water

MDPI

Article

Wastewater Treatment System Optimization for Sustainable Operation of the SHARON–Anammox Process under Varying Carbon/Nitrogen Loadings

Paulina Vilela [1,*], Kijeon Nam [2] and Changkyoo Yoo [2,*]

[1] ESPOL Polytechnic University, Escuela Superior Politécnica del Litoral, ESPOL, Facultad de Ingeniería en Ciencias de la Tierra, Campus Gustavo Galindo Km. 30.5 Vía Perimetral, P.O. Box 09-01-5863, Guayaquil 090112, Ecuador

[2] Integrated Engineering, Department of Environmental Science and Engineering, College of Engineering, Kyung Hee University, 1732 Deogyeong-daero, Giheung-gu, Yongin-si 17104, Republic of Korea

* Correspondence: pvilela@espol.edu.ec (P.V.); ckyoo@khu.ac.kr (C.Y.); Tel.: +82-31-201-3824 (C.Y.)

Abstract: Partial nitritation (PN) coupled with the anaerobic ammonium oxidation (Anammox) process has improved ammonium removal in wastewater treatment plants (WWTPs). The operation conditions of this process, i.e., the dissolved oxygen (DO) and the influent ammonium and nitrite concentrations, drive the process to an equilibrium to suppress nitrite-oxidizing bacteria and achieve a proper nitrite over ammonium (NO_2/NH_4) ratio. This study aimed to implement a set of control strategies in a WWTP model BSM2-SHAMX, combining PN in a single reactor system for high-activity ammonia removal over nitrite (SHARON) to an Anammox reactor, using proportional–integrative–derivative (PID) control and model predictive control (MPC) in a cascade. For correct coupling, the PN should maintain an output NO_2/NH_4 ratio between 1 and 1.3, suitable for the Anammox process. In the cascade controller feedback loop, the primary control loop controls the NO_2/NH_4 ratio through the DO concentration from the secondary control loop, which guarantees better effluent nitrogen removal. The performance of the plant was assessed by evaluating the control strategies with different influent carbon/nitrogen (C/N) loadings. The study results showed that the MPC controllers provided better results, with an improvement of 36% in the operational cost compared to the base case with a cost around 26,000 EUR/d, and better nitrogen removal surpassing 90% removal, 10% more than the base case.

Keywords: cascade control strategy; resource recovery; benchmark model; partial nitritation; SHARON; anammox process; C/N ratio

Citation: Vilela, P.; Nam, K.; Yoo, C. Wastewater Treatment System Optimization for Sustainable Operation of the SHARON–Anammox Process under Varying Carbon/Nitrogen Loadings. *Water* **2023**, *15*, 4015. https://doi.org/10.3390/w15224015

Academic Editor: Antonio Zuorro

Received: 22 October 2023
Revised: 13 November 2023
Accepted: 15 November 2023
Published: 19 November 2023

1. Introduction

Wastewater treatment problems are progressively becoming global, making it essential to focus policies and investigations on designing and operating wastewater treatment plants (WWTPs) for water reuse, resource recovery, and sustainable biological nutrient removal [1,2]. A huge concern in WWTPs is the variation in high-strength ammonium wastewaters from anaerobic digester effluent [1,3], which negatively affect WWTPs' performance because they are recirculated to the plants' main stream, increasing the nitrogen loading and inhibition effects of microorganisms on the main stream of the plant. Aerobic ammonia oxidizers are inhibited at ammonium concentrations in the range of 10 to 150 mg/L, and nitrite oxidation is inhibited when the ammonium concentration is 0.08 to 0.82 mg/L [1]. Those conditions affect the nitrogen removal performance of the plant because the influent nitrogen overloads the system, making it difficult to achieve effluent quality standards [4]. Therefore, high-strength ammonium loading must be controlled to meet quality standards in WWTPs.

Novel technologies have been studied over the years to overcome the effects of nitrogen overloads, such as the configurations of oxic–anoxic treatment process [5], the combined nitrification/denitrification and deammonification process, complete autotrophic nitrogen removal over nitrite (CANON) [6], single reactor system for high-activity ammonia removal over nitrite (SHARON), and the anaerobic ammonium oxidation (Anammox) [7–10]. The combined SHARON–Anammox process has been reported to present a substantial advantage in nitrogen removal, reducing operational costs and benefiting resource recovery [4,7,11]. SHARON and Anammox can be effectively controlled and monitored by adjusting the key factors of pH, dissolved oxygen (DO) concentration, NO_2/NH_4 ratio, and temperature conditions, for maintaining the microorganisms activity in the treatment process [12].

The SHARON process can achieve nitritation while stabilizing the sludge retention time (SRT). This mechanism helps in the growing of nitrite-oxidizing biomass at high temperatures and a pH of 7. Because of these conditions, the SHARON reactor can then carry out the denitrification process for pH control in its original layout, and through partial nitritation, it can function similarly, generating great savings in the operation of WWTPs [4]. Furthermore, nitrogen removal can be achieved more sustainably through the coupling of the SHARON and Anammox reactors. This coupling can represent huge advantages leading to cost savings via the reduction in aeration usage and waste sludge for instance [7]. The Anammox reactor helps to prevent the oxidation of nitrite to nitrate and enhance the ammonium and nitrite conversion to nitrogen gas through the activity of autotrophic microorganisms [4]. In a nutshell, the combined SHARON and Anammox process allows the oxidation of ammonium to nitrite first in the SHARON reactor, and later, when mixed with the ammonium entering the Anammox reactor, it is converted to nitrogen gas in anaerobic conditions [4,7].

Although the SHARON and Anammox processes can improve nitrogen removal, many factors of their implementation and performance remain unexplored and need to be analyzed [13]. For instance, process control in WWTPs could be advanced to develop feasible systems for enhanced nitrogen removal. Existing research has addressed the implementation of control strategies to optimize operation conditions in WWTPs for nitrogen removal, cost minimization, and further improvements in effluent quality standards for sustainable operation [4,14,15]. In WWTP systems, ammonia-based aeration control strategies have gained attention for providing enough aeration to nitrify ammonia to meet the discharge standards and save operational costs while increasing denitrification [16]. Similarly, refs. [17–19] described pH control strategies for SHARON and Anammox processes in submerged attached-growth bioreactors with low carbon-to-nitrogen (C/N) ratio conditions. Furthermore, artificial intelligence (AI) techniques have been implemented with WWTP systems to maximize removal efficiency and operational conditions [20]. However, despite the wide range of research on control strategies for WWTPs, cascade control strategies, which could optimize the operation of SHARON and Anammox processes in WWTPs, have not been studied much.

Control strategies involving proportional–integrative–derivative (PID) control [4,15,21] or advanced model predictive control (MPC) [18,21,22] are regularly depicted in research, where they have outperformed other strategies. Advanced control strategies, such as the cascade control, can surpass the performance of simple PID or MPC controls by integrating them. For instance, a cascade control was implemented by [15] to control the ammonium concentration in the aerobic tank of a WWTP. In that work, a DO controller used the oxygen transfer coefficient to maintain the oxygen concentration in the fourth tank, while an ammonium controller manipulated the oxygen controller to maintain the ammonium concentration in the last tank. That strategy offered good control of the ammonium concentration and reduced the carbon dosage. Ref. [23] described a cascade control composed of feedforward loops that adjusted the influent ammonium loading by manipulating the aeration flow into the aerobic tank. Cascade controllers can work accurately and quickly to achieve good effluent quality. Although cascade controllers are highly recommended and outperform single controllers in WWTP applications, their implementation in the deammonification process is still lacking. Therefore, this study investigates the use of cascade controllers in different control strategies to enhance nitrogen removal and WWTP performance.

Because the deammonification process requires certain factors for appropriate operation, the optimization of operational conditions needs to be researched. Few studies have presented the effects of varying effluent from the anaerobic digester, which can present a different C/N ratio as the influent to the partial nitritation process [1] and an inappropriate NO_2/NH_4 ratio as the influent to the Anammox process [24]. An optimal and low C/N ratio, for nitrogen removal, has the potential to completely convert ammonium to nitrogen gas (N_2) in ammonium-rich wastewater [1,5,25,26]. The NO_2/NH_4 ratio is an underlying condition for the correct operation of the Anammox process. Given that the effluent from the anaerobic digester should be able to oxidize half of the ammonium to nitrite, an adequate product mixture from the partial nitritation process can be obtained by manipulating the NO_2/NH_4 ratio, which affects the nitrogen removal efficiency in the Anammox process by reducing nitrate production in the deammonification process [12]. A NO_2/NH_4 ratio of around 1 to 1.3 prevents the oxidation of nitrite to nitrate, influencing the bacterial growth needed [1,24,27]. Thus, the conditions needed to achieve the correct NO_2/NH_4 ratio in the operation of the deammonification process need to be thoroughly analyzed. This work proposes the use of cascade controllers to evaluate the optimal operation of the deammonification process and maximize nitrogen removal.

The objective of this study is to optimize the nitrogen removal strategy in a WWTP by implementing the SHAMX process in the Benchmark Simulation Model No. 2 (BSM2) of a WWTP, the BSM2-SHAMX model. To do that, the SHARON and Anammox processes are first integrated into BSM2 to analyze the removal efficiency of the system. The SHARON–Anammox processes are coupled after the dewatering process. Second, five established control strategies, PID control for DO, PID control for ammonia, cascade PI-PI, cascade PI-MPC, and cascade MPC-MPC, are compared. The controllers are implemented in a cascade control strategy under several influent scenarios to enhance nitrogen removal efficiency while increasing the resource recovery potential of the SHAMX process. Third, the performance and resource recovery potential of the control strategies are evaluated by considering the aeration energy (AE), pumping energy (PE), sludge production (SP), operation cost (OC), and methane production (METP).

2. Materials and Methods

2.1. Problem Statement

This study evaluated the performance of a WWTP system using different cascade controllers for the deammonification, partial nitritation, SHARON (SH), and Anammox (AMX) processes to treat high-strength ammonium wastewaters from anaerobic digestion. The flowrate of high-strength ammonium wastewaters from reject water affects nitrogen removal in the WWTP, and SHAMX is used to mitigate that condition. However, the AMX process requires a sufficient NO_2/NH_4 ratio, which can be difficult to achieve naturally in WWTP reject water. Therefore, cascade controllers can be integrated into the system to achieve that ratio and improve the plant's overall nitrogen removal.

