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# A kinetic study on the nitrification process in the upflow submerged biofilter reactor

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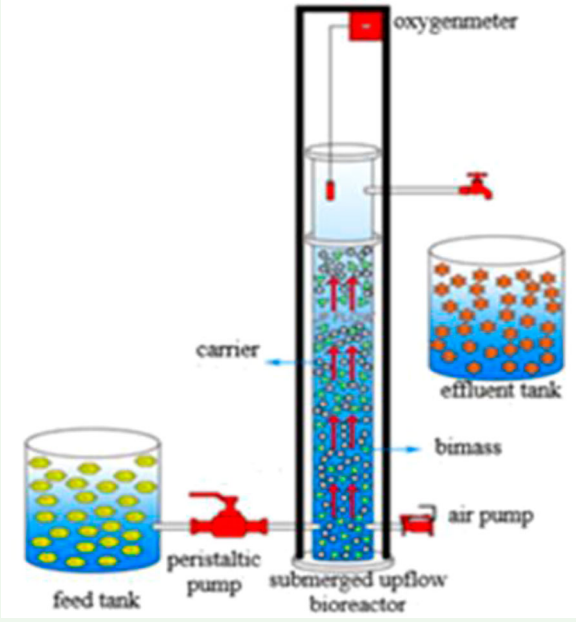
**ABSTRACT**

In extent of this study, ammonium removal from wastewater through biological nitrification process was performed in upflow biofilm reactors. The effects of hydraulic retention time (HRT) and nitrogen loading rate (NLR) on the nitrification process were investigated. For the nitrification process, the optimum HRT and NLR were determined to be 80 hr and 0.044 kg/m$^3$.day, respectively. It is observed that the efficiency increased from 53% to 96% along with the increase in HRT from 22 hr to 80 hr and the decrease in NLR from 0.165 kg/m$^3$.day to 0.044 kg/m$^3$.day.The substrate consumption kinetics were studied in the attached growth reactor, and the Monod kinetic model, first-order kinetic model, modified Stover-Kincannon and Grau second-order kinetic models were examined. For the substrate consumption kinetic study, experimental studies were performed at 125, 150, 175, 200, 225 mg $NH_4$-N/L substrate concentrations and 62 hr at HRT during the nitrification process. As a result of the considering kinetic studies, it was determined that the kinetic study was suitable for the modified Stover-Kincannon kinetic model that had the highest coefficient of regression by 0.997 and when the effluent $NH_4$-N concentrations and $NH_4$-N removal efficiencies calculated using kinetic models were examined, it was observed that the results closest to the experimental results (4.5, 10.1, 19.7, 26.2 and 42.3 mg $NH_4$-N/L) were obtained through the modified Stover-Kincannon model (4.16, 10.71, 18.92, 28.12 and 39.51 mg $NH_4$-N/L).

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## Introduction

The accumulation of ammonia in water bodies is serious long-term pollution [1]. Some industries, such as petrochemical, fertilizer and food industry, discharge wastewater with high nitrogen concentration [2]. When wastewater is discharged to receiving water bodies without treatment, it leads to many environmental problems such as eutrophication [3–5], toxic algae bloom [3,5], propagation of aquatic plants [5].

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Furthermore, it harms the freshwater ecosystem by causing oxygen consumption and consequently the loss of important aquatic species [5]. The removal of these pollutants in wastewater treatment plants is important to improve the quality of receiving water bodies [4]. Although various methods such as chemical precipitation, membrane technologies, ion exchange and adsorption are used for nutrient removal from wastewater, biological processes are more preferred due to their advantages such as less sludge production, more flexibility and lower cost [6]. Nowadays, Nitrification and denitrification processes are usually used to remove nitrogen [4].

Biological processes are classified into two categories: suspended and biofilm (attached growth) systems [7,8]. When attached growth technologies are compared with suspended growth technologies, they allow the enrichment of slow-growing nitrifying organisms due to their high specific surface area [8,9] and immobilizing ability and create systems with high nitrification biomass depending on the processes occurring in the biofilm [9]. Biofilm systems also offer advantages such as ensuring high sludge age, which is highly important for nitrifying bacteria [10,11]. In biofilm systems, sludge separation and recycling are not necessary to maintain the biomass in the bioreactor, since the biomass forms as a biofilm on the support medium [12]. Benefits of fixed bed systems include nitrogen removal, elimination of high microbial diversity and efficiency [13].

In order to design and optimize wastewater treatment processes in environmental engineering [14], kinetics models have been developed. For understanding the mechanisms of biological and transport, a kinetic model is an effective tool [15] and explain the complex processes of pollutant removal in the bioreactor [16]. Kinetic models are used to predict the performance of bioreactors [16,17] and optimize plant design [16]. In process kinetics, there are operational and environmental factors affecting substrate consumption rate. Through a kinetic study, optimizing the plant design and predicting the treatment plant is possible [18]. Kinetic models are usually nonlinear, and for estimating kinetic constants, a nonlinear method is utilized. Nonlinear models are converted to linear models for the determination of empirical constants. Therefore, arranging and organizing experimental data is possible with kinetics models in accordance with a specific framework in order to control and monitor the performance of system better [14]. For various operating conditions of reactor, various kinetic models are applied. In the Monod model, microorganisms growth in the initial phase of the reactor and a high concentration of substrate with or without inhibition is generally described. For describing reactors start up and stable operation, the modified Stover-Kincannon model and the Grau second-order model are commonly utilized [19].

Kinetic studies in attached growth processes are more complex than in suspended growth systems and have not been applied much to upflow submerged biofilter reactor; in addition, the studies carried out are not sufficient today. The main purpose of this study is to investigate the substrate removal kinetics (Monod, First-order model, modified Stover-Kincannon model and the Grau second-order model) in the upflow submerged biofilter reactor and to have information about the process performance by determining the appropriate substrate consumption kinetic model. In addition, it was aimed to perform $NH_4$-N removal by nitrification in the upflow submerged biofilter reactor and to determine the optimum hydraulic retention time (HRT) and nitrogen loading rate (NLR) values by investigating the effect of HRT and NLR on the nitrification process.

## Materials and methods

### *Synthetic wastewater*

Synthetic wastewater was prepared using distilled water. The composition of synthetic wastewater was (mg/L): $Na_2EDTA$, 4.83; $CuSO_4$, 0.0046; $ZnSO_4.7H_2O$, 0.023; $CoCl_2.6H_2O$, 0.0119; $Na_2MoO_4.2H_2O$, 0.066; $MgSO_4.7H_2O$, 36.97; $NaHCO_3$, 226; $CaCl_2.2H_2O$, 36.74; $H_3BO_3$, 1.0; $FeCl_3.6H_2O$, 0.316; $KH_2PO_4$, 1920 [20].

### *Enrichment of microorganism*

In all experimental studies for the nitrification process, the activated sludge brought from the aerobic unit of Sivas Municipality Wastewater Treatment Plant was used after being developed in the laboratory for about one year. For 10 days of sludge age (solid retention time), continuous completely stirred biomass was removed from the batch unit, and the development of nitrifying organisms was ensured. The batch biological unit was operated at a volume of 5 L with a magnetic stirrer by providing complete stirring. The biological process was monitored daily by pH, ammonium ($NH_4$+-N), nitrate ($NO_3$-N) and nitrite ($NO_2$-N) measurements.

### *Experimental setup*

Experimental studies for the nitrification process were performed in the upflow bioreactor made of laboratory-scale stainless steel at room temperature (≈25 ± 2 °C) (Figure 1). In the attached growth reactor, a 12 m long and 1.5 cm diameter plastic hose was cut and

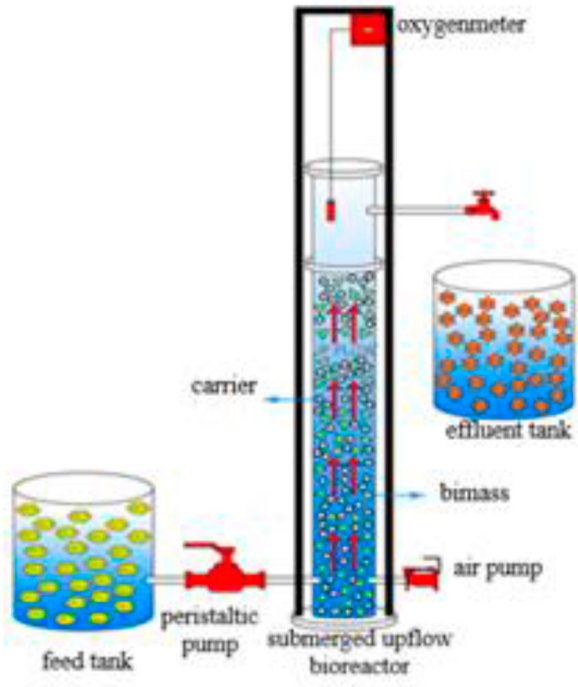


**Figure 1.** Chematic diagram of the upflow submerged biofilter reactor.

used as the filling material. After the filling material was placed in the reactor, the active biological reactor void volume was determined. Other features of the laboratory scale biofilm system are indicated in Table 1. The most suitable conditions were determined by operating the nitrification reactor at different $NH_4^+$-N loading, pH and dissolved oxygen (DO) concentrations. Initially, 2500 mg MLSS/L microorganism was added to the nitrification reactor. The reactor reached steady-state conditions after a period of 200 days, and the nitrification process was monitored daily by checking the effluent $NO_3$-N and $NO_2$-N concentrations. The reactor was operated at flow rates in the range of 0.44–23.55 L/day until it reached a stable condition at the end of the period state, it was determined that there was a negligible $NO_2$-N concentration (<1 mg/L), and nitrification was successfully achieved. After the reactor reached steady-state conditions, the effect of HRT and NLR and substrate consumption kinetics were investigated.

## Analytical method

In the nitrification process, the measurements were determined by separating the solid content of water samples collected from the influent and effluent water by filtering through cellulose acetate membrane filters with a pore diameter of 0.45 µm. During the experiment periods, $NH_4^+$-N, $NO_2$-N and $NO_3$-N concentrations were measured daily using ready-made kits ($NH_4^+$-N kit no:1.14752, $NO_2$-N kit no: 1.14776, $NO_3$-N kit no: 1.09713) in the MERCK brand Spectroquant Phoro 100 model spectrophotometer. By utilizing from the HANNA brand and pH metre, pH was measured daily, and values of the biological reactor influent were adjusted with 10 M $H_2SO_4$ and 10 M NaOH solutions. For the nitrification process, dissolved oxygen concentrations were monitored using the HACH brand HQ40d model oxygen metre.

## Substrate consumption kinetics in the submerged biofilter system for the nitrification process

For the substrate consumption kinetic study, experimental studies were performed at 125, 150, 175, 200, 225 mg $NH_4$-N/L substrate concentrations during the nitrification process, and bicarbonate was used as an inorganic carbon source. The experimental studies were maintained at a flow rate of 1.7 L/day and 62 hr HRT with an $NH_4$-N removal efficiency of over 90%. To this end, the Monod kinetics, first-order kinetics, modified Stover-Kincannon kinetic model and Grau second-order kinetics were examined.

### Monod kinetics

The kinetics were developed by Jacques Monod in 1942 and are used to describe microbial growth [21]. The relationship between growth rate and substrate concentration is mathematically defined by the Monod equation utilizing the maximum possible rate of growth [15]. The Monod kinetics, used for representing the biofilm nitrification kinetics transport complexity and enzymatic reactions in the biofilter. This theory is based on Michaelis-Menten enzyme kinetics [22]. The substrate mass balance (Equation (1)) is written according to the continuous-flow completely stirred reactor, and $dS/dt=0$ is accepted under steady conditions. Equation (3) is obtained when the Monod growth kinetics equation given in Equation (2) is written in its place in Equation (1), and Equation (4) is found after linearization [21].

**Table 1.** Properties of upflow submerged biofilter reactor.

| Reactor properties | Nitrification reactor |
|---|---|
| Filling height | 70 cm |
| Reactor volüme | 5.3 L |
| Reactor volid volüme | 4.370 L |
| Filling material surface area | 2.26 $m^2$ |
| Temperature | Room temperature (≈25 ± 2 °C) |
| pH | 8.0-–8.5 |
| DO concentrations | 6 mg/L |
| Influent substrate concentrations | 150 $NH_4^+$-N/L |

Substrate Mass Accumulation = Influent Substrate Concentration – Effluent Substrate Concentration + Substrate Consumed by Biodegradation

$$V_r = Q.S_0 - Q.S_e + V_r.R \quad (1)$$

$$R = \frac{R_{\max} X S_e}{K_S + S_e} \quad (2)$$

$$0 = Q(S_0 - S_e) + V_r\left(\frac{R_{\max}.X.S_e}{K_s + S_e}\right) \quad (3)$$

$$\frac{XV_r}{Q(S_0 - S_e)} = \frac{1}{R_{\max}} + \frac{K_s}{R\max}\frac{1}{S_e} \quad (4)$$

where $Q$ is the inflow rate (L/d), $V_r$ is the effective volume of the reactor (L), $S_0$ and $S_e$ are the substrate concentrations in influent and effluent, respectively, $X$ concentration of biomass in reactor [21], $K_s$ is the saturation concentration (g/L), and $R_{\max}$ is the maximal substrate utilization rate (g substrate/g MLSS/d). The values of $K_s$ and $R_{\max}$ are attained by plotting $XV_r/Q(S_0\text{-}S_e)$ against $1/S_e$ [23].

### First order kinetics

Assuming that the first-order substrate removal model can be applied to reactors, the rate of change of substrate concentration in a completely mixed reactor can be shown using Equation (5) [18,24–27].

$$-\frac{dS}{dt} = \frac{Q.S_0}{V_r} - \frac{Q.S_e}{V_r} - k_1.S_e \quad (5)$$

The rate of change in substrate concentration ($-dS/dt$) under pseudo-steady conditions can be neglected and modified, as can be seen in Equations (5) and (6).

$$\frac{Q(S_0 - S_e)}{V_r} = k_1.S_e \quad (6)$$

where $k_1$ is first-order substrate removal rate constant (1/d).

The substrate consumption rate constant value ($k_1$) can be measured from the line slope when the $Q(S_0\text{-}S_e)/V_r$ graph is drawn versus $S_e$.

### Modified Stover-Kincannon kinetic model

In order to determine kinetic constants in biofilm systems, the Stover-Kincannon model is one of the most frequently utilized mathematical model [18,25]. In this model, the substrate consumption rate is described as a function of organic loading rate by monomolecular kinetics for biofilm reactors such as rotating biological contactors and biological filters [24,28,29]. The Stover-Kincannon model refers to the substrate consumption as a function of nitrogen loading rate in a biofilm reactor. In the modified form of this model, the reactor volume is used instead of the surface volume of the reactor. This model has a higher correlation compared to other models and can be commonly utilized for determining biokinetic constants of attached growth systems. A low $K_B$ value indicates that the biofilm reactor has a low potential in the degradation of resistant wastewater [15]. The modified Stover-Kincannon model is indicated in Equation (7) [18,23,24,28,30].

$$\frac{dS}{dt} = \frac{R_{\max}\left(Q.\frac{S_0}{V_r}\right)}{K_B + \left(Q.\frac{S_0}{V_r}\right)} \quad (7)$$

On the other hand, in the following model $dS/dt$ is described

$$\frac{dS}{dt} = \frac{Q}{V_r}x(S_0 - S_e) \quad (8)$$

Equation (8) obtained from linearization of Equation (9) as follows:

$$\frac{V_r}{Qx(S_0 - S_e)} = \frac{K_B}{R_{\max}}\frac{V_r}{QxS_0} + \frac{1}{R\max} \quad (9)$$

where is the substrate removal rate (g/L/d), $R_{\max}$ and $K_B$ are the maximal substrate removal rate and saturation rate constant, respectively (g/L/d).

The values of $R_{\max}$ and $K_B$ are attained through from approximate curve by plotting $V/Q(S_0{-}S_e)$ against $V/QS_0$.

### Grau second-order substrate removal kinetics

This model was developed for the removal of multi-component substrates in a system [31]. The second-order model general equation is shown in Equation (10) [18,29].

$$-\frac{dS}{dt} = k_2X\left(\frac{S_e}{S_0}\right)^2 \quad (10)$$

Equation (10) obtained from linearization of Equation (11) as follows:

$$\frac{S_0.\mathrm{HAS}}{S_0 - S_e} = \mathrm{HRT} + \frac{S_e}{k_2.X} \quad (11)$$

If the second term of the right part of the equation is accepted as a constant, Equation (11) will be modified as follow:

$$\frac{S_0.\mathrm{HRT}}{S_0 - S_e} = a + b\mathrm{HRT} \quad (12)$$

where $a = S_0/k_2.X$, $b$ is a constant greater than unity [33]. $b$ (dimensionless Grau second-order constant) is close to one and reflects the impossibility of attaining a zero value of substrate concentration and $k_s$ is the second-order substrate removal rate constant ($day^{-1}$) [33–36]. The kinetic constants $a$ and $b$ can be calculated

**Table 2.** Linear and nonlinear forms of the kinetic models.

| Kinetic model | Non-linear form | linear form | Calculated constants |
|---|---|---|---|
| Monod | $R = \frac{R_{max} X S_e}{K_S + S_e}$ | $\frac{XV_r}{Q(S_0 - S_e)} = \frac{1}{R_{max}} + \frac{K_s}{R\max}\frac{1}{S_e}$ | $R_{max}$, $K_s$ |
| First-Order | $-\frac{dS}{dt} = \frac{Q.S_0}{V_r} - \frac{Q.S_e}{V_r} - k_1.S_e$ | $\frac{Q(S_0 - S_e)}{V_r} = k_1.S_e$ | $k_1$ |
| Modified Stover-Kincannon | $\frac{dS}{dt} = \frac{R_{max}\left(Q.\frac{S_0}{V_r}\right)}{K_B + \left(Q.\frac{S_0}{V_r}\right)}$ | $\frac{V_r}{Qx(S_0 - S_e)} = \frac{K_B}{R_{max}}\frac{V_r}{QxS_0} + \frac{1}{R\max}$ | $R_{max}$, $K_B$ |
| Grau Second-Order | $-\frac{dS}{dt} = k_2 X\left(\frac{S_e}{S_0}\right)^2$ | $\frac{S_0.\mathrm{HRT}}{S_0 - S_e} = a + b\mathrm{HRT}$ | $k_2$ |

respectively from the intercept and slope of the line by plotting *HRT* versus ($S_0$.*HAS*)/($S_0$-$S_e$) [32,33,35,37].

The linear and nonlinear forms of the kinetic models used in experimental studies are summarized in Table 2.

## Results and discussion

### *The effect of HRT and NLR on the upflow submerged nitrification process*

Studies were conducted at HRT values of 22, 32, 40, 48, 62, and 80 hr and at NLR values of 0.044, 0.057, 0.074, 0.096, 0.113, and 0.165 kg/m$^3$.day in for investigating the effect of HRT and NLR (kg/m$^3$.day) on NH4$^+$-N removal. As is seen in Figure 2, it is observed that the efficiency increased from 53% to 96% along with the increase in HRT from 22 to 80 hr and the decrease in NLR from 0.165 kg/m$^3$.day to 0.044 kg/m$^3$.day. As it has been predicted in previous studies, $NH_4^+$-N removal efficiency increases with the increase in biological reaction time, which can be attributed to the increase in contact time between the biomass and the substrate with the increase in HRT, and the biomass having sufficient time to oxidize the substrate.

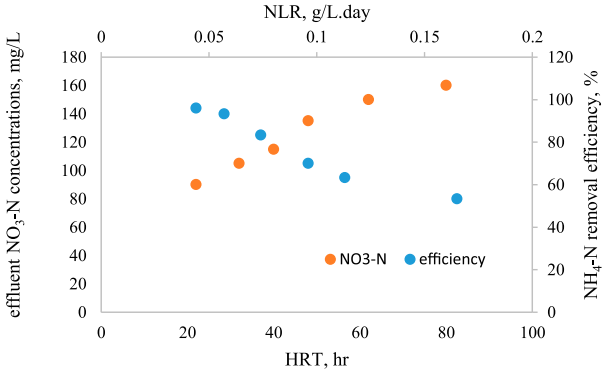


**Figure 2.** Effect of HRT and NLR on $NH_4$-N removal.

In the experimental study of determining HRT and NLR, the levels that can be applied to the attached growth reactor under operating conditions are defined, and their kinetic studies are performed under these conditions. Furthermore, the experimental study results indicate that the $NO_2$-N concentration (<0.1 mg/L) occurring in the system during the study period is negligible. In the biological nitrification process, in some studies, $NH_4^+$-N was converted to $NO_2$-N by *Nitrosomonas*, however, when the HRT was reduced, it was determined that $NO_2$-N could not be converted to $NO_3$-N by *Nitrobacter* since the reaction time was not sufficient [20]. In this study, no change was found in $NO_2$-N concentration in the effluent for the HRT studied. The lack of change is predicted to be due to the high concentration nitrite oxidizing bacteria (NOB) in the reactor.

Similar results were also reported by Jokela et al. (2002). It was indicated that nitrification efficiencies were above 90% at HRT values in the range of 1.4–3.8 days (34–91 hr) and at NLR values in the range of 0.110–0.130 kg/m$^3$.day in the upflow filter, at an HRT value of 7.3 days (175 hr) and at an NLR value around 0.100–0.125 kg/m$^3$.day in the downflow filter, and at an HRT value of 1.6 days (38.4 hr) and at an NLR value of 0.100 kg/m$^3$.day in the suspended carrier biofilm system. It was reported by Shayan et al. (2016) that the removal of $NH_4^+$ was achieved by 92% at an HRT value of 2 days (48 hr), while it was almost removed at an HRT value of 6 days (144 hr).

**Table 3.** HRT values selected for the nitrification process in the studies.

| Reactor | HRT (hr) | References |
|---|---|---|
| Submerged Membran Bioreactor | 96 | [34] |
| Activated Sludge | 96 | [35] |
| Rotating Algal Biofilm Reactor | 48–144 | [36] |
| Biofilter | 24–84 | [37] |
| Fluidized Bed Filter | 71–139 | [38] |
| Up-Flow Submerged Biofilter | 80 | This study |

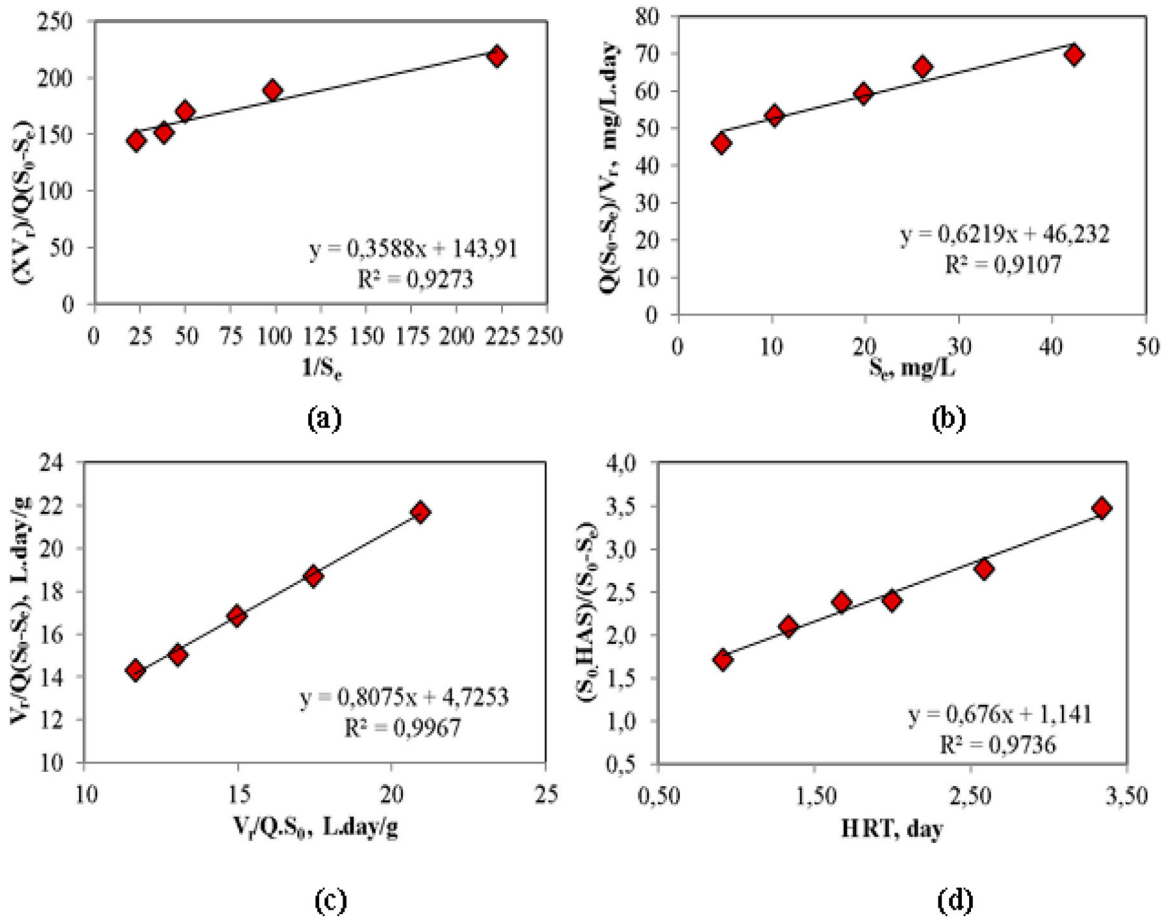


**Figure 3.** Substrate removal plots for $NH_4$-N removal in nitrification bioreactor: (a) Monod model (b) First-order model; (c) Modified Stover-Kincannon model; (d) Grau second-order model.

The HRT values selected for the nitrification process in various studies are presented in Table 3.

### *Substrate consumption kinetics in the biofilm for the nitrification process*

For substrate consumption kinetic study, the flow rate was 1.7 L/day and the HRT was kept constant by 62 hr, and $NH_4$-N volumetric loadings changed by changing the influent $NH_4$-N concentrations. The volumetric loadings of 0.048, 0.058, 0.068, 0.077, and 0.087 g/Lday were studied for 125, 150, 175, 200, and 225 mg $NH_4$-N/L substrate concentrations, respectively.

In order to predict the performance of bioreactor and evaluate the removal of substrate, kinetics models are required. Information attained through kinetic models is utilized in order to predict effluent concentration, substrate removal rate, and system efficiency [14]. The kinetic graphs drawn using Equations (4), (6), (9) and (12) are presented in Figure 3, and the kinetic coefficients calculated from the slope of the lines obtained from the graphs are presented in Table 5.

Kinetic data showed that the kinetic model of the reactor was more appropriate to the Stover-Kincannon kinetic model according to the regression coefficients and kinetic coefficients in the laboratory scale biofilm nitrification reactor.

In Table 4, the kinetic coefficients of the kinetic models applied are compared with the existing studies. It was observed that the kinetic constants $R_{max}$ and $K_B$ of the modified Stover-Kincannon kinetic model for the upflow bionitrification reactor were lower than the kinetic constants $R_{max}$ and $K_B$ determined in the systems performing organic matter removal, which was considered to be due to the low substrate consumption rate caused by nitrifying organisms. Borghei et al. (2008) based the kinetic constants $R_{max}$ and $K_B$, which they found higher than the existing studies, on the higher substrate consumption rate. It is known that low $R_{max}$ and $K_B$ values are caused by low NLR [26]. Low $K_B$ values indicate that the biofilm reactor has a low potential in the degradation of resistant wastewater [15].

As a result of the influent substrate concentration and microorganism concentration in the reactor in upflow

**Table 5.** Effluent $NH_4$-N concentrations and $NH_4$-N removal efficiencies calculated using kinetic models

| | Measured values | | Kinetic models | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | First-order kinetic | | Modified stover-kincannon kinetic | | Grau second-order kinetic | |
| $S_0$, mg/L | Se, mg/L | Efficiency, % | Se, mg/L | Efficiency, % | Se, mg/L | Efficiency, % | Se, mg/L | Efficiency, % |
| 125 | 4.5 | 96.4 | 47.57 | 61.9 | 4.16 | 96.7 | 7.06 | 94.4 |
| 150 | 10.1 | 93.3 | 57.09 | 61.9 | 10.71 | 92.9 | 18.03 | 88.0 |
| 175 | 19.7 | 88.7 | 66.60 | 61.9 | 18.92 | 89.2 | 30.76 | 82.4 |
| 200 | 26.2 | 87 | 76.12 | 61.9 | 28.63 | 85.7 | 44.95 | 77.5 |
| 225 | 42.3 | 81.2 | 85.63 | 61.9 | 39.51 | 82.4 | 60.38 | 73.2 |

**Table 4.** Kinetic coefficients determined in existing studies.

| | | | Kinetic paremeters | | | | |
|---|---|---|---|---|---|---|---|
| Kinetic model | Reactor type | Subtrate | $R_{max}$ | $K_s$ | $R^2$ | | References |
| Modified stover-kincannon kinetic model | Fixed-Bed Aerobic Biological Reactor | Organic Matter (COD) | 101 | 106.8 | 0.9975 | | [24] |
| | Moving-Bed Biofilm Sequencing Batch Reactor | Organic Matter (BOD) | 21.123 | 19.361 | 0.99 | | [21] |
| | Internal-Loop Airlift Bio-Particle Reactor (PN-Anammox) | $NH_4$-N | 22.29 | 27.25 | 0.9810 | | [18] |
| | Partially packed upflow anaerobic fixed film reactor | low-strength synthetic rubber wastewater | 6.57 | 0.31 | 0.9989 | | [15] |
| | Anaerobic packed column reactor | Dyestuff | 0.47 | 0.43 | 0.9902 | | [39] |
| | Attached growth membrane bioreactor | COD | 0.013<br>0.33<br>0.26 | 0.10<br>0.32<br>0.76 | 0.8683<br>0.7924<br>0.6163 | | [26] |
| | UASB-Annamox | $NH_4$-N<br>$NO_2$-N | 0.892<br>1.00 | 1.019<br>1.11 | 0.94<br>0.98 | | [40] |
| | **Up-Flow Submerged Biofiter Reactor (Nitrification)** | **$NH_4$-N** | **0.212** | **0.171** | **0.9967** | | **This study** |
| First-order kinetic model | | | $k_1$ | $R^2$ | | | |
| | Upflow Filter (Anammox) | $NH_4$-N | 0.4395 | 0.1715 | | | [25] |
| | Moving-Bed Biofilm Sequencing Batch Reactor | Organik Matter (BOD) | 18.184 | 0.9847 | | | [21] |
| | Internal-Loop Airlift Bio-Particle Reactor (PN-Anammox) | $NH_4$-N | 66.90 | 0.6018 | | | [18] |
| | Fixed-Bed Aerobic Biological Reactor | Organic Matter | 14.549 | 0.742 | | | [24] |
| | Upflow Anaerocic Sludge Blanket Reactor (Anammox) | $NH_4$-N | 11.64 | 0.8043 | | | [27] |
| | UASB-Annamox | $NH_4$-N<br>$NO_2$-N | 0.458<br>0.561 | 0.43<br>0.04 | | | [40] |
| | **Up-Flow Submerged Biofiter Reactor (Nitrification)** | **$NH_4$-N** | **0.6219** | **0.9107** | | | **This study** |
| Monod kinetic model | | | $R_{max}$ | $K_s$ | $R^2$ | | |
| | Cylindrical Column Reactor (Anammox) | $NH_4$-N | 0.952 | 0.107 | 0.993 | | [23] |
| | Anaerobic Filter | Soybean Wastewater | 0.802 | 0.565 | 0.915 | | [41] |
| | Moