two-step (nitrification and denitrification) process for designing an MPC-based system were proposed. Amand and Carlsson presented an optimal control strategy involving a supervisory feedback ammonia control loop.

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Moreover, enhanced pH control of the process at a low temperature is discussed in the literature.\textsuperscript{25} In the present work, the control methods developed for side-stream wastewater treatment, with the objective to improve the nitrogen RT (NRE), are reviewed extensively. Rule-based control strategies applied to minimize the aeration energy, sludge production, and carbon reagent dosage and to improve system performance are highlighted.\textsuperscript{15,31} Feedback and feedforward control\textsuperscript{32} aiming at improving the disturbance rejection performance by manipulating the RT are discussed, along with the combination of feedback–feedforward control for faster rejection of disturbance in organic carbon and ammonia concentration.\textsuperscript{33} The ratio control logic\textsuperscript{34} deals with the total ammonium nitrogen concentration in the effluent, to obtain a stable performance at low temperature. For system robustness improvement in the presence of long-term influent disturbances, fuzzy control logic is presented.\textsuperscript{35} Regulatory, cascade, and nested cascade optimal control focuses on the improvement of NRE.\textsuperscript{36} The implementation of control strategies are explained with the help of pictorial illustrations. The pros and cons of the control strategies are also analyzed. A partial nitrification/ANAMMOX process is discussed along with the associated terminology. Additionally, a brief description of the model development using constitutive relationships and a general concept of the control system are provided.

2. PRELIMINARIES

2.1. Wastewater Treatment Techniques. The physico-chemical techniques for wastewater treatment include membrane filtration, ion exchange, coagulation–floculation, chemical precipitation, adsorption, and electrochemical treatments. Coagulation–floculation and chemical precipitation are used for removal of high metal content (concentration > 1000 mg L\textsuperscript{−1}) from wastewater, whereas ion exchange and adsorption are used for lower levels of metal concentrations (10–100 mg L\textsuperscript{−1}). Electrochemical treatment and membrane filtration are only used for special purposes, owing to their high cost. The selection of an appropriate technique largely depends on the influent and the desired effluent-water quality levels. Methods of treating wastewater to recover or remove impurities by means of biological processes have gained increased popularity over the above-mentioned conventional techniques due to improved performance, cheap raw materials,\textsuperscript{37–40} and availability of bacterial population.\textsuperscript{41} However, the involvement of microbial groups in biological processes increases the complexity involved in the system control design.

Biological nitrification refers to the process of ammonia oxidation to nitrates in the presence of aerobic bacteria, followed by oxidation to nitrites. Examples of conventional biological nitrification methods are Bardenpho 4 stage, pre-denitrification, bio-denitro, sequencing batch reactor (SBR), and oxidation ditch. The Bardenpho process introduced in the 1970s is a continuous flow growth suspended process for wastewater nitrogen removal.\textsuperscript{42} The original process is a single sludge four stage process (anoxic–aeration–anoxic–aeration). The process was later modified by adding an initial anaerobic zone to remove phosphorus, along with nitrogen. The pre-denitrification process includes the anoxic stage followed by anoxic stage. This process has a distinct advantage over others, as the influent undergoes anoxic treatment first, which leads to short aerobic duration and high NRE.\textsuperscript{43} In addition, bio-denitro was introduced in the 1970s. The flow and process reaction conditions are sequentially altered in the interconnected tanks. The SBR is a type of activated sludge and a single step batch process, wherein the biological treatment steps (fill–aeration–settling–decanting) occur sequentially. Oxidation ditch is a modified activated sludge process that applies the long solid retention time concept. They comprise large circular basins equipped with aerators and are usually complete mix systems but can be modified for plug flow. The step feeding involves the feeding of the wastewater to the aeration tank in several phases.\textsuperscript{44} By manipulating the inflow, the step feed plant can be operated in many modes (plug flow, contact stabilization, and standard step feed). The advantages and limitations of these methods are listed in Table 1.

The main limitation of conventional processes is the presence of different micro-organisms for nitrification and denitrification. For the sustainable operation of the process, favorable microbial conditions are required. Moreover, high oxygen demand is required for complete nitrification, and high dosage of the carbon source is required for denitrification. These factors are directly associated with the plant operating costs and are the main driving force for the development of new technologies. The specifications of wastewater of a few industries are given in Table 2.

2.2. Partial Nitrification/ANAMMOX Process. The ANAMMOX process is a two-step process, introduced in the 1990s, performed in continuation in the presence of two separate

### Table 1. Conventional Biological Processes for Ammonia Removal from Wastewater: Advantages and Limitations

<table>
<thead>
<tr>
<th>process</th>
<th>advantage</th>
<th>limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bardenpho, 4 stage</td>
<td>no chemicals, low operating cost, simple operation, stable sludge, energy efficient</td>
<td>large reactor volume, low efficiency of 2nd anoxic tank</td>
</tr>
<tr>
<td>pre-denitrification</td>
<td>adaptable, low total nitrogen (5–8 mg L\textsuperscript{−1}) achievable</td>
<td>DO control required</td>
</tr>
<tr>
<td>post-denitrification</td>
<td>low total nitrogen (&lt;3 mg L\textsuperscript{−1}) achievable</td>
<td>high operating cost, high carbon dosage</td>
</tr>
<tr>
<td>bio-denitro</td>
<td>5–8 mg L\textsuperscript{−1} total nitrogen achieved, resistant to high influent disturbances</td>
<td>complex process and high construction cost</td>
</tr>
<tr>
<td>sequencing batch reactor</td>
<td>compact size, flexible process, easy to operate and control</td>
<td>extensive knowledge of process required for producing effluent water with required quality, cannot handle high influent load</td>
</tr>
<tr>
<td>(SBR) treatment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>oxidation ditch</td>
<td>reliable and simple process, can handle influent disturbances without affecting effluent quality, economical</td>
<td>large construction space required, no scope for plant capacity expansion</td>
</tr>
<tr>
<td>step feeding</td>
<td>load distribution for uniform oxygen supply, adaptable to existing activated sludge processes</td>
<td>DO control required, flow split control required for optimal operation</td>
</tr>
</tbody>
</table>

### Table 2. Wastewater from Different Industries

<table>
<thead>
<tr>
<th>wastewater</th>
<th>NH\textsubscript{4}\textsuperscript{+} (mg L\textsuperscript{−1})</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>petroleum oil refinery</td>
<td>15</td>
<td>6–8.5</td>
</tr>
<tr>
<td>monosodium glutamate</td>
<td>56.7 ± 0.8</td>
<td>3.6 ± 0.6</td>
</tr>
<tr>
<td>paper mill</td>
<td>0.2 ± 0.04</td>
<td>12.5 ± 0.5</td>
</tr>
<tr>
<td>fertilizer industry</td>
<td>60</td>
<td>6.5–8.5</td>
</tr>
</tbody>
</table>
processes are given in eqs 1 and 2, respectively. The metabolism of anaerobic ammonium oxidizing bacteria (AnAOB). Under anoxic conditions, the nitrite ions act as electron acceptors. The remaining ammonium is oxidized to nitrogen gas in the presence of ammonium oxidizing bacteria (AOB). The PN process is followed by the ANAMMOX process, wherein the ammonium is partially converted into nitrites and nitrates are also formed. This may be attributed to the presence of nitrate and nitrite compounds. Owing to their relatively high growth rate, complete removal of heterotrophic bacteria is a challenging task. One way to control the growth of heterotrophic bacteria is to regulate the amount of biomass decay and chemical oxygen demand (COD) availability. A number of mathematical models that describe a bioreactor with granular sludge were developed by several researchers. These models take into account the soluble component bulk as well as the granular microbe concentrations. Models for the biofilm scale, reactor scale, and species generation or consumption are defined and linked together using the existing relationships. Being autotrophic in nature, the growth of ANAMMOX bacteria does not require availability of biodegradable organic matter. Advantages, limitations, and probable applications of the ANAMMOX process are listed in Table 3.50,51 Ammonia-rich water containing different concentrations of suspended solids, organics, sulfates, and toxic chemicals could be effectively treated by means of ANAMMOX or PN/ANAMMOX processes. The main advantages of ANAMMOX over nitrification/denitrification are listed in Table 4.

**Table 3. ANAMMOX Process: Advantages, Limitations, and Applications**

<table>
<thead>
<tr>
<th>advantages</th>
<th>limitations</th>
<th>applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>reduction in energy consumption, organic carbon cost (100%)</td>
<td>operational temperature range limited</td>
<td>sludge liquor, digestate, and supernatant</td>
</tr>
<tr>
<td>reduction in oxygen usage by 60%</td>
<td>slow start-up</td>
<td>partially nitrified sludge digestate slaughterhouse and piggery wastewater</td>
</tr>
<tr>
<td>reduction in CO2 and NO2 emission</td>
<td>inhibition by substrates a, organic matter b, salts, heavy metals, phosphate, and sulfide</td>
<td>synthetic coke-oven wastewater monosodium glutamate wastewater pharmaceutical waste dry-spun acrylic fiber wastewater</td>
</tr>
<tr>
<td>reduction in amount of sludge production (80%)</td>
<td>SRT regulation</td>
<td></td>
</tr>
<tr>
<td>no biodegradable organic matter required</td>
<td>pH regulation</td>
<td></td>
</tr>
</tbody>
</table>

“Substrates: ammonia and nitrite. aOrganic matter: nontoxic and toxic organic matter.

bacterial groups.45–47 The first step is referred to as the PN process, wherein ammonium is partially converted into nitrates in the presence of ammonium oxidizing bacteria (AOB). The PN process is followed by the ANAMMOX process, wherein the remaining ammonium is oxidized to nitrogen gas in the presence of anaerobic ammonium oxidizing bacteria (AnAOB). Under anoxic conditions, the nitrite ions act as electron acceptors. The chemical reactions representing the PN and ANAMMOX processes are given in eqs 1 and 2, respectively. The metabolism and microbiology are reviewed in ref 48.

\[
\text{NH}_4^+ + 1.38 \text{O}_2 + 0.09 \text{CO}_2 \\
\rightarrow 0.018 \text{CH}_3\text{NO}_2 + 0.98 \text{NO}_2^- + 1.98 \text{H}^+ + 0.95 \text{H}_2\text{O}
\]

(1)

\[
\text{NH}_4^+ + 1.31 \text{NO}_2^- + 0.066 \text{HCO}_3^- + 0.13 \text{H}^+ \\
\rightarrow 1.02 \text{N}_2 + 0.26 \text{NO}_3^- + 0.066 \text{CH}_3\text{O}_3\text{O}_{0.5}\text{N}_{0.15} \\
+ 2.03 \text{H}_2\text{O}
\]

(2)

The overall PN/ANAMMOX process can be represented in the form of eq 3.

\[
\text{NH}_4^+ + \text{NO}_2^- \rightarrow \text{N}_2 + 2\text{H}_2\text{O}
\]

(3)

The operational conditions, pH values, temperature, DO content, presence of suspended solids, and influent alkalinity affect the performance of the ANAMMOX process.52,53 The pH value and DO content affect the microbial activity, which directly affects the free ammonia and free nitrous concentrations.54 A high pH value inhibits the growth of ANAMMOX bacteria. Temperature also plays a crucial role in the microbial activity that occurs during the ANAMMOX process. Various factors, such as substrate, organic matter, salinity, heavy metals, phosphates, and sulfide, inhibiting the process are discussed in ref 51. The optimal temperature for maximum bacterial activity is in the range 33–37 °C. A large number of suspended solids tend to increase the production of nitrates and the sludge waste. Alkalinity of the influent affects the nitrification and denitrification processes. In addition to these factors, the NRE depends on the ammonia-to-nitrite ratio present at the end of the PN process. Commencement of the ANAMMOX process depends on the seeding sludge and varies from 100 to 250 days. The nitrification sludge demonstrates the minimum startup time, and combined nitrification sludge and up-flow anaerobic sludge blanket demonstrate maximum startup time. There exists, therefore, a significant need to exercise control over the above-mentioned parameters to maximize the ANAMMOX process efficiency. With the availability of modern monitoring systems, the implementation of various control strategies is possible.
3. CONTROL STRATEGIES FOR PN/ANAMMOX PROCESS

Ammonium control in the PN/ANAMMOX process has been proven to be beneficial for steady and continuous process operations. Advantages of the control system include:

1. Control over AOB inhibition caused by free ammonia.
2. Control over NOB inhibition by free ammonia to obtain NOB-free biomass.
3. Regulation of ANAMMOX feeding and biomass activity.
4. Improved effluent quality and process failure.
5. Maximization of reactor capacity and process reliability.
6. Regulation of oxygen constraints, aeration energy, and reduced pollutant emission.

In order to design a control system, the most important step is to formulate the objective function and subsequently select appropriate manipulated and control variables. Pairing between manipulated and control variables is based on the degree of interaction between them. For this purpose, the relative gain array (RGA) and Niederlinski index are employed. For multivariable systems, the Niederlinski index (NI) and the relative gain array (A) are defined as

\[ \text{NI}(s) = \frac{\text{det}(G)}{\prod_{i=1}^{n} \lambda_i} \quad \text{and} \quad A = G \otimes [G^{-1}]', \]

respectively, where \( G \) is the transfer function matrix for the system. The key manipulated variable with regards to a wastewater treatment plant is the oxygen supply rate, expressed in terms of the mass transfer coefficient. The most commonly used controller is the PID that can be designed based on model-based tuning rules. It is the governing equation (eq 4) of a PID control structure.

\[ u(t) = K_i \left( 1 + \frac{1}{\tau_i} \int e(t) \, dt + \frac{\tau_d}{\tau_i} \frac{de(t)}{dt} \right) \quad (4) \]

A robust control system must be able to incorporate any nonlinearity effect that may occur within a system. The nonlinearity may arise from the time-variant nature of the process, the growth rate of bacterial groups, valve characteristics, saturation of DO concentration, and so on. In order to incorporate tolerance to nonlinearity, an advanced control system must be designed. Such systems include those based on fuzzy logic control, model predictive control (linear, nonlinear, and adaptive), rule-based control logic, model-based control, and linear quadratic control. Implementation of these advanced control systems involves incurring an additional cost of sensors and corresponding connections to the control the system. However, successful implementation of these systems helps in significantly reducing the process cost (carbon sources, aeration energy, and sludge handling cost). Table 5 summarizes the control strategies considered in this work. The control strategies may be implemented dynamically using aquatic ecosystem simulation (AQUASIM), activated sludge simulation (ASIM), simulations programs for die Biologische Abwasserreinigung (SIMBA), wastewater treatment plant engine for simulation and training (WEST), general purpose simulator (GPS)-X, BioWin, Texchem, equivalent forced outage rate (EFOR), and sewage treatment operation and analysis over time (STOAT) software packages.

In addition to ammonia, nitrite is another crucial parameter that exhibits inhibitory actions. Nitrite control is imperative in ANAMMOX reactions, as its prolonged presence in high concentrations causes deterioration in the ANAMMOX activity. Owing to the level of complexity involved in the microbial process, several sensors are required for monitoring. The selection of set points for DO level and pH depend on the field conditions. Dependency on DO levels for process control is fairly unreliable as it is not a proper indicator of concentration change or the microbial activity. Control strategies have been developed to address the following issues:

1. The buildup of total ammonium, nitrite, nitrogen, and nitrate concentrations.
2. Foaming, scaling, sludge settling, separation, and retention.

Control actions are required to include adjustment of feed flow and aeration rates, time of biological cycles (aerobic and anoxic phases), sludge removal rate, the dosage of antifoaming and flocculation agents, maintenance of constant pH value, and temperature. Major challenges faced by process engineers include controlling the process at lower than optimum temperatures, inhibition of nitrite-oxidizing bacteria, selective retention of the ANAMMOX biomass, and disturbance.
handling for ammonia concentration in the water. Most control strategies are developed and successfully implemented as side-stream processes in the treatment of rejected water, but there are still certain shortcomings in effective implementation of strategies. Implementation of the PN/ANAMMOX process in the main wastewater stream is presently being conducted and is known as the MANAMMOX (mainstream ANAMMOX) process. Future trends and prospects concerning utilization of the ANAMMOX process in wastewater treatment have been highlighted in ref 64.

3.1. Real-Time Control. Two rule-based control strategies are discussed in the following section. The first strategy, rule-based control by Martin and Gonzalez Ospina, is a time-based control in which the time of the aeration cycle and the anoxic cycle are changed based on the DO content and conductivity, whereas in rule-based control by Gonzalez Ospina, the ratio of NO₂⁻ and NH₄⁺ determines the aeration and nonaerobic phase timings.

3.1.1. Rule-Based Control by Martin and Gonzalez Ospina. A system design for the treatment of nitrogen-rich influent wastewater in terms of the removal of nitrogen-based compounds is proposed in this section. The method includes performance of ammonium oxidation and denitrification in a single SBR. In this method, influents are fed into SBR in successive volume fractions. The number of volume fractions fed to the reactor determines the number of subcycles. At the beginning of each subcycle, the high concentration of the ammonium ions enhances the activity of the nitrifying bacteria. Each volume fraction undergoes two biological phases, aeration phase and anoxic phase, followed by the settling and drain-off phases. The aeration phase involves oxidation of ammonia in the presence of oxygen to produce nitrates, while the anoxic phase involves the conversion of nitrates to nitrogen gas in the absence of oxygen. The nitrates produced are also converted to nitrogen with the help of a carbon source in the anoxic phase. The proposed method exhibits high RT for influents with nitrogen concentration exceeding 100 mg L⁻¹. The process workflow may be automated by means of a controller with NRE defined as the control variable and aeration flow rate as the manipulated variable. The role of the controller is to assess the influent (measuring flow rate and conductivity) and decide the number of subcycles, time of biological phase, and carbon-source addition. The controller also computes the nitrogen RT in the effluent and allows modifications to be made during the process. Furthermore, during the treatment cycles, the controller ensures proper progression of the process inside the reactor. In order to implement the method described above, the first step is to calculate the minimum number of feed cycles \( N_{\text{lim}_{\text{min}}} \) using eq 5. \( N_{\text{lim}_{\text{min}}} \) depends on the availability of ammonium feed and minimum volume inside the reactor.

\[
N_{\text{lim}_{\text{min}}} = \frac{F_{\text{NH₄}}}{\left(\left[\text{NH₄}⁺\right]_{\text{inhib}} - \left[\text{NH₄}⁺\right]_{\text{eff}}\right) V_{\text{min}} N_{\text{SBR}}}
\]  

(5)

Here, \( N_{\text{lim}_{\text{min}}} \) is the minimum number of feed cycles, \( F_{\text{NH₄}} \) is the daily nitrogenous feed, \( \left[\text{NH₄}⁺\right]_{\text{inhib}} \) is the amonium concentration in the effluent exiting the reactor, \( V_{\text{min}} \) is the minimum liquid volume (after extraction and before feeding), \( N_{\text{SBR}} \) is the number of cycles completed in a day, and \( \left[\text{NH₄}⁺\right]_{\text{eff}} \) is the inhibiting ammonium concentration present within the nitrating biomass. A minimum volume in the reactor is required in order to prevent the inhibition of NOB, which tends to dilute the concentration of the incoming feed. The value of \([\text{NH₄}⁺]_{\text{inhib}}\) is calculated using eqs 6 and 7, where \([\text{NH₄}⁺]_{\text{inhib}}\) is described as a function of temperature, pH value, and the ammonium concentration \([\text{NH₄}⁺]_{\text{inhib}}\) which tends to inhibit the bacterial population growth within the reactor.

\[
[\text{NH₄}⁺]_{\text{inhib}} = \frac{14}{17} \left(\left[\text{NH₄}⁺\right]_{\text{inhib}} \left(\frac{K_w}{K_b} + 10^{\text{pH}}\right)\right)
\]  

(6)

\[
K_w = e^{344/(273+T)}
\]  

(7)

Once the minimum number of feed cycles have been determined, the time for completion of the biological cycle \( t_C \) may be determined based on the total SBR cycle time, total feed time, settling phase time, drain-off phase time, and number of subcycles, as described in eq 8.

\[
t_C = t_{\text{SBR}} - t_{\text{lim}} - t_{\text{sedim}} - t_{\text{extract}} /
\]  

(8)

The biological time may be divided into the aeration and anoxia times. Depending on oxygen requirements (determined using reaction kinetics), the theoretical aeration and anoxic times may be calculated. Appropriate conditions must be maintained in the reactor to facilitate the presence of nitrifying bacteria and the suppression of the activities of nitrating bacteria. During the aeration phase, the DO concentration increases, and it reduces to zero during the anoxic phase. Low DO concentration is maintained in the reactor, thereby preventing the formation of nitrites. The pH plays an important role in the activity and growth of bacteria. The pH decreases during the aerobic phase and exhibits an increase during the anoxic phase. Thus, a continuous self-regulation of pH occurs due to the progression of alternate nitrification and denitrification phases. The ionic conductivity inside the reactor helps to determine the anoxic phase time, because the derivative of the ionic conductivity reduces to zero during the anoxic phase as nitrogen ions are converted to nitrogen gas, indicating complete conversion. Successful implementation serves to reduce the aeration energy and the sludge production. In addition, the carbon reagent usage is reduced. The process is, therefore, economically beneficial, and this method is suitable for the treatment of anaerobic digestor supernatants, gas producing condensates, and landfill leachates. The implementation of this method is simplified by the flowchart depicted in Figure 1. The following are pros and cons of the method:

**Advantages:**

1. 25% reduction of aeration energy
2. 30% reduction of sludge production
3. 40% reduction of carbon reagent usage

**Limitations:**

1. proper sensor calibration required
2. high number of sensors required

3.1.2. Rule-Based Control by Gonzalez Ospina. This method involves the treatment of the ammonia-containing effluent inside an SBR. It is a two-step process; the first step involves the aeration phase, wherein ammonium is oxidized either completely or partially in the presence of oxygen to produce nitrites. The second step involves reactions between nitrites and ammonium to produce nitrogen gas in an oxygen-depleted environment. The second step is known as the nonaerobic
phase, wherein the nitrates act as electron acceptors. One complete cycle of effluent treatment involves several subcycles. Each subcycle involves a sequence of steps starting from the effluent volume fraction feeding to SBR followed by the aeration and nonaeration phases to facilitate nitrification and production of nitrogen gas, respectively. This process helps to exert pressure on the bacterial selection to improve the development and the activity of the NOB.

Two different approaches for the effluent treatment are proposed. In the first approach, the ammonium stream fed to the SBR is partially (40−60%) converted to nitrates during the aeration phase. The leftover ammonium (that which is not oxidized during the aeration phase) and nitrates (produced during the aeration phase) react together to produce nitrogen gas during the nonaeration phase. In the second approach, the ammonium stream is completely oxidized to produce nitrates during the aeration phase. In the nonaeration phase, the effluent is again fed into the SBR to ensure maintenance of the proper ratio of ammonia to nitrate concentration. Ammonium is then made to react with nitrates thus generated to produce nitrogen gas. In the post-treatment, the effluents are settled down, and the treated water is drained off. If required, the extra amount of sludge is removed. Nonaeration phase conditions must be properly maintained, as they facilitate anaerobic bacterial growth.

Completion of the treatment cycle requires 4−8 h. The effluent feeding time to the SBR is usually 7−10% of the total treatment cycle duration. The number and duration of subcycles are altered based on real-time measurements of the flow rate, DO levels, conductivity, and pH value of the effluent to be treated, and the amount of wastewater is removed. The conductivity varies with the concentration of ammonium, nitrates, and nitrates. In general, with increasing nitrogen oxidation state, effluent conductivity has been observed to increase. The measurement of effluent conductivity and DO level plays a crucial role in regulating the duration of the phases. Concentration of DO during the aeration phase must be maintained within the range of 0.1−0.6 mg L\(^{-1}\). The aeration phase usually lasts for approximately 32−35% of the total cycle time. In order to achieve maximum efficiency, the ratio of nitrite to ammonium ions at the beginning of the nonaeration phase must be maintained in the range of 0.9−1.5. The nonaeration phase duration depends on the effluent conductivity value. If the conductivity reaches the lower threshold value, the nonaeration process is stopped. The nonaeration phase usually last for approximately 45% of the total cycle time.

The controlling device integrates the measurements and makes necessary adjustments for the process to work efficiently. The method is more suitable for the treatment of water containing ammonium, municipality water, water originating from industry, food-processing plants, dehydration of digested sludge, sludge drying condensates, sludge treatment by wet oxidation, liquid manures, landfill leachates, and so on, irrespective of the ammonium concentration and the operating temperature. Figure 2 illustrates a flowchart of both approaches involved in this method. The key advantages and limitations of the method are the following:

**Advantages:**

1. Less time to reach 95% RT.
2. No provision of external biomass.
3. Process efficiency is not affected by the change in influent disturbances in ammonia concentration.

**Limitations:**

1. Proper sensor calibration required to measure the concentrations.

### 3.2. Feedback Control Logic

The feedback control system modifies the system response without causing a change in the system components. The method, proposed by Vangsgaard et al.,\(^{32,65}\) is advantageous in cases where rejection of the disturbance within the organic carbon concentration of the feed is required. The rule-based feedback control logic involves the controller manipulating the air flow rate to control the removal efficiency (RT). The RT of the process is defined as the ratio of the total nitrogen removed to the total nitrogen contained in the feed. Mathematically, the RT can be expressed as:

\[
RT = \frac{\Delta TN}{TN_{\text{in}}} = \frac{[(NH_4^+ + NO_2^- + NO_3^-)_{\text{in}} - (NH_4^+ + NO_2^- + NO_3^-)_{\text{out}}]}{[(NH_4^+ + NO_2^- + NO_3^-)_{\text{in}}]}\]

The feedback control loop used to implement the logic discussed herein, is depicted in Figure 3. The error in the RT \((e(t) = RT_{\text{sp}} - RT(t))\) helps in determining the control action. The cause of the error can be either an air supply excess or the lack of it. The ratio of the amount of ammonia removed to the total nitrogen removed \((R_{\text{ammonia}})\) is used to determine the effectiveness of the system. The value of \(R_{\text{ammonia}}\) indicates the accumulation of nitrate, nitrite, or ammonium ions, each of which tends to lower the RT. A higher value of \(R_{\text{ammonia}}\) indicates an accumulation of nitrates and nitrates, whereas a lower value of
Figure 2. Schematic for implementation of real time rule based control logic by Ospina et al.31

Figure 3. Structure of rule-based feedback control logic.
$R_{amm, tot}$ indicates an accumulation of ammonium ions. $R_{amm, tot}$ can be expressed as

$$R_{amm, tot} = \frac{(NH_4^+)_{in} - (NH_4^+)_{out}}{[(NH_4^+ + NO_2^- + NO_3^-)_{in} - (NH_4^+ + NO_2^- + NO_3^-)_{out}]}$$  \hfill (10)

In order to control the RT, the air flow rate is altered (increased or decreased) depending on RT. For the correct implementation of the control strategy, a PI controller may be employed, and $R_{amm, tot}$ is used to determine the direction of the required control action. The control law is expressed as

$$K_{L,a}(t) = \begin{cases} K_{L,a} - Ke(t) - \frac{K}{\tau_1} \int_{0}^{t} e(t) \, dt & R_{amm, tot}(t) > R_{amm, tot, SP} \\ K_{L,a} + Ke(t) + \frac{K}{\tau_1} \int_{0}^{t} e(t) \, dt & R_{amm, tot}(t) \leq R_{amm, tot, SP} \end{cases} \hfill (11)$$

where $K$ and $\tau_1$ represent PI controller parameters and $e(t) = RT_{SP} - RT(t)$. In order to tune the controller in accordance with the model, the nonlinear process may be approximated as a first-order or second-order model using different methods described in the literature. 66,67 Dwyer 62 summarized the rules for tuning the controller for both stable and unstable processes. The advantages and limitations are the following:

**Advantages:**

1. faster rejection of disturbances in organic carbon
2. high RT

**Limitations:**

1. slower response
2. high offset in influent disturbance control (NH$_4^+$ concn)

### 3.3. Feedforward Control Logic

When a disturbance occurs in a given process, the feedforward control logic acts without waiting for the process variable to deviate from the set point. The feedforward control measures disturbances when they are far from the system, anticipates the effect of these disturbances, and takes corrective measures in advance. The generation of control actions is based on disturbance measurements. Reference 32 presented the feedforward control logic to deal with disturbances that may occur in ammonium concentration. The control logic is based on the optimal value of the oxygen to ammonium volumetric loading ratio (RO). In light of results obtained via simulations, it was observed that process operation at lower-than-optimal ratios led to the accumulation of ammonium. The AOB act as limiting agents with regards to NRE. On the other hand, process operation at above-optimal RO values led to accumulation of the nitrites or nitrates. This led to a compromise in the NOB growth or AnAOB inhibition. Operation under both scenarios resulted in the attainment of lower RT during the process.

Assuming the bulk oxygen concentration to be negligible, RO can mathematically be expressed as

$$RO = \frac{K_{L,a} S_{O_2, sat}}{\left(\frac{NH_4^+}{HRT}\right)}$$  \hfill (12)

Equation 12 can be modified to express the control law in the following form:

$$K_{L,a} = \frac{RO_{SP} S_{O_2, sat}}{NH_4^+ \left(\frac{HRT}{HRT}\right)}$$  \hfill (13)

Implementation of the feedforward control logic is depicted in Figure 4.

**Advantages of feedforward control logic:**

1. faster response to influent disturbances (NH$_4^+$ concn)
2. easy implementation
3. highly suitable when large disturbances exist in the input

**Limitations:**

1. no action taken in case of model mismatch or microbial conversion failure
2. failed to reject disturbance in organic carbon

### 3.4. Ratio Control Strategy

The ammonium concentration inside SBR has a significant influence on the RT and system performance. Ammonium concentration directly affects ammonia and NOB activities. It is desirable to maintain an appropriate value for the nitrite-to-ammonia concentration ratio in the effluent upon completion of the nitration process. Reference 34 presented a closed feedback loop, which maintains DO concentration within acceptable limits, and the use of a PI controller was prescribed for precise control. Along with the DO control loop, a feedback control loop for regulating the concentration of total ammonia nitrogen (TAN) in bulk liquid was implemented using an elementary on–off controller. The influent flow rate was used as the manipulated variable. Figure 5 depicts the structure of the ratio control strategy implemented. Set points of both control loops were linked together using a proportionality constant, $R_{SP}$, given in eq 14.

$$DO_{SP} = R_{SP} \times TAN_{SP}$$  \hfill (14)

The DO and TAN control loops can mathematically be expressed as

$$\frac{d[DO]}{dt} = K_{L,a} (DO_{SP} - DO)$$  \hfill (15)
where $K_{i,a}$ and $K_c$ represent the oxygen mass transfer coefficient and controller proportional gain, respectively. If a high value of $R_{SP}$ ($R_{SP} > 1$ mg of O$_2$ mg$^{-1}$ of TAN) is selected, the corresponding TAN concentration becomes the limiting agent, whereas for low values of $R_{SP}$ ($0.02 > R_{SP} > 0.01$ mg of O$_2$ mg$^{-1}$ of TAN), the DO concentration acts as the limiting agent. An accurate control of the DO-to-TAN ratio helps in regulating the nitrate concentration. Based on the efficiency of the ratio control strategy, the nitration process may be sustained. The control strategy has the following advantage and limitation:

**Advantage**

1. stable full nitration at low temperature

**Limitation**

1. RT depends on the selection of the $R_{SP}$ value

### 3.5. Feedback–Feedforward Control

A combination of the feedforward and feedback control logic theories has been observed to significantly improve system performance. The feedforward system suppresses the effect of measured disturbances before they affect the system, and the feedback system tracks changes in the variable set point and suppresses the effect of unmeasured disturbances that occur inside the system. A combination of both algorithms offers a better strategy for disturbance elimination. Figure 6 depicts the typical structure of the feedback–feedforward control system. The study combined two strategies to eliminate the disturbances in ammonium as well as organic carbon concentrations. The resulting control system aimed at realizing a process operation at the highest possible NRE. The method utilizes the RT, defined in eq 9, as the control variable, because the DO concentration level (the commonly used control variable) lies beyond the detection limits in this process. The mass transfer coefficient is considered as a manipulated variable. As discussed earlier, for the feedback loop, the control action is determined by the offset in RT. The direction of the control action is decided by $R_{amm,tot}$ defined in eq 10. In the feedforward loop, the value of the manipulated variable is altered to account for changes in ammonium concentration. Major disturbances in the process have been observed to occur owing to changes in the ammonium and organic carbon concentrations.

The proposed feedback–feedforward control structure for the ANAMMOX process is depicted in Figure 7. The stability of the feedback loop is not affected by the presence of the feedforward loop, and both loops may be designed independently of each other. The feedback loop updates the set point for the feedforward loop, in accordance with eq 17.

$$Q_{in} = Q_{in,q} \left[ 1 + K_i \left( \frac{TAN_{SP} - TAN}{TAN_{SP}} \right) \right]$$  \hspace{1cm} \text{(16)}$$

where $K_i,a$ and $K_c$ represent the oxygen mass transfer coefficient and controller proportional gain, respectively. If a high value of $R_{SP}$ ($R_{SP} > 1$ mg of O$_2$ mg$^{-1}$ of TAN) is selected, the corresponding TAN concentration becomes the limiting agent, whereas for low values of $R_{SP}$ ($0.02 > R_{SP} > 0.01$ mg of O$_2$ mg$^{-1}$ of TAN), the DO concentration acts as the limiting agent. An accurate control of the DO-to-TAN ratio helps in regulating the nitrate concentration. Based on the efficiency of the ratio control strategy, the nitration process may be sustained. The control strategy has the following advantage and limitation:

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$$R_{OF}(t) = \begin{cases} R_{OF,0} - K_c e(t) & R_{amm,tot}(t) > R_{amm,tot,SP} \\ R_{OF,0} + K_c e(t) & R_{amm,tot}(t) \leq R_{amm,tot,SP} \end{cases}$$  \hspace{1cm} \text{(17)}$$

where $e(t) = RT_{SP} - RT(t)$.
Once the value of RO_sp is set, the value of $K_a$ may be calculated using eq 13. The value of the proportional gain, $K_P$, may be determined as the inverse of the process gain, $K_P$. To determine the $K_a$ value, the system may be simulated with both a positive and a negative step change in the $K_a$ value in an open loop system with no controller. Using the process reaction curve, the value of $K_a$ may be determined. In order to ensure that the DO concentration does not exceed the upper threshold, an override loop is provided to produce a decrease in the aeration intensity (eq 18) as soon as DO levels attain a value close to the upper threshold DO* for negative values of $K_a$, the aeration flow rate may be set to zero.

$$K_a = \begin{cases} K_a & \text{DO < DO}^* \\ K_a - K_c(\text{DO - DO}) & \text{DO \geq DO}^* \end{cases}$$ (18)

To facilitate real-time experimentation, a relation between the air flow rate and the mass transfer coefficients was obtained, as given in eq 19, via curve fitting.

$$Q_a = 0.0022K_a$$ (19)

The air flow rate could be manipulated with a mass flow controller. The mass flow controller adjusts the flow rate in line with the following correlations (eqs 20 and 21), obtained via experimental calibrations.

$$Q_a = 0.0351\text{MFC}_P + 0.0241 \quad \text{for} \quad \text{MFC}_P < 25\%$$ (20)

$$Q_a = 0.0168\text{MFC}_P + 0.556 \quad \text{for} \quad 25\% \leq \text{MFC}_P < 50\%$$ (21)

Advantages:
(1) faster disturbance rejection in organic carbon and ammonia concentration
(2) use of RT as control variable is more reliable

Limitations:
(1) complicated design and high number of sensors required

3.6. Fuzzy Logic Control.35 Fuzzy control provides a methodology to build a nonlinear controller based on heuristic data. Fuzzy controllers operate mainly in three steps, fuzzification, fuzzy interference system, and defuzzification. Figure 8 depicts a typical structure of the fuzzy logic controller. The fuzzification and defuzzification steps are performed by the membership functions (MFs). The fuzzy logic control system provides user-friendly operation, while focusing on the maximization of process performance. The study35 developed a systematic method to design the fuzzy logic control structure for the PN/ANAMMOX system. The objective of the fuzzy controller was to achieve high NRE, and it primarily focused on the development of MFs in an organized manner by formulating optimization objective functions at each step. The control variables (CV) considered include $R_{\text{Nit-ammonia}}$ (NH$^+_3$ ions consumed and total amount of nitrogen removed ratio), $R_{\text{Nit-ammonia}, \text{eff}}$ (NO$^+_2$ and NH$^+_3$ ions present in the effluent ratio), $R_{\text{NOB}, \text{eff}}$ (NO$^+_2$ and NH$^+_3$ ions produced and total nitrogen removed ratio), and $R_{\text{RT}}$ (NH$^+_3$ RT).

The fuzzy logic controller uses oxygen supply as the manipulated variable, which is represented by the mass transfer coefficient ($K_a$). System parameters indicating microbial activity in the biomass include the complete autotrophic nitrogen removal (CANR) performance index, AOB activity, and AnAOB activity. To incorporate the process nonlinearity and effects of all parameters on the process, two fuzzy logic controllers were developed. The first, called the fuzzy logic diagnosis (FLD), is a diagnosis controller capable of detecting the current microbial activity of the biomass present within the system with the help of indicator parameters. The second, called the fuzzy logic controller (FLC), generates proper control actions based on diagnosis results provided by FLD.

The development of these controllers required the system to be divided into three operating states or four bounds, namely, the optimal state (RT greater than 92%), the suboptimal state (RT greater than 75% but less than 92%), and the worst state (RT less than 75%). The controller alters the manipulated variable each time the microbial activities are compromised. The objective function, which identifies these critical points, was defined so that the error between the RT and each of the four bounds of the system state is minimized. At certain critical points, the deviation of the control variables from the corresponding critical values indicates the existence of microbial imbalance. Fuzzy sets are identified once the key critical variables have been determined for each biological scenario. The MFs are triangular trapezoidally shaped. The values of the variables are considered inputs to the FLD. The FLD then determines the CANR performance index, AOB activity, NOB activity, and AnAOB activity as the output, which subsequently serves as an input to the FLC. The FLC decides the control action based on the microbial activity of the biomass and yields the mass transfer coefficient as an output. During defuzzification, the area technique, which yields outputs in the range of −1 to 1, is implemented. The value of $K_a$ is appropriately scaled to determine the oxygen flow rate. Figure 9 demonstrates the overall structure of the fuzzy logic control system. Based on this knowledge, the IF–THEN rule-based logic has been developed.
in the fuzzy inference system (FIS) to relate the input and the output. The linguistic rule logic incorporates the nonlinearity associated with biological processes. The pros and cons of the fuzzy logic control system are the following:

**Advantages:**
1. capable of rejecting long-term influent disturbance
2. RT = 92%
3. open-loop NRE of the system is improved by 4%
4. robust against measurement noises, and filter sensor noise
5. nonlinearity and complexity of the process are taken into consideration
6. method does not depend on model parameters
7. able to handle persistent influent disturbances, measurement noises, and actuator errors

**Limitations:**
1. complex design
2. rules are based on knowledge
3. implementation of this strategy increases the operating cost of the system

3.7. Optimal Control System (H∞ control) Reference 36 proposed a methodology for developing an optimal control system for efficient removal of nitrogen during wastewater treatment. Based on stoichiometric reactions, it is observed that optimal removal of nitrogen is obtained when the ratio of nitrite-to-ammonium concentration is 1.3 at the end of partial nitration. The corresponding optimal ranges of pH values and DO concentration are 6.8–7.8 and 0–0.5 g m⁻³, respectively. Possible candidates for manipulated and control variables include DO concentration, pH value, TAN, total nitrite nitrogen (TNN), and TAN/TNN ratio. The manipulated variables are selected using the relative gain array (RGA) and closed loop disturbance gain (CLDG) plots. The degree of interaction and pairing between the control and manipulated variables is determined by RGA. The different control variables are ranked on the basis of priority by H∞ analysis, which involves the formulation of an optimization objective function that can be solved to determine the controller. The controller thus obtained, is suitable for particular objective functions. All control variables are grouped in all possible combinations and used to solve the optimization problem. The controller is determined by minimizing the H∞ norm for a desired closed loop shape at all frequencies. The H∞ norm is given by

\[ \| F(G, C) \|_\infty = \max_{j \omega} \sigma(F(G, C)(j\omega)) \]

Here, \( \sigma \) represents the maximum singular value, and \( F \) is the closed loop transfer function between plant \( G \) and controller \( C \). The sensitivity \( S \) and complementary sensitivity \( T \) functions are used to define the mixed sensitivity stacked H∞ control, expressed as

\[ \max_{c} \| F(G, C) \|_\infty \]

In the eq 23,

\[ F = \begin{pmatrix} W_pCS \\ W_pT \\ W_pS \end{pmatrix}; \quad S = (1 + CS)^{-1}; \quad T = CS(1 + CS)^{-1} \]

\( W \) represent the weighting functions that may be determined from the shape of the closed loop transfer function for each control variable. The controller determined by solving eq 23 is considered stabilized if it satisfies the inequalities described in eqs 24 and 26. A low value of \( \gamma \) indicates the availability of a better candidate as control variable.

\[ \sigma(CS(j\omega)) \leq \gamma \sigma(W_{U}^{-1}(j\omega)) \]  \hspace{1cm} (24)

\[ \sigma(T(j\omega)) \leq \gamma \sigma(W_{T}^{-1}(j\omega)) \]  \hspace{1cm} (25)

\[ \sigma(S(j\omega)) \leq \gamma \sigma(W_{p}^{-1}(j\omega)) \]  \hspace{1cm} (26)

The TAN/TNN ratio is selected as the control variable with the above process. The best pairing is found to be between the pH and the acids/bases and the DO concentration and mass transfer coefficient. The CLDG plots are also found to agree with the RGA results.

Three different control structures to achieve the desired objective are proposed. The first comprises a regulatory control logic system. The second comprises a cascade control logic system. The third comprises a multiloop control logic system.
structure, as shown in Figure 10. It employs a basic control logic designed with CLDG plots. The optimal set points for pH and DO concentration are determined to be 7.3 and 0.2 g m$^{-3}$, respectively, for an influent nitrite-to-ammonium ratio of 1.3. The set points of pH and DO concentration are determined for a particular set of influent conditions, and the set points are observed to change with corresponding changes in the influent nitrite-to-ammonium ratio. To consider a continuous change in DO concentration and pH value, the cascade control logic, depicted in Figure 11, was developed. It manipulates the set points of the DO level based on the influent nitrite-to-ammonium ratio. This control logic affects the ammonium microbial activity of oxidizing bacteria, thereby governing the extent of ammonium dissociation.

Table 6. Pros and Cons of the Different Structures of Optimal Control System (H$_\infty$ Control)

<table>
<thead>
<tr>
<th>Pros</th>
<th>cascade control</th>
<th>nested cascade control</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRE of 85% applicable on complex processes measured variables (DO and pH) are unaffected by change in disturbance</td>
<td>NRE of 92% applicable on complex processes DO set point is regulated by effluent TNN/TAN ratio</td>
<td>NRE of 95% applicable on complex processes TNN/TAN set point is regulated by nitrite and ammonia concentration in the reactor</td>
</tr>
<tr>
<td>DO set point is selected for a particular condition and effluent TNN/TAN ratio varies if the feed condition changes</td>
<td>DO set point is regulated by effluent TNN/TAN ratio</td>
<td>control objective not addressed complex structure</td>
</tr>
</tbody>
</table>

Figure 12. Structure of nested cascade control logic.

To further improve the NRE, the nested cascade control logic was proposed, wherein the set point of nitrite-to-ammonia ratio is determined based on their respective concentrations within the ANAMMOX reactor. The feed to ANAMMOX must possess the optimum nitrite-to-ammonium ratio (1.3). Nitrite and ammonium concentrations are measured within the ANAMMOX reactor, and the difference between them is minimized. If the ammonium concentration is greater or less than that inside the ANAMMOX reactor, the set point is altered in order to achieve the optimum concentration ratio of 1.3 in the feed. Figure 12 depicts the nested control logic structure. The pros and cons of each control strategy are provided in Table 6.

3.8. Feedback Control Logic

This study proposed four feedback control strategies to reduce the effect of disturbances on system performance and improve overall

Figure 13. Structure of feedback control strategy.
Table 7. Pros and Cons of the Different Structures of Feedback Control Logic

<table>
<thead>
<tr>
<th>fixed NH$_4^+$ set point feedback control</th>
<th>fixed NH$_4^+$ set point feedback control with DO limit</th>
<th>fixed DO set point feedback control</th>
<th>adaptive NH$_4^+$ set point feedback control with DO limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pros</td>
<td>prevents inhibition of ANAMMOX bacteria</td>
<td>suitable for fixed NH$_4^+$ concentration feed</td>
<td>set point varies according to the reactor concentration</td>
</tr>
<tr>
<td>Cons</td>
<td>selection of DO limit depends on granular conditions in the field</td>
<td>insufficient/excess DO provided for different feed conditions</td>
<td>implementation is costly and complicated</td>
</tr>
</tbody>
</table>

NRE. With the first control strategy, ammonia concentration in the effluent water is regulated by manipulating the oxygen supply rate. The ammonia concentration in the effluent is measured, and a PI controller is used to reduce the error between the set point and the measured value. With the second, DO concentration control is implemented through a PI controller that sets a limit on the acceptable DO levels. The controlled and measured variables remain similar to those in the previous control strategy. With the third, the DO concentration is maintained at a fixed value regardless of the feed condition. In this case, DO is used as the control variable and the air flow rate serves as the manipulated variable. The fourth utilizes adaptive control and alters the set point of the ammonia concentration based on disturbances. The method involves measuring the feed disturbances and using the correlation in eq 27 to determine the set point of ammonia concentration. To prevent increases in DO levels, a dedicated DO level controller is also implemented.

\[
\text{NH}_4\text{SP}^+ = \text{NH}_4^+ + k_1 \left( \frac{Q_{NH}_4^+}{Q_{NH}_4^0} - 1 \right) - k_2(T - 20)
\]  

(27)

Here, $k_1$ and $k_2$ are adjustment coefficients corresponding to the load and temperature, respectively. Figure 13 depicts the structure of all four control logics discussed in this section. Each of the design structures offers some advantages and has some limitations, as listed in Table 7.

4. DISCUSSION

The performance of an optimum control strategy is highly dependent on the accuracy of the measurement sensors. For practical applications, there are no reliable nitrite or nitrate concentration sensors available. Consequently, control strategies that involve measurements of these variables inevitably result in poor system performance. However, sensors for the measurement of ammonium and DO concentrations are very accurate and commonly used in the wastewater treatment plant. Due to the high complexity of the wastewater treatment mechanism and properties, it is necessary to know the model accurately to estimate the parameters. Two-input, two-output models of the system are available in literature to develop the model based control strategies and decentralized control strategies. Nonlinear models for such processes are described by refs 34 and 55. The difficulties in quantifying the online sensors are discussed in the literature.

The impact of feed disturbances and biomass microbial activity on system performance has also been considered while designing the control structures discussed. The proposed control strategies assist in realizing the capability of the nitrogen removal technology in full-scale plant applications. The conventional feedback–feedforward control logic is easy to implement with little complexity.

However, with regards to incorporation of nonlinear and time-variant characteristics of the system, advanced control designs of fuzzy controls and optimal control systems have great potential to be developed further.

Two real-time control logic designs that require online sensor measurement are discussed, and their control strategy is implemented using an algorithm code based on the proposed logic. Both methods were patented in the past decade. The method proposed in ref 30 reduces the aeration energy consumption by 25%, the sludge production by 30%, and the carbon dosage by 40%, while the one proposed by Gonzalez and Opinsa reduces the time required to achieve NRE of 95%. Eight sensors are required by the former method to measure effluent conductivity and flow, wastewater conductivity and flow, DO, redox potential, pH, and temperature. The latter method requires 11 sensors for the measurement of flow rate, conductivity, temperature, and pH of the effluent to be treated, dissolved oxygen, temperature, pH, conductivity, and ammonium concentration in SBR, and conductivity and flow rate of the wastewater. The number and maintenance of the sensors make the process economically costly.

The ratio control strategy in ref 34 is able to operate at full nitration state at 20 °C, and the modeling results predict stable operation at 15 °C. The nitrite accumulation in the reactor depends on the disturbance time scale. In the presence of disturbances in the TAN concentration, the ratio DO/TAN is kept constant by manipulating the DO, resulting in full nitration and maximization of the efficiency of the ratio control strategy. The fuzzy logic control strategy has been found to improve the process efficiency by 4% but is a complex process and requires extensive knowledge of the process and the microbiological behavior.

The fuzzy control strategy requires less computational time (on the order of minutes), and the use of $H_\infty$ takes into consideration the one-way interactions, which are overlooked by the RGA. The method is applicable in model mismatch as the control techniques applied are robust. The dependency of $\gamma$ on the process does not allow the decision of a threshold for the CV selection. The RGA/$H_\infty$ analysis, along with CLDG plots, helps in CV selection. The first cascade loop added in the control structure helps in improving the NRE, whereas the second cascade loop maximizes the efficiency. In the cascade control structure, the carbon dosage is 40% less than the demand for regulatory control. However, the nested cascade structure requires 4% more than the cascade structure. The implementation requires four sensors to measure DO, pH, TAN, and TNN.

It is observed that the control strategy with fixed ammonium concentration cannot be used for mainstream water treatment owing to the large-scale accumulation of nitrate ions. When operating under low temperature, maintaining ammonia concentration at the specified set point tends to increase the DO concentration, thereby causing inhibition of ANAMMOX bacteria. In the second control strategy, by introducing a DO
level control, the inhibition of ANAMMOX bacteria is prevented. This extra control makes this strategy implementable in the treatment of mainstream wastewater. It is also observed that an increase in the NOB concentration at the beginning of the process tends to increase the NRE. Compared to the other feedback logic, this control strategy is easier to implement because it requires a minimum amount of measurement data. In the third control strategy, the DO level set points tend to deteriorate the process performance. As the ammonium concentration in the feed is now fixed at different values, correspondingly different DO concentrations are required. For a feed containing low ammonium concentration, a high DO concentration leads to accumulation of nitrite ions. In contrast, in a high ammonium concentration feed, a lower DO concentration leads to an increase in ammonium ions. Therefore, this strategy is not implementable in the PN/ANAMMOX process. Factors such as temperature, COD, ammonium concentration, and biomass availability tend to affect the DO concentration. The adaptive control strategy involves the measurement of disturbances. Based on these measurements, the set point of the ammonium concentration is updated. Results obtained from sensitivity analysis indicate that, as a control variable, ammonium concentration is preferable compared to the DO concentration. Only one sensor is required for the implementation of the control logic.

5. CHALLENGES AND FUTURE TRENDS: CONTROL AND OPERATION

The research on the PN/ANAMMOX process was carried out on various ammonium-rich wastewaters (sludge liquor, sludge supernatant, partially nitrified sludge, sludge digestate, slaughterhouse, piggery wastewater, etc.). Currently, the main two areas of ANAMMOX process application are the treatment of digested sludge rejected water and that of landfill leachate. Major challenges in the application of the PN/ANAMMOX process include the inhibition by exogenous compounds and substrates, the management of the COD N\(^{-1}\) ratio, low-temperature operation, microbial retention, slow start-up, and mainstream application. The majority of the full-scale PN/ANAMMOX processes are implemented in side stream treatment of wastewaters. A survey reported that 75\% of full-scale plants are operating for treatment of side streams. ANAMMOX has been operated in full-scale plants for treating sludge digestion supernatant in The Netherlands. The full-scale process involves treatment of industrial wastewater with ammonia concentrations on the order of 1 g of N L\(^{-1}\), which is much higher compared to the ammonia concentration present in municipal or domestic wastewaters. An interesting prospect of converting the biodegradable organic matter to biogas has emerged, making the plant energy self-sufficient or energy producing. Although the concept was projected two decades ago, the implementation has not yet been realized.

Owing to the slow growth rate of ANAMMOX bacteria, the start-up process of the reactor is very slow. The condition may, however, be improved by controlling the sludge retention time. Various reactor configurations (moving bed biofilm reactor, up-flow anaerobic sludge blanket reactor, SBR, and rotating biological contactor) have been proposed to improve the start-up time of the system. Even after incorporating all necessary precautions, biomass washout is unavoidable under certain operating conditions.

To extend the application of the strategies implemented on the side stream to mainstream wastewater treatment, the first challenge involves appropriate handling of high C/N ratios (7–12 g of COD g\(^{-1}\) of N) in the mainstream treatment when compared to the side stream treatment (<1 g of COD g\(^{-1}\) of N). A high C/N ratio leads to accumulation of the heterotrophic bacteria that hinder the AOB and ANAMMOX activities. The development of real-time control strategies capable of dealing with the varying influent characteristics caused by seasonal variations and heavy rains is required. More studies focusing on carbon absorption and storage mechanisms, improving process efficiency under various SRT, HRT, DO, and temperature conditions, and bioflocculation and coagulation are recommended. Under side stream wastewater treatment, NOB activities are suppressed by the presence of free ammonia and free nitrous acid, whereas in municipal wastewater treatment, the NOB is much more active. The control of NOB suppression presents yet another challenge. It makes the control process more complex. Low activity of AnAOB forms another bottleneck. Operation under low temperatures is observed to tend to reduce bacterial growth and activity by approximately ten times when the temperature drops from 30 to 10 °C. ANAMMOX bacteria have been found to be not very active at low temperatures. This difference in bacterial growth rates at different temperatures causes an imbalance in the microbial activity, thereby reducing the NRE. Determination of a suitable operational condition is therefore necessary. An additional hindrance to the process is caused by the post-treatment or final polishing of the treated water, which is performed to improve the effluent water quality. This post-treatment process tends to increase the energy consumption and the operational cost of the plant, which outweighs the benefits of the ANAMMOX process. Recent developments in advanced control systems and soft sensors technology have enabled accurate and regular monitoring of ammonium, nitrite, and nitrate concentrations during the ANAMMOX process. Although its implementation is still not popularized, there is a need to further investigate the issues mentioned above. In addition, the design of a functional and stable ANAMMOX reactor, comprising a sensor-mediated robust control system and mechanical equipment, is required.

6. CONCLUDING REMARKS

Systematic computational strategies and control-structure designs for wastewater treatment have been suggested recently by several researchers. The basic objective underlying these control-structure designs is to maximize the NRE and improve the effluent water quality in accordance with environmental laws and regulations. The study discusses the design and implementation of different control structures, proposed by various researchers, in applications concerning the PN/ANAMMOX system. The biological process requires apt pairing of the control and manipulated variables. The methodology for selecting suitable candidate variables and determining the corresponding pairing criteria was also provided herein.

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NOMENCLATURE

PN  partial nitration
DO  dissolved oxygen
NRE  nitrogen RT
NI  Niederlinski index
RGA  relative gain array
SP  proportionality constant
DOu upper threshold of dissolved oxygen
kR  feedback gain
TNN total nitrite nitrogen
STOAT sewage treatment operation and analysis over time
WEST wastewater treatment plant engine for simulation
AQUASIM aquatic ecosystem simulation
ASIM activated sludge simulation
COD  chemical oxygen demand
DO  dissolved oxygen
PN  partial nitration
NOMENCLATURE

Abbreviations

$N_{\text{lim}}$ minimum number of feed cycles
$F_{\text{NH}_4}$ daily nitrogenous feed
$t_c$ time for completion of the biological cycle
$R_{\text{ammonia}}$ total nitrogen removed
$K_{i,a}$ mass transfer coefficient
$K_c$ controller proportional gain
MFs membership functions
S sensitivity
$k_1$ and $k_2$ adjustment coefficients
$V_{\text{min}}$ minimum liquid volume
$N_{\text{SSR}}$ number of cycles completed in a day
RT  removal efficiency
$R_{\text{sp}}$ proportionality constant
$K_p$ process gain
DO* upper threshold of dissolved oxygen
$\bar{\sigma}$ maximum singular value
$F$ closed loop transfer function between plant (G) and controller (C)

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