The WWTP model consists of the biological process in the main line and the sludge and reject water treatment in the sidestream. The model contains information about the flowrates, sludge concentration, and physical and operational conditions of the biological reactors, settlers, anaerobic digester (AD), and SHARON and Anammox processes. The influent flowrate used in the model is presented in Figure S1a, and the influent-suspended solids and ammonia concentrations are shown in Figure S1b for a period of 153 days. The developed model includes the following three main points:

1. The data include the influent flowrate and the flowrate of the components, such as nitrate, ammonia, and oxygen, as well as the sludge concentration, among others in form of model input data such as nitrite, C/N ratio, solids, particulate matter, etc. All of these are required for the model.
2. The processes of a simple biological treatment are given in the WWTP model as one primary clarifier, five biological reactors, one secondary clarifier, one AD, one SHARON, and one Anammox reactor.

The data for the operations and design of the system are contained in the model for both the biological treatment and the reject water treatment (AD, SH, and AMX).

2.2. Proposed Method

The framework proposed in this study is comprehensively presented in Figure 1. It is divided into three main parts: BSM2-SHAMX system modeling including parameter calibration, evaluation through the sensitivity analysis for controller's implementation, and control performance analysis. The sensitivity analysis was developed to obtain insights into the variations in the model caused by different influent concentrations and various operating conditions that influence nitrogen removal in the plant. Then, two single-loop controllers and three cascade controllers were implemented using the BSM2-SHAMX model. The single-loop controllers are PI controllers, and the cascade controllers are PI-PI, PI-MPC, and MPC-MPC controls.

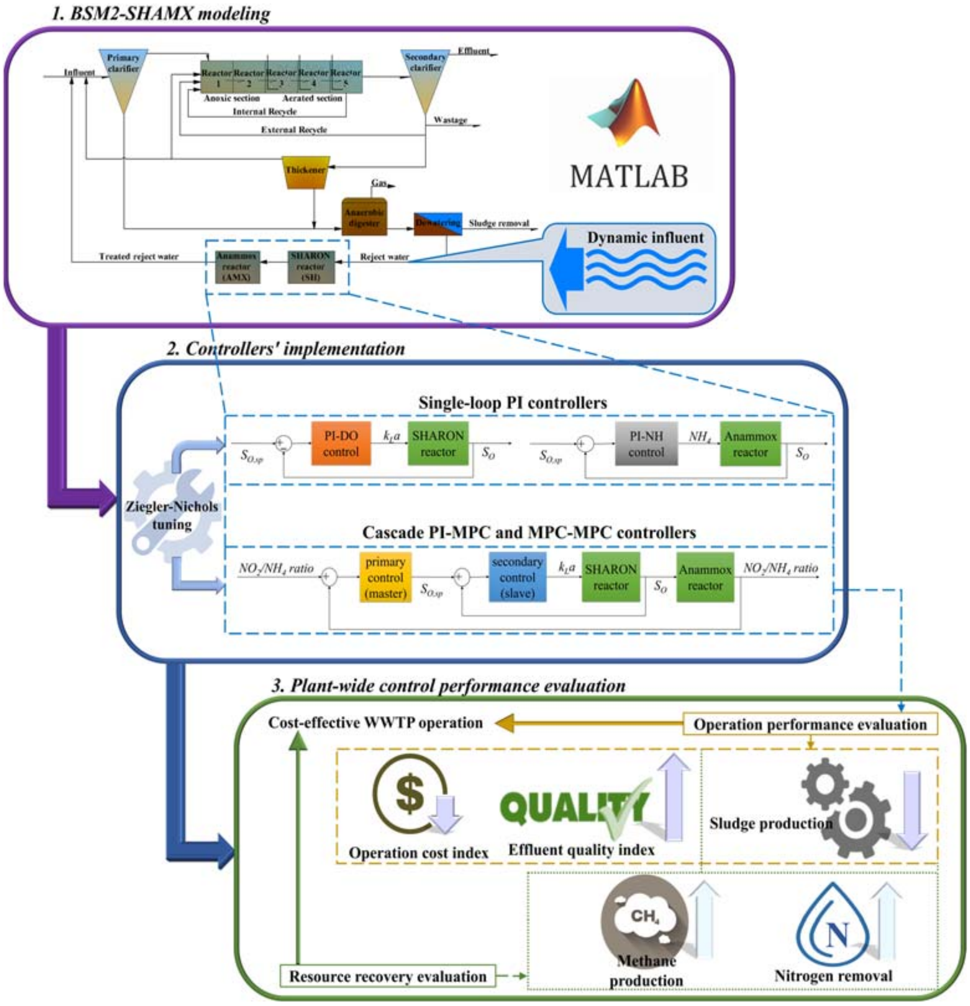


Figure 1. Research framework for BSM2-SHAMX modeling, control implementation, and evaluation.

The control performance of the plant was assessed in terms of effluent quality and resource recovery potential. The conditions encountered during the sensitivity analysis and parameters taken from the literature [4,18] were used for the process control implementation on the BSM2-SHAMX model. Five control strategies were evaluated for their nitrogen removal efficiency to assess the resource recovery potential of the model-based WWTP.

2.3. BSM2-SHAMX Model

The kinetics and stoichiometry of the deammonification process (SHARON and Anammox) were adapted to the BSM2 model. The BSM2-SHAMX model was extended from the BSM2, which is a WWTP benchmark developed by the Institute of Water Association (IWA) [28,29]. The BSM2 is composed of a primary clarifier, five biological reactors, a secondary clarifier, and a thickener; in the sidestream is an AD, a dewatering unit, and a storage tank [28]. The biological treatment in the BSM2 follows activated sludge model No. 1 (ASM1) [28,29]. More detailed information about the BSM2 design is presented in Supplementary Materials.

To this layout, the SHARON and Anammox units were integrated into the sidestream after the dewatering unit under the assumption that they would improve the removal efficiency by treating reject water [4,7,18]. The SHARON and Anammox models were adapted from [4]. The plant configuration is presented in Figure S2, and the components considered in the BSM2-SHAMX model are presented in Tables S1–S3 of Supplementary Materials. The kinetic and stoichiometric parameters of the SH and AMX models are presented in Table S4, and additional Petersen matrices for the BSM2-SHAMX model are presented in Tables S5–S7. The kinetic parameters of the model were additionally calibrated using ranges defined from the literature, as presented in Table S8. Later, they were calibrated to operational influent loadings, as given in Table S9 of Supplementary Materials. Appropriate coefficient and process rates for the models were adapted from the literature [4,14]. More detailed information about the SHAMX design is presented in Supplementary Materials.

2.4. MPC State Space Model

Cascade controllers using nonlinear MPC were implemented to define advanced control strategies that could improve the effluent quality and nitrogen removal. MPC uses the receding horizon principle (RHP) (Figure S4). At sample instant k, an open-loop optimal control problem is solved, and a prediction is made considering the current and future constraints. The future outputs are then computed over the prediction horizon, H_P. The control moves over a control horizon to estimate the optimal trajectory for a defined optimization criterion. Thus, only the first move of the optimal sequence is applied to the plant; after that, the state estimated is corrected with the measured output at the present sampling instant. That process is then repeated at sampling time $k + 1$ using the present state $x(k + 1)$ [30,31]. Overall, MPC consists of the RHP and the optimization for choosing the best sequence of control actions in the time horizon. The optimization comprises the optimization model, an internal MPC model, and its optimization solver [32]. For the control process, the state-space model (SSM) is established assuming the current state $x(k)$, control input $u(k)$, disturbance input $d(k)$, and output $y(k)$ (Equations (1) and (2)) [30,31].

$$x(k+1) = Ax(k) + B_1u(k) + B_2d(k) \tag{1}$$

$$y(k) = Cx(k) + D_1u(k) + D_2d(k) \tag{2}$$

where A, B_1, B_2, C, D_1, and D_2 are the respective coefficient matrices. The output $y(k + 1)$ of the next step is estimated from the iteration of Equations (1) and (2), as presented in Equation (3).

$$y(k+1) = C(Ax(k) + B_1u(k) + B_2d(k)) + D_1u(k) + D_2d(k) \tag{3}$$

The iteration is continued until the step of the prediction horizon (H_P) (Equations (4)–(10)). From Equations (4) and (5), the SSM establishes relationships among the system output, current state, control input, and disturbances from which the system behavior for the next steps can be predicted.

$$X(k+1) = \overline{A}x(k) + \overline{B}_1 \Delta u(k) + \overline{B}_2 \Delta d(k) \tag{4}$$

$$\overline{y}(k) = \overline{C}X(k) + \overline{D}_2 d(k) \tag{5}$$

$$X(k) = \begin{bmatrix} \Delta x(k) \\ y(k) \end{bmatrix} \tag{6}$$

$$\overline{A} = \begin{bmatrix} A^{H_P} & 0 \\ C^{H_P} A^{H_P} & I \end{bmatrix} \tag{7}$$

$$\overline{B} = \begin{bmatrix} B_1^{H_P} \\ C^{H_P} B_1^{H_P} \end{bmatrix} \tag{8}$$

$$\overline{B}_2 = \begin{bmatrix} 0 \\ D_1^{H_P} \end{bmatrix} \tag{9}$$

$$\overline{C} = \begin{bmatrix} 0 & I \end{bmatrix} \tag{10}$$

In this study, ammonia ($S_{NH,AMX}$) in the AMX reactor is the controlled variable, and the manipulated variable is the DO ($S_{O,SH}$) from the SH reactor. The linear model matrices A, B, C, and D are determined by minimizing the error between the process measurements and the simulated model outputs, which are estimated using the MPC toolbox in MATLAB R2016a. In this work, the following matrices represent the MPC model (Equations (11)–(14)):

$$\overline{A} = \begin{bmatrix} 0.8950 & -0.0056 \\ 0.6715 & 1.0487 \end{bmatrix} \tag{11}$$

$$\overline{B} = \begin{bmatrix} -0.067 \\ 11.1464 \end{bmatrix} \tag{12}$$

$$\overline{C} = \begin{bmatrix} 56.3987 & -0.5147 \end{bmatrix} \tag{13}$$

$$\overline{D} = \begin{bmatrix} 0 \end{bmatrix} \tag{14}$$

2.5. Sensitivity Analysis of BSM2-SHAMX

A sensitivity analysis shows which measures should be prioritized to improve nitrogen removal efficiency [33–37]. SHAMX model operation requires the selection of priority parameters, in this case to achieve nitrogen removal efficiency before the control strategies in the system can be evaluated. To make those selections, Monte Carlo simulations with the dimension of N = 1000 were conducted and evaluated using model regressions with the objective of reducing the DO concentration in the SH reactor, the total nitrogen concentration in the SH reactor, and the total ammonia concentration in the SHAMX. Equations S20 to S27 present the process for that analysis. More details about the sensitivity analysis metrics are presented in Section 1.4 of Supplementary Materials.

2.6. Control Strategy Modeling and Evaluation

2.6.1. Implementation of the Control Strategies

The goal of process control is to limit the process output and make the system behave in a desired way by manipulating the process input while reducing utility consumption and operating costs [38]. To compare the performance of control strategies in this study, single PID controllers were implemented as well as MPC cascade controllers. MATLAB R2016a/Simulink software was used to develop the process model and control algorithms.

A detailed description of the control strategies is presented in Table 1. The structures of the single-loop control strategies (C1 and C2) are presented in Figure S5, and the cascade control strategies (C3 to C5) are presented in Figure 2.

Table 1. Configuration of the proposed control strategies on BSM2-SHAMX.

Control Strategy	Base Case C0	C1	C2	C3	C4	C5
Controlled variable	-	SO from SHARON reactor (SO,SH)	SNH from Anammox reactor (SNH,AMX)	SNH from Anammox reactor (SNH,AMX)	SNH from Anammox reactor (SNH,AMX)	SNH from Anammox reactor (SNH,AMX)
Set point	-	SO,SH = 0.0354 * mg/L	SNH,AMX = 12 * mg/L	SNH,AMX = 12 * mg/L	SNH,AMX = 12 * mg/L	SNH,AMX = 12 * mg/L
Manipulated variable	-	KLa in SHARON reactor (KLa,SH)	KLa,SH; SO,SH	KLa,SH; SO,SH	KLa,SH; SO,SH	KLa,SH; SO,SH
Measured variable	-	SO,SH	SNH,AMX	SNH,AMX	SNH,AMX	SNH,AMX
Control algorithm	-	1 feedback PI control	1 feedback PI control	1 cascade PI-PI control	1 cascade PI-MPC control	1 cascade MPC-MPC control
Proportional gain (Kp)	-	689.23	79.88	0.181	79.88	-
Integral gain (Ti)	-	1.98	3.17	3.33	3.17	-

* Value adapted from [3].

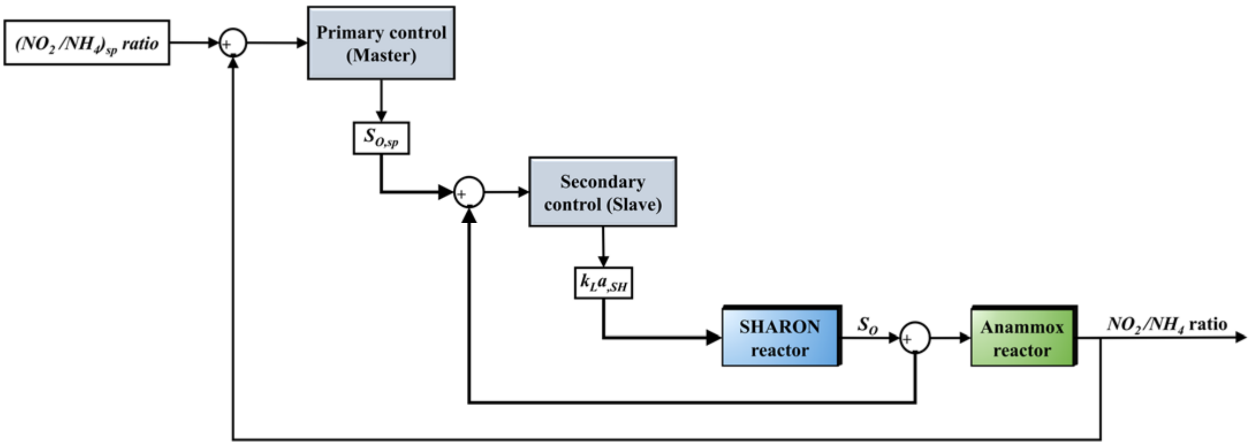


Figure 2. Block diagram of the proposed cascade control strategy (C3 to C5). The secondary control loop calculates the dissolved oxygen concentration (S_O) at the set point given, $S_{O,sp}$, and tracks the S_O set point by adjusting the k_La of the system. The primary control loop compensates for the errors in the S_O measurement to attain the desired NO_2/NH_4 ratio. The primary and secondary control loops are obtained by the feedback of the S_O and NO_2/NH_4 ratio, respectively.

C0 has been defined as a starting point for comparison purposes because this control strategy represents an open-loop system. This configuration represents the BSM2-SHAMX with no controller integration. C1 is proposed as a DO controller on the SHARON process to control the partial nitritation process for the Anammox operation. This control strategy consists of a PI controller that controls the DO concentration from the SH reactor ($S_{O,SH}$) by manipulating the oxygen transfer coefficient in the SH reactor ($K_La_{,SH}$). C2 uses an NH_4 controller on the Anammox process to regulate the NH_4 concentration going into the main stream of the system. The controlled variable is the ammonia concentration in the AMX reactor ($S_{NH,AMX}$), and the manipulated variable is the $S_{O,SH}$. C3 proposes a cascade control comprising PI-PI controllers. $S_{NH,AMX}$ is the controlled variable in the primary control loop, and the manipulated variables are $S_{O,SH}$ in the primary control loop and $k_La_{,SH}$ in the secondary control loop. This control scheme aims to control the deammonification process to reduce the plant's final nitrogen concentration.

A similar concept is implemented in control strategies C4 and C5. The proposed MPC cascade control algorithms present a PI-DO controller and MPC-NH4 controller in

C4, and an MPC-DO controller and MPC-NH4 controller in C5. The incorporation of MPC controllers is proposed to enhance the nitrogen removal. In this work, nitrogen control strategies were implemented by considering the nitrogen and ammonia component variables that represent their removal. More details associated with the calculations of the PID controllers are presented in Section 1.5 of Supplementary Materials.

The simulation results are given for realistic influent data containing daily variations. Figure 3 presents the influent chemical oxygen demand (COD) and N concentrations for C4 and C5. The influent is described for three conditions of influent variation: low C/N ratio (below 1), intermediate C/N ratio (equal to 1), and high C/N ratio (above 1). The ratio value was defined considering previous studies conditions for WWTPs [1,5,25,26]. The low-strength stream data from [28] and high-strength stream data adapted from [4] were used in this study. In [28], the average influent flowrate was 20,648.36 m^3/d, with an average COD of 592.53 mg/L. Those data simulate the wastewater flowrate with daily and seasonal variations, from which dry weather data were adopted. The data from [4] were adopted for a period of 153 days, with an average influent flowrate of 16,730 m^3/d, average ammonia concentration of 24.42 mg/L, average nitrite concentration of 121.2 mg/L, and average nitrate concentration of 337.9 mg/L.

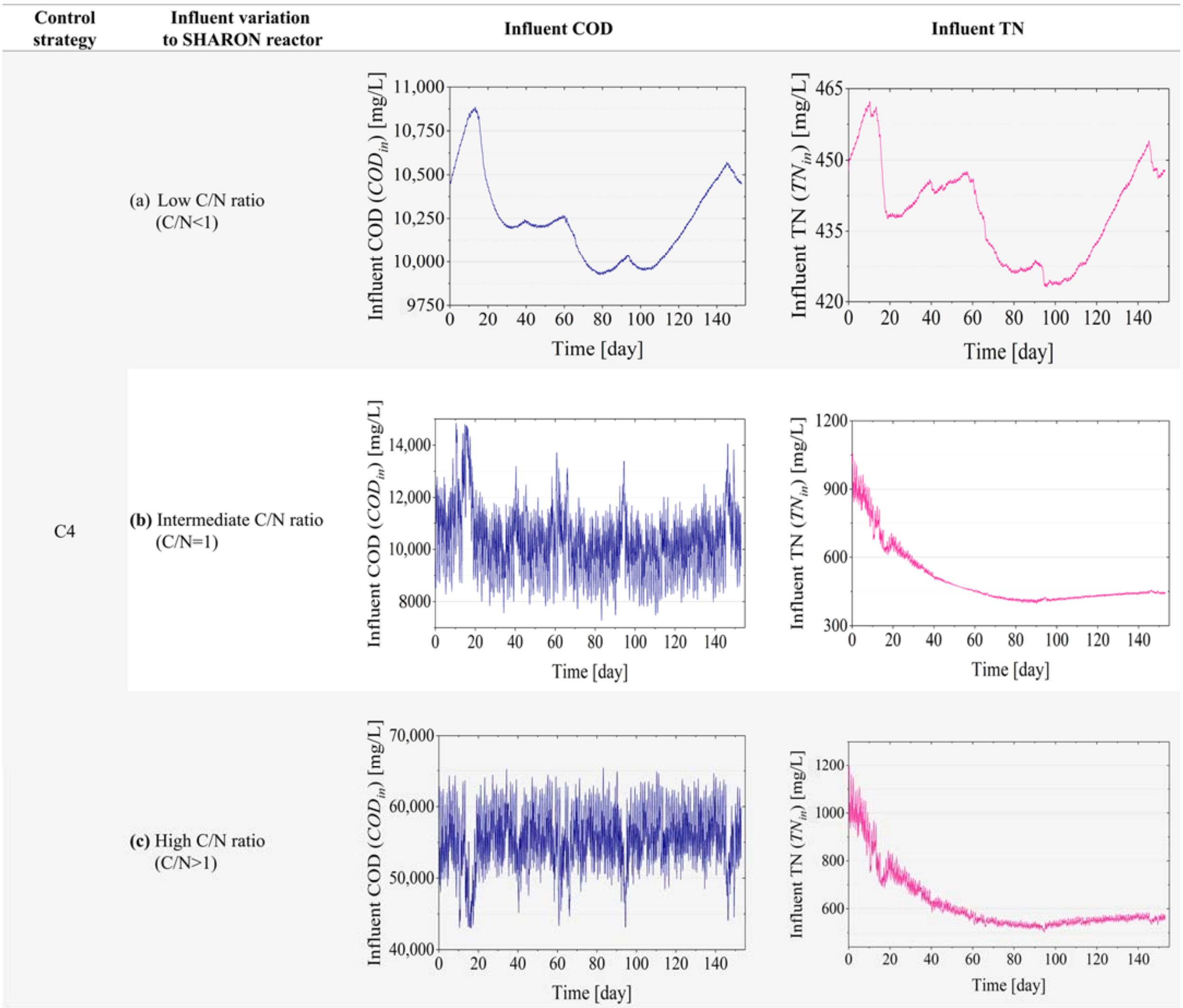


Figure 3. *Cont.*

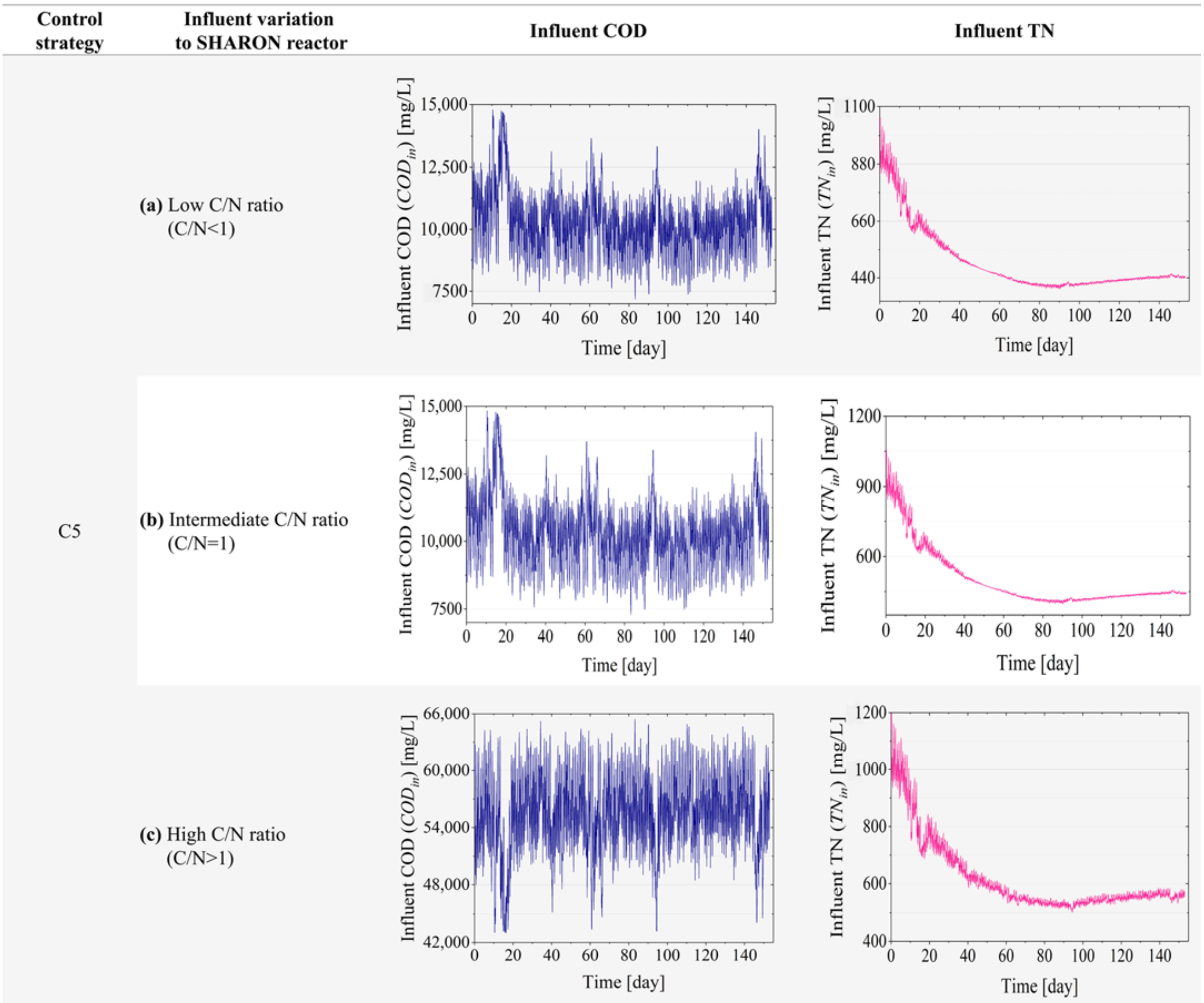


Figure 3. COD and N in the different influent variations for C4 and C5. (**a**) Low C/N ratio: COD and N influent to SH. (**b**) Intermediate C/N ratio: COD and N influent to SH. (**c**) High C/N ratio: COD and N influent to SH.

2.6.2. Control Performance Indices

The plant performance with each of the control strategies was evaluated in terms of the effluent quality and operating cost. Equation (15) represents the effluent quality index (EQI), adopted from the study of [28], which is calculated by weighting the different components of the effluent loadings.

$$EQI = \frac{1}{1000(t_f - t_0)} \int_{t_0}^{t_f} \begin{pmatrix} \beta_{TSS} TSS_e(t) + \beta_{COD} COD_e(t) + \beta_{BOD} BOD_e(t) + \\ \beta_{TKN} TKN_e(t) + \beta_{NO} NO_e(t) \end{pmatrix} Q_e(t)dt \quad (15)$$

where t_0 and t_f represent the time at the starting point of the simulation and the time at the end of the simulation, respectively; TSS_e, COD_e, BOD_e, TKN_e, and NO_e are the total suspended solids, chemical oxygen demand, biological oxygen demand, total Kjeldahl nitrogen, and nitrogen in the effluent concentrations in mg/L, respectively; Q_e is the effluent flowrate in mg/L; and β_{TSS}, β_{COD}, β_{BOD}, β_{TKN}, and β_{NO} are the weighting factors for TSS, COD, BOD, TKN, and NO, respectively, whose values are 2, 1, 2, 20, and 20, respectively [28]. Furthermore, the assessment incorporates an analysis of the operating cost (OC) to determine the cost per day of each control strategy in a WWTP. Equation (16) presents the OC calculation, which has been adapted from [28,39,40].

$$OC = \gamma_1 AE + \gamma_1 PE + \gamma_2 SP \quad (16)$$

where AE is the aeration energy in kWh/d, PE is the pumping energy in kWh/d, and SP is the sludge production disposal in kg/d. The weighting factors of OC were defined as 0.1 EUR/kWh for γ_1 and 0.5 EUR/kg for γ_2. These values were adopted from the previous studies of [39,40]. Equation (17) presents the SP calculation, which has been adapted from [28,39,40].

$$SP = \frac{1}{t_f - t_0}\left(TSS_f - TSS_0 + 0.75\left(\int_{t_0}^{t_f} (X_{S,e} + X_{I,e} + X_{B,H,e} + X_{B,A,e})(Q_e)(t)dt\right)\right) \quad (17)$$

Here, $X_{S,e}$ represents the parameter of particulate biodegradable organics in the effluent flow in mg/L, $X_{I,e}$ is the particulate undegradable organics in mg/L, $X_{B,H,e}$ is the active heterotrophic biomass in mg/L, and $X_{B,A,e}$ is the active autotrophic biomass in mg/L. Equation (18) shows the calculation of methane production, adapted from [28].

$$METP = \frac{16(P_{atm})(13.89)}{25.62(t_f - t_0)}\left(\int_{t_0}^{t_f} \frac{Q_{gas}(t) \cdot p_{gas,CH_4}(t)}{P_{gas}(t)}dt\right) \quad (18)$$

Here, P_{atm} represents the atmospheric pressure with a value of 1.013, Q_{gas} is the methane gas (CH_4) flowrate in kWh/d, p_{gas,CH_4} is the methane gas pressure in bar, and P_{gas} is the gas pressure considering CO_2, H_2, and H_2O in bar. More details on the performance evaluation indices are presented in Section 1.3 of Supplementary Materials.

2.6.3. Resource Recovery Evaluation

The resource recovery of the plant with the different control strategies was briefly assessed in this study. The recovery potential of the system was estimated using the nitrogen removal, SP, and METP of BSM2-SHAMX. SP is described in Equation (17), and METP is calculated based on Equation (18). In the resource recovery analysis, nutrient recycling is a fundamental concept that evaluates the advantages of reusing and capturing the nutrients present in wastewater [41]. Nitrogen recovery in wastewater treatment systems can be complex, costly, and time-consuming, given that the process by which it is synthesized. As a main disadvantage, this process consumes a large amount of energy, which increases the cost of operations and supply. Moreover, nutrient recovery has been studied from raw wastewater, semi-treated wastewater, and byproducts [41,42]. Although nitrogen recovery is still a complex process, the evaluation in this study is based on an estimation of the potential for nitrogen recovery and reuse. This evaluation is complemented by other products that can be recovered from wastewater, such as sludge and methane, with the overall goal of reducing energy consumption and lowering operational costs.

3. Results and Discussion

3.1. Sensitivity Analysis

The sensitivity analysis was carried out using Monte Carlo simulations. Figure 4 shows the parameters that influenced the DO and ammonia concentrations required for the control strategies implemented in the BSM2-SHAMX model. The DO and ammonia concentration variations are presented as they reflect changes in the parameters, such as the volumes of the primary clarifiers, and the first and third reactors, the oxygen transfer coefficient in the SHARON reactor, oxygen transfer coefficient in the fifth reactor, return sludge flowrate, and wastage flowrate.

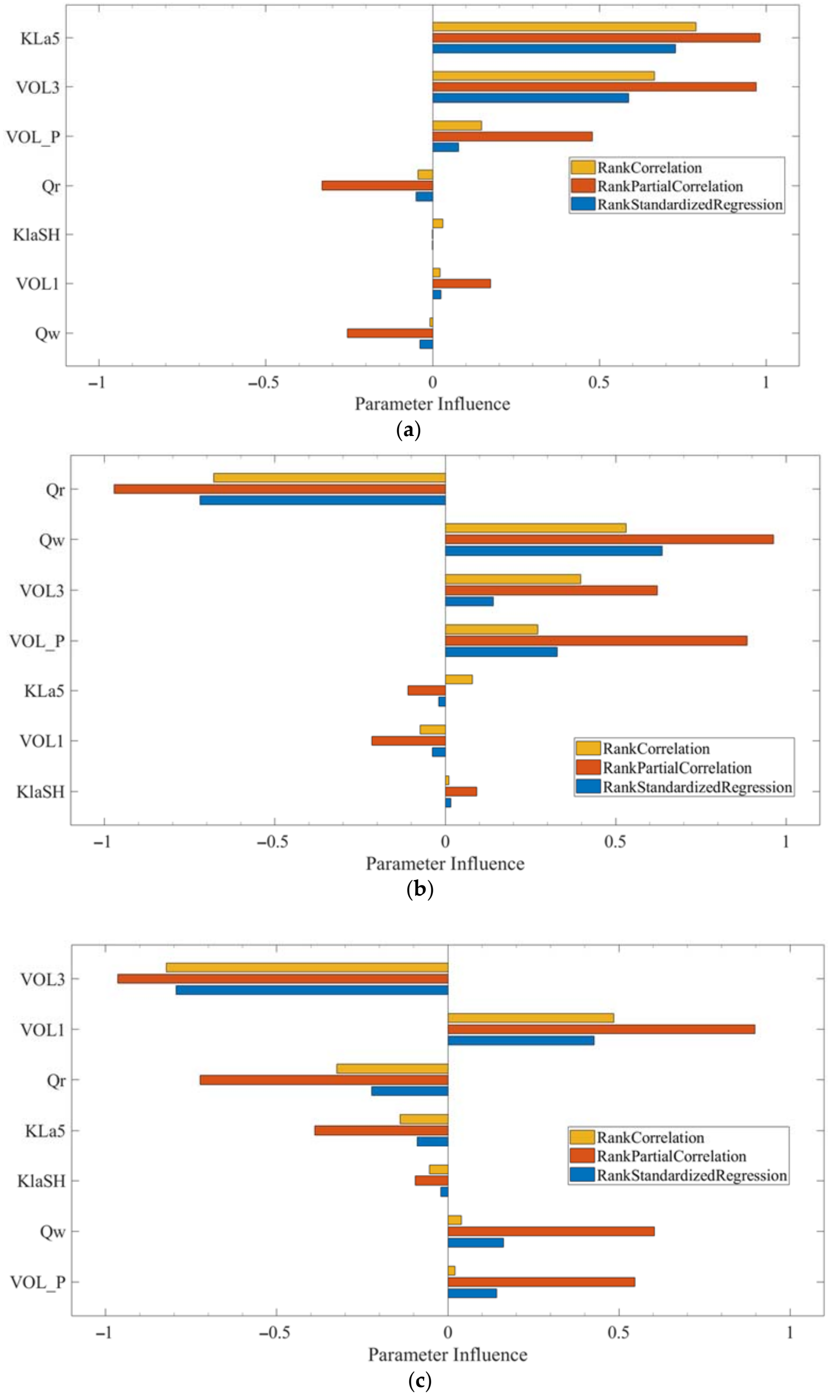


Figure 4. Sensitivity results for (**a**) dissolved oxygen effluent concentration, (**b**) nitrate effluent concentration, and (**c**) ammonia effluent concentration. KLa5 and KlaSH are the oxygen transfer coefficient in the fifth and SHARON reactors, respectively; VOL1, VOL3, and VOL_P are the volumes of the first and third reactors and the primary clarifier, respectively; Qr is the sludge return flowrate; Qw is the wastage flowrate.

Figure 4 shows scatterplots of the correlations between selected input parameters and the model output. The plots present the rank correlations, rank partial correlations, and rank standardized regressions, which are explained in Section 1.4 of Supplementary Materials. From those ranks, the rank partial correlation and rank standardized regression were used because they showed the highest correlations. Figure 4a presents the correlations between the plant's operational parameters and the DO concentration in the partial nitritation process. The most influential variables for DO were the oxygen transfer coefficient of the fifth reactor (k_La_5) and the volume of the third reactor. Figure 4b,c show the correlations between the parameters and the effluent nitrate and ammonia concentrations, respectively. In Figure 4b, the parameters of importance for the nitrate effluent concentration are the waste flowrate and the volume of the primary clarifier. Similarly, for the ammonia effluent concentration, the most influential parameters are the volume of the first reactor, the waste flowrate, and the volume of the primary clarifier (Figure 4c).

3.2. Control Performance

The performance of the five control strategies is summarized in Table 2. The performance indices are the EQI, OC, and SP, and the comparison to the base case, C0, is detailed based on the percentage of improvement. EQI, which represents the environmental load through the discharge of pollutants, was estimated and analyzed for each control strategy. As shown in Table 2, C1 and C2 had the lowest EQI for all the influent variations, indicating that the WWTP system was able to remove the most pollutants with those control strategies, in which the DO was controlled in the SH reactor. On the contrary, the second highest EQI was presented by C3, in which a PI-PI cascade controller was implemented.

Analyzing the EQI alone, the system seems to better meet the effluent quality standards with a single-loop controller because C1 and C2 showed a small decrease in EQI, and C3 had an increase of 3.01%. That occurs because the effluent quality of the plant strongly depends on the dynamic behavior of the concentrations controlled and the biological process dynamics, as described in previous studies. The highest EQI was found with control strategies C4 and C5 for all influent variations, with an increase of 71.15%. Assessing the variations in EQI in terms of variations in the SHARON influent shows no major variance, indicating that this condition does not influence the removal efficiency of the plant. Overall, of the five control strategies (C1 to C5), only C1 and C2 decreased the plant's EQI compared with the base case in which no control was implemented.

Analyzing the OC values in Table 2 obtained for each control strategy according to variations in the SHARON influent, the lowest OC was for C5 with low C/N and high C/N. C5 implemented an MPC-MPC cascade controller in which the secondary MPC control loop maintains the DO concentration at the SH reactor to limit the output NO_2/NH_4 ratio, which later influences the primary MPC control loop to maintain the NH_4 concentration, enhancing the plant's nitrogen removal. The OC in C5 was reduced by 36.73%, representing a total of 9596.71 EUR/d, an important improvement in plant operations.

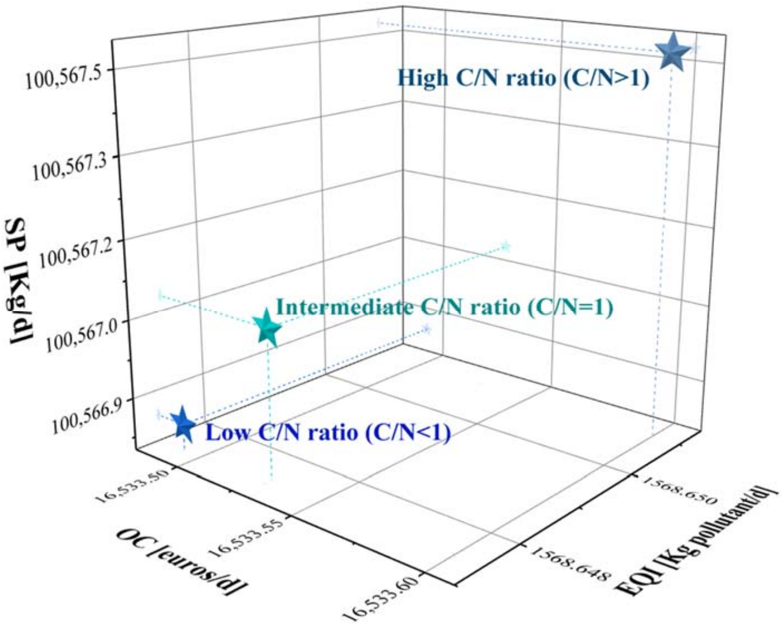
The NO_2/NH_4 ratio helps achieve good nitrogen removal in the Anammox process by decreasing nitrate production. C5 presents the lowest OC in part through lower SP, which stems from the lower TSS in the system. On the other hand, the highest OC among the control strategies was with C3 and C4 for all influent variations. However, the increase compared to C0 is small. Efficient nitrogen removal and efficient operational costs are achieved with all the control strategies because the controlled variables include the DO concentration in the SHARON reactor and the ammonia concentration in the Anammox reactor. Those variables directly influence nitrogen removal in WWTPs, affecting the microorganisms in the sludge and the denitrification process in the main line.

The C5, MPC-MPC cascade controller, also showed the lowest SP with all the influent variations detailed (Table 2). The TSS, particulate biodegradable organics, particulate unbiodegradable organics, active heterotrophic biomass, and active autotrophic biomass concentrations of the system decreased greatly with this control strategy thanks to the operational enhancement that the MPC-MPC control structure provided for the secondary line (reject water) of the WWTP system. Besides the base case (C0), the highest SP was presented by C3 and C4, with a very low and negative percentage of improvement as SP increased compared with C0. For SP, the DO concentration is fundamental because it provides the oxygen supply in the solids. Finally, with the MPC-MPC cascade control of C5, the plant performed better in terms of the OC and SP, demonstrating that better nitrogen removal was achieved by controlling the ammonia concentration in the deammonification process.

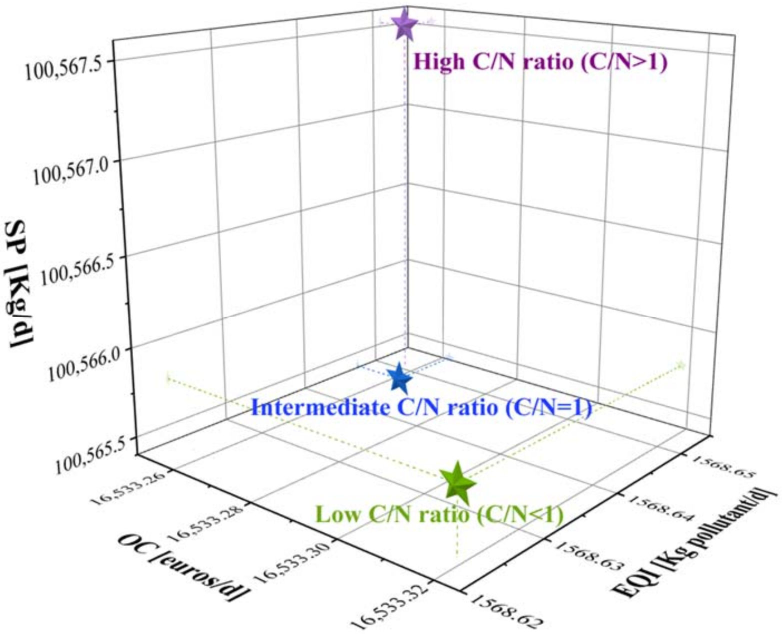
Table 2. Plant performance indices for the two single-loop controllers (C1–C2) and three cascade controllers (C3–C5) compared with the base case (C0).

Influent Variation to SHARON	Control Strategy	Base Case C0	C1	C2	C3	Improvement (%)	C4	Improvement (%)	C5	Improvement (%)
Low C/N ratio (C/N < 1)	EQI (kg of pollutants/d)	916.53	916.49	916.50	944.08	−3.01%	1568.65	−71.15%	1568.65	−71.15%
	OC (EUR/d)	26,129.97	26,129.98	26,130.02	26,130.02	0.00%	26,130.02	0.00%	16,533.26	36.73%
	SP (kg/d)	160,544.83	160,544.92	160,545.13	160,545.13	0.00%	160,545.13	0.00%	100,565.38	37.36%
Intermediate C/N ratio (C/N = 1)	EQI (kg of pollutants/d)	916.53	916.49	916.50	944.08	−3.01%	1568.65	−71.15%	1568.62	−71.15%
	OC (EUR/d)	26,129.97	26,129.98	26,130.02	26,488.35	−1.37%	16,533.53	36.73%	16,533.32	36.73%
	SP (kg/d)	160,544.83	160,544.92	160,545.13	162,784.71	−1.40%	100,567.08	37.36%	100,565.76	37.36%
High C/N ratio (C/N > 1)	EQI (kg of pollutants/d)	916.53	916.49	916.50	944.08	−3.01%	1568.65	−71.15%	1568.65	−71.15%
	OC (EUR/d)	26,129.97	26,129.98	26,130.02	26,130.02	0.00%	26,130.02	0.00%	16,533.26	36.73%
	SP (kg/d)	160,544.83	160,544.92	160,545.13	160,545.13	0.00%	160,545.13	0.00%	100,565.41	37.36%

Figure 5 presents variations in EQI, OC, and SP in terms of the varied conditions for the SHARON influent. For C4, Figure 5a shows that the low C/N ratio (C/N < 1) performed the best for the plant's operation, as at that point it had the lowest values for EQI, OC, and SP. On the contrary, a high C/N ratio (C/N > 1) produced plant underperformance. Overall, with C4, a lower C/N ratio correlated with better plant performance. Similarly, with C5, a low C/N ratio correlated with good plant performance (Figure 5b). With C5, the intermediate C/N ratio (C/N = 1) produced results close to those with the low C/N ratio values. In general, C/N ratio variation in the influent to SHARON, seems to represent a difference of thousands of EUR/d for operational cost but not much difference in EQI or SP.



(**a**)



(**b**)

Figure 5. Results comparison of EQI, OC, and SP for SH influent with various C/N ratios in (**a**) C4 and (**b**) C5.

Comprehensively, C5 is the most suitable control strategy for the WWTP because it can decrease the operational cost and SP even though the EQI was higher than C0. The results of C5 based on the plant's overall treatment performance are presented in Figure 6. For this scenario, the optimal DO concentration is in the nitrite-oxidizing bacteria (NOB) suppression region, for which the S_O setpoint is close to zero, which resulted in a NO_2/NH_4 ratio of 1.15 for a low C/N ratio (Figure 6a), a small decrease to 1 for the intermediate C/N ratio (Figure 6b), and a lower NO_2/NH_4 ratio of 0.96 for a high C/N ratio (Figure 6c). Moreover, with C5, the MPC-MPC cascade controller outperformed the other control schemes on nitrogen removal, enhancing the operation of the system.

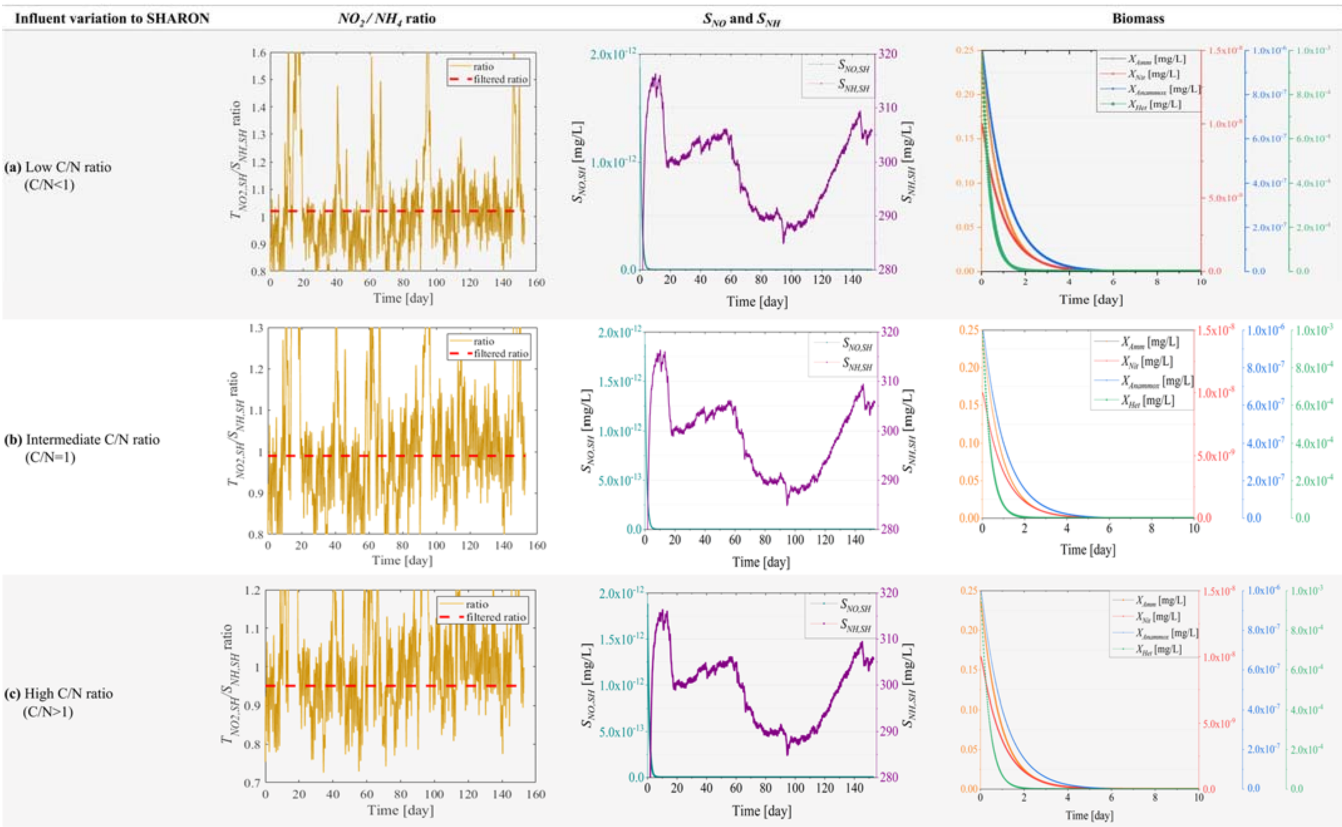


Figure 6. Results for the C5 MPC-MPC cascade controller. (**a**) Low C/N ratio: NO_2/NH_4 output ratio from SH, SO setpoint, and biomass concentration of ammonia-oxidizing biomass (X_{Amm}), nitrite-oxidizing biomass (X_{Nit}), anammox biomass ($X_{Anammox}$), and heterotrophic biomass (X_{Het}) from SH. (**b**) Intermediate C/N ratio: NO_2/NH_4 output ratio from SH, SO setpoint, and biomass concentration of X_{Amm}, X_{Nit}, $X_{Anammox}$, and X_{Het} from SH. (**c**) High C/N ratio: NO_2/NH_4 output ratio from SH, SO setpoint, and biomass concentration of X_{Amm}, X_{Nit}, $X_{Anammox}$, and X_{Het} from SH.

Figure 6 shows the biomass concentration from the SHARON process for X_{Amm}, X_{Nit}, $X_{Anammox}$, and X_{Het} at all the influent variation conditions. The biomass concentration did not vary with the different influent conditions. X_{Amm} showed the highest values of around 0.20 mg/L, which later decreased to zero in the period tested. On the other hand, the highest biomass concentration was for $X_{Anammox}$, around 8 mg/L, followed by the X_{Nit}, showing an increase in Anammox bacteria over ammonia-oxidizing bacteria (AOB) and NOB. The nitrate concentration decreased as the NOB was suppressed, which also influenced the ammonia concentration from SHARON. In general, according to the influent conditions evaluated, the most significant result is that the NO_2/NH_4 ratio is somewhat affected, improving when the C/N ratio is intermediate or low but underperforming when it is high. More results from control strategies C1 to C3 are presented in Supplementary Materials.

Figure 7 shows the comparison of effluent ammonia concentration obtained with the different control strategies (C1 to C5). Ammonia concentration was evaluated because it indicates the highest fraction of nitrogen in the biological treatment. The average ammonia concentrations with control strategies C4 and C5 were the lowest, as expected given the advantages of the cascade MPC controllers and corroborating the higher performance of those control strategies. C4 and C5 produced an ammonia effluent concentration of around 25 mg/L, whereas C1 and C2 produced 27 mg/L, and C3 produced 35 mg/L. C1 and C2 produced low values because the local controllers targeted the oxygen and ammonia concentrations, respectively.

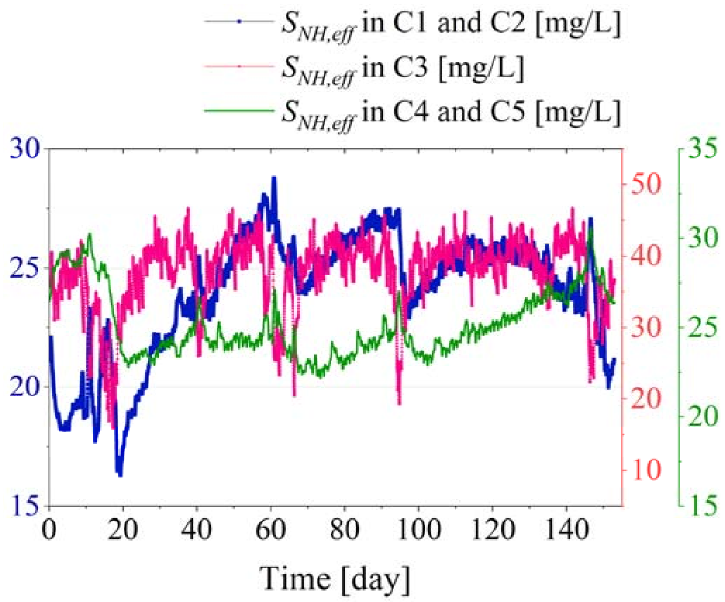


Figure 7. Ammonia concentration ($S_{NH,eff}$) in the effluent for control strategies C1 to C5 with a low C/N ratio.

Overall, the results show that the cascade control strategies proposed here are robust enough to be used for high-strength wastewater because they allow the controller to benefit from periodic identification of the most sensitive parameters. The ammonium feedback loops define a desirable NO_2/NH_4 ratio, and the setpoint for the controller then helps to establish it. Moreover, given that the selection factor is the DO concentration, the influent stream from the AD effluent is treated without modifying the flowrates in the partial nitritation process. In that way, when assuming a negligible nitrite concentration in the SHARON input, the ammonium concentration can be controlled instead of the NO_2/NH_4 ratio.

3.3. Resource Recovery Potential

Resource recovery has been assessed in this study by analyzing the nutrient recovery potential of the plant as a way to mitigate the consumption of resources in the WWTP. Thus, the resource recovery potential of the control strategies was analyzed in terms of nitrogen removal, SP, and METP, which are key variables from WWTPs that can be reused and highly influence operational cost and management. Table 3 presents the results of the variables evaluated for resource recovery. C2 to C5 reduced SP by controlling ammonia. Sludge from municipal wastewater can be disposed of or reused as fertilizer. In this study, the goal was to minimize SP because it generates operational costs in WWTPs. However, as an additional way of disposing of sludge, the creation of fertilizer remains a good way to maximize the resource recovery of the plant.

Table 3. Resource recovery potential of the control strategies implemented on BSM2-SHAMX.

Influent Variation to SHARON	Evaluation Criteria	Control Strategies					
		Base Case C0	C1	C2	C3	C4	C5
Low C/N ratio (C/N < 1)	Effluent nitrogen concentration (mg/L)	7.5536×10^{-9}	2.6178×10^{-9}	2.6178×10^{-9}	5.9164×10^{-6}	0.00	0.00
	Sludge production (kg/d)	160,544.83	160,544.92	160,545.1	162,784.71	100,567.52	100,565.38
	Methane production (kg CH_4/d)	980.17	980.48	980.47	994.22	0.00	0.00
Intermediate C/N ratio (C/N = 1)	Effluent nitrogen concentration (mg/L)	1.0641×10^{-6}	2.6178×10^{-9}	2.6178×10^{-9}	5.9164×10^{-6}	0.00	0.00
	Sludge production (kg/d)	160,544.83	160,544.92	160,545.1	162,784.71	100,567.08	100,565.76
	Methane production (kg CH_4/d)	980.17	980.48	980.47	994.22	0.00	0.00
High C/N ratio (C/N > 1)	Effluent nitrogen concentration (mg/L)	7.5536×10^{-9}	2.6178×10^{-9}	2.6178×10^{-9}	5.9164×10^{-6}	0.00	0.00
	Sludge production (kg/d)	160,544.83	160,544.92	160,545.1	162,784.71	100,566.85	100,565.41
	Methane production (kg CH_4/d)	980.17	980.48	980.47	994.22	0.00	0.00

C4 and C5 greatly reduced methane production. This great reduction in methane is likely due to the conditions from the control types of these scenarios. The control that is applied in C4 for DO and NH_4, influences on the later process of anaerobic digestion, similarly occurs for the C5 where the same variables are controlled under an MPC control type. Methane, as a biogas, is one of the most robust and valuable resources produced by WWTPs. Biogas commonly fails to be exploited for energy generation. At least 70% of methane can generate energy for use in the WWTP itself to reduce the operational cost of the system. In analyzing the effluent nitrogen concentration, which was completely removed in the C4 and C5 systems, it can be seen that the cascade controls outperformed the single-loop controls. Nitrogen removal in WWTPs is fundamental to prevent eutrophication, which can also be reused as fertilizer.

Among the resource recovery routes evaluated, methane recovery from COD in the anaerobic digestion process presents drawbacks in the form of high energy losses, which affect the energy efficiency of the entire process by about 15%, as described in the literature. COD recovery in terms of organic materials instead of energy is a good alternative because organic chemicals have an adequately high monetary value. In other words, given that COD-derived product recovery routes could require trade-offs, the value of the recovered products is also an important criterion when selecting the most suitable resource recovery route. Overall, the search for new practices to enhance resource recovery in WWTPs needs reliable data. The products of resource recovery from WWTP systems also need support from value-chain actors willing to share the risks of innovation when implementing them in WWTPs.

4. Conclusions

MPC cascade controllers were implemented to enhance nitrogen removal in WWTPs through deammonification. Single-loop control algorithms are generally underfitting, and the MPC cascade controllers proposed in this study were able to determine the optimal operation conditions and improve nitrogen removal. Compared with the single-loop control strategies, the MPC cascade controllers displayed better control performance in terms of the lowest OC and SP. Therefore, the MPC cascade controllers can efficiently handle the control objectives of WWTPs by varying the set-points of local controllers to accommodate the influent conditions, maximizing nitrogen removal while reducing both operational costs and SP. Moreover, for high-strength wastewater, the cascade controllers achieved a NO_2/NH_4 ratio suitable for the Anammox process. In future work, this study could be extended to include more specific environmental and economic objectives for an integrated analysis of the control strategies proposed. In addition, more varied scenarios considering C/N ratio would be considered in future work, allowing for a more integral study.

Furthermore, the resource recovery potential of the plant was evaluated. Although domestic wastewater cannot fully satisfy the elemental needs of industrialized societies, it represents a substantial resource that should be fully exploited in the future. SP and METP have large advantages in energy savings and operational cost reductions in WWTPs. In addition, the most precious resource from municipal wastewater is the water itself. Wastewater reuse can provide an alternative source of fresh water in regions or communities where lasting shortages are expected in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15224015/s1, refs. [43–57] are cited in supplementary materials.

Author Contributions: Conceptualization, P.V.; methodology, P.V. and K.N.; formal analysis, P.V.; investigation, P.V.; writing—original draft preparation, P.V.; writing—review and editing, P.V., K.N. and C.Y.; visualization, P.V.; supervision, C.Y.; project administration, C.Y.; funding acquisition, C.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2021R1A2C2007838), and the project for Collabo R&D between Industry, Academy, and Research Institute funded by the Korea Ministry of SMEs and Startups in 2022 (Project No. S3301144).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Langone, M. Simultaneous Partial Nitritation, Anammox and Denitrification (SNAD) Process for Treating Ammonium-Rich Wastewaters. Ph.D. Thesis, University of Trento, Trento, Italy, 2013.
2. Safder, U.; Kim, J.; Pak, G.; Rhee, G.; You, K. Investigating Machine Learning Applications for Effective Real-Time Water Quality Parameter Monitoring in Full-Scale Wastewater Treatment Plants. *Water* **2022**, *14*, 3147. [CrossRef]
3. Rahimi, S.; Modin, O.; Mijakovic, I. Technologies for Biological Removal and Recovery of Nitrogen from Wastewater. *Biotechnol. Adv.* **2020**, *43*, 107570. [CrossRef]
4. Volcke, E.I.P. Modelling, Analysis and Control of Partial Nitritation in a SHARON Reactor. Ph.D. Thesis, Ghent University, Gent, Belgium, 2006.
5. Leong, C.L.; How, S.W.; Rabuni, M.F.; Mohd Aris, A.; Khor, B.C.; Curtis, T.P.; Chua, A.S.M. Pilot Study of Oxic–Anoxic Process under Low Dissolved Oxygen for Nitrogen Removal from Low COD/N Tropical Wastewater. *Water* **2023**, *15*, 2070. [CrossRef]
6. Wang, J.; Liu, S.; Zhang, Y.; Zhang, S.; Liu, J. Effect of Anammox Granular Sludge Type on the CANON Process with Immobilized Fillers Treating Domestic Wastewater. *Water* **2023**, *15*, 354. [CrossRef]
7. Sri Shalini, S.; Joseph, K. Combined SHARON and ANAMMOX Processes for Ammoniacal Nitrogen Stabilisation in Landfill Bioreactors. *Bioresour. Technol.* **2018**, *250*, 723–732. [CrossRef]
8. Sri Shalini, S.; Joseph, K. Nitrogen Management in Landfill Leachate: Application of SHARON, ANAMMOX and Combined SHARON–ANAMMOX Process. *Waste Manag.* **2012**, *32*, 2385–2400. [CrossRef]
9. Peng, Y.; Zhu, G. Biological Nitrogen Removal with Nitrification and Denitrification via Nitrite Pathway. *Appl. Microbiol. Biotechnol.* **2006**, *73*, 15–26. [CrossRef] [PubMed]
10. Ali, M.; Okabe, S. Anammox-Based Technologies for Nitrogen Removal: Advances in Process Start-up and Remaining Issues. *Chemosphere* **2015**, *141*, 144–153. [CrossRef] [PubMed]
11. Sengupta, S.; Nawaz, T.; Beaudry, J. Nitrogen and Phosphorus Recovery from Wastewater. *Curr. Pollut. Rep.* **2015**, *1*, 155–166. [CrossRef]
12. Gut, L.; Płaza, E.; Hultman, B. Assessment of a Two-Step Partial Nitritation/Anammox System with Implementation of Multivariate Data Analysis. *Chemom. Intell. Lab. Syst.* **2007**, *86*, 26–34. [CrossRef]
13. Saxena, N.; Nawaz, A.; Lee, M. Comprehensive Review of Control and Operational Strategies for Partial Nitration/ANAMMOX System. *Ind. Eng. Chem. Res.* **2019**, *58*, 10635–10651. [CrossRef]
14. Valverde-Pérez, B.; Mauricio-Iglesias, M.; Sin, G. Systematic Design of an Optimal Control System for the SHARON-Anammox Process. *J. Process Control* **2016**, *39*, 1–10. [CrossRef]

15. Barbu, M.; Vilanova, R.; Meneses, M.; Santin, I. On the Evaluation of the Global Impact of Control Strategies Applied to Wastewater Treatment Plants. *J. Clean. Prod.* **2017**, *149*, 396–405. [CrossRef]
16. Regmi, P.; Bunce, R.; Miller, M.W.; Park, H.; Chandran, K.; Wett, B.; Murthy, S.; Bott, C.B. Ammonia-Based Intermittent Aeration Control Optimized for Efficient Nitrogen Removal. *Biotechnol. Bioeng.* **2015**, *112*, 2060–2067. [CrossRef]
17. Shannon, J.M. *Partial Nitritation-Anammox Using PH-Controlled Aeration in Submerged Attached Growth Bioreactors*; University of Iowa: Iowa City, IA, USA, 2014; Volume 1560696.
18. Valverde-Pérez, B.; Mauricio-Iglesias, M.; Sin, G. Modelling and Control Design for SHARON/Anammox Reactor Sequence. In Proceedings of the 17th Nordic Process Control Workshop, Kgs Lyngby, Denmark, 25–27 January 2012.
19. Durán, U.; Val Del Río, A.; Campos, J.L.; Mosquera-Corral, A.; Méndez, R. Enhanced Ammonia Removal at Room Temperature by PH Controlled Partial Nitrification and Subsequent Anaerobic Ammonium Oxidation. *Environ. Technol.* **2014**, *35*, 383–390. [CrossRef] [PubMed]
20. Pang, J.; Yang, S.; He, L.; Chen, Y.; Ren, N. Intelligent Control/Operational Strategies in WWTPs through an Integrated Q-Learning Algorithm with ASM2d-Guided Reward. *Water* **2019**, *11*, 927. [CrossRef]
21. Nikita, S.; Lee, M. Control of a Wastewater Treatment Plant Using Relay Auto-Tuning. *Korean J. Chem. Eng.* **2019**, *36*, 505–512. [CrossRef]
22. Stare, A.; Hvala, N.; Vrečko, D. Modeling, Identification, and Validation of Models for Predictive Ammonia Control in a Wastewater Treatment Plant—A Case Study. *ISA Trans.* **2006**, *45*, 159–174. [CrossRef]
23. Mauricio-Iglesias, M.; Katrine, A.; Gernaey, K.V.; Smets, B.F.; Sin, G. A Novel Control Strategy for Single-Stage Autotrophic Nitrogen Removal in SBR. *Chem. Eng. J.* **2015**, *260*, 64–73. [CrossRef]
24. Fux, C.; Boehler, M.; Huber, P.; Brunner, I.; Siegrist, H. Biological Treatment of Ammonium-Rich Wastewater by Partial Nitritation and Subsequent Anaerobic Ammonium Oxidation (Anammox) in a Pilot Plant. *J. Biotechnol.* **2002**, *99*, 295–306. [CrossRef]
25. Wang, H.; Jiang, C.; Wang, X.; Xu, S.; Zhuang, X. Application of Internal Carbon Source from Sewage Sludge: A Vital Measure to Improve Nitrogen Removal Efficiency of Low c/n Wastewater. *Water* **2021**, *13*, 2338. [CrossRef]
26. Chen, M.; Tang, Q.; Zou, J.; Lv, X.; Deng, Y.; Ma, X.; Ma, S. Sugarcane Bagasse as Carbon Source and Filler to Enhance the Treatment of Low C/N Wastewater by Aerobic Denitrification Flora. *Water* **2022**, *14*, 3355. [CrossRef]
27. Jamilis, M.; Garelli, F.; De Battista, H.; Volcke, E.I.P. Stability and Control of a Partial Nitritation Reactor with Biomass Retention. *Chem. Eng. Res. Des.* **2016**, *144*, 318–333. [CrossRef]
28. Alex, J.; Benedetti, L.; Copp, J.; Gernaey, K.V.; Jeppsson, U.; Nopens, I.; Pons, M.; Rieger, L.; Rosen, C.; Steyer, J.P.; et al. *Benchmark Simulation Model No. 2 (BSM2) Report*; IWA Task Group on Benchmarking of Control Strategies for WWTPs: London, UK, 2008.
29. Henze, M.; Grady, C.; Gujer, W.; Marais, G.; Matsuo, T. Activated Sludge Model No. 1. IAWPRC Sci. Tech. Reports, 1. *Water Sci. Technol.* **1987**, *29*.
30. Tang, X.; Sun, Y.; Zhou, G.; Miao, F. Coordinated Control of Multi-Type Energy Storage for Wind Power Fluctuation Suppression. *Energies* **2017**, *10*, 1212. [CrossRef]
31. Weijers, S.R.; Preisig, H.A. Robustness Analysis of Model Predictive Control of Activated Sludge Plants. *IFAC Proc. Vol.* **2000**, *33*, 545–550. [CrossRef]
32. Lund, N.S.V.; Falk, A.K.V.; Borup, M.; Madsen, H.; Steen Mikkelsen, P. Model Predictive Control of Urban Drainage Systems: A Review and Perspective towards Smart Real-Time Water Management. *Crit. Rev. Environ. Sci. Technol.* **2018**, *48*, 279–339. [CrossRef]
33. Neumann, M.B. Comparison of Sensitivity Analysis Methods for Pollutant Degradation Modelling: A Case Study from Drinking Water Treatment. *Sci. Total Environ.* **2012**, *433*, 530–537. [CrossRef]
34. Ruano, M.V.; Ribes, J.; De Pauw, D.J.W.; Sin, G. Parameter Subset Selection for the Dynamic Calibration of Activated Sludge Models (ASMs): Experience versus Systems Analysis. *Water Sci. Technol.* **2007**, *56*, 107–115. [CrossRef]
35. Vilela, P.; Liu, H.; Lee, S.; Hwangbo, S.; Nam, K.; Yoo, C. A Systematic Approach of Removal Mechanisms, Control and Optimization of Silver Nanoparticle in Wastewater Treatment Plants. *Sci. Total Environ.* **2018**, *633*, 989–998. [CrossRef]
36. Jamilis, M.; Garelli, F.; De Battista, H.; Volcke, E.I.P. Combination of Cascade and Feed-Forward Constrained Control for Stable Partial Nitritation with Biomass Retention. *J. Process Control* **2020**, *95*, 55–66. [CrossRef]
37. Vilela, P.; Safder, U.; Heo, S.K.; Nguyen, H.T.; Lim, J.Y.; Nam, K.J.; Oh, T.S.; Yoo, C.K. Dynamic Calibration of Process-Wide Partial-Nitritation Modeling with Airlift Granular for Nitrogen Removal in a Full-Scale Wastewater Treatment Plant. *Chemosphere* **2022**, *305*, 135411. [CrossRef] [PubMed]
38. Sung, S.W.; Lee, J.; Lee, I.-B. *Process Identification and PID Control*; Wiley: Hoboken, NJ, USA, 2009.
39. Guerrero, J.; Guisasola, A.; Vilanova, R.; Baeza, J.A. Improving the Performance of a WWTP Control System by Model-Based Setpoint Optimisation. *Environ. Model. Softw.* **2011**, *26*, 492–497. [CrossRef]
40. Ostace, G.S.; Baeza, J.A.; Guerrero, J.; Guisasola, A.; Cristea, V.M.; Agachi, P.Ş.; Lafuente, J. Development and Economic Assessment of Different WWTP Control Strategies for Optimal Simultaneous Removal of Carbon, Nitrogen and Phosphorus. *Comput. Chem. Eng.* **2013**, *53*, 164–177. [CrossRef]
41. Ferreira Matafome, B. *Techno-Economic Analysis and Benchmarking of Resource Recovery Technologies for Wastewater Treatment Plants*; Instituto Superior Técnico: Lisbon, Portugal, 2016; pp. 1–11.

42. Kehrein, P.; Van Loosdrecht, M.; Osseweijer, P.; Garfí, M.; Dewulf, J.; Posada, J. A Critical Review of Resource Recovery from Municipal Wastewater Treatment Plants-Market Supply Potentials, Technologies and Bottlenecks. *Environ. Sci. Water Res. Technol.* **2020**, *6*, 877–910. [CrossRef]
43. Alex, J.; Beteau, J.F.; Copp, J.B.; Hellinga, C.; Jeppsson, U.; Marsili-Libelli, S.; Pons, M.N.; Spanjers, H.; Vanhooren, H. Benchmark for Evaluating Control Strategies in Wastewater Treatment Plants. In Proceedings of the 1999 European Control Conference (ECC), Karlsruhe, Germany, 31 August–3 September 1999; pp. 3746–3751.
44. Alex, J.; Benedetti, L.; Copp, J.; Gernaey, K.V.; Jeppsson, U.; Nopens, I.; Pons, M.; Rieger, L.; Rosen, C.; Steyer, J.P.; et al. Benchmark simulation model No. 2 (BSM2) report: General protocol and exploratory case studies. *Water Sci. Technol.* **2007**, *56*, 67–78.
45. Jeppsson, U.; Pons, M.N. The COST Benchmark Simulation Model-Current State and Future Perspective. *Control Eng. Pract.* **2004**, *12*, 299–304. [CrossRef]
46. Iacopozzi, I.; Innocenti, V.; Marsili-Libelli, S.; Giusti, E. A Modified Activated Sludge Model No. 3 (ASM3) with Two-Step Nitrification-Denitrification. *Environ. Model. Softw.* **2007**, *22*, 847–861. [CrossRef]
47. Henze, M.; Gujer, W.; Mino, T.; van Loosdrecht, M. *Activated Sludge Models ASM1, ASM2, ASM2D, ASM3*; IWA publishing: London, UK, 2000.
48. Bozkurt, H.; Quaglia, A.; Gernaey, K.V.; Sin, G. Environmental Modelling & Software A Mathematical Programming Framework for Early Stage Design of Wastewater Treatment Plants. *Environ. Model. Softw.* **2015**, *64*, 164–176. [CrossRef]
49. Ostace, G.S.; Cristea, V.M.; Agachi, P.Ş. Cost Reduction of the Wastewater Treatment Plant Operation by MPC Based on Modified ASM1 with Two-Step Nitrification/Denitrification Model. *Comput. Chem. Eng.* **2011**, *35*, 2469–2479. [CrossRef]
50. Giusti, E.; Marsili-libelli, S.; Spagni, A. Environmental Modelling & Software Modelling Microbial Population Dynamics in Nitritation Processes. *Environ. Model. Softw.* **2011**, *26*, 938–949. [CrossRef]
51. Montgomery, D.C.; Runger, G.C.; Hubele, N.F. *Engineering Statistics*; John Wiley & Sons: Hoboken, NJ, USA, 2010.
52. COST European Cooperation of Scientific and Technical Research. *The COST Simulation Benchmark: Description and Simulator Manual*; COST: Brussels, Belgium, 1998.
53. Kim, M.; Rao, A.S.; Yoo, C. Dual Optimization Strategy for N and P Removal in a Biological Wastewater Treatment Plant. *Ind. Eng. Chem. Res.* **2009**, *48*, 6363–6371. [CrossRef]
54. Frey, H.C.; Patil, S.R. Identification and Review of Sensitivity Analysis Methods. *Risk Anal.* **2002**, *22*, 553–578. [CrossRef] [PubMed]
55. Hamby, D.M. A Review of Techniques for Parameter Sensitivity. *Environ. Monit. Assess.* **1994**, *32*, 135–154. [CrossRef]
56. Benesty, J.; Huang, Y.; Cohen, I. Pearson Correlation Coefficient. In *Noise Reduction in Speech Processing*; Springer: Berlin/Heidelberg, Germany, 2009.
57. Sin, G.; Gernaey, K.V.; Neumann, M.B.; van Loosdrecht, M.C.M.; Gujer, W. Global Sensitivity Analysis in Wastewater Treatment Plant Model Applications: Prioritizing Sources of Uncertainty. *Water Res.* **2011**, *45*, 639–651. [CrossRef] [PubMed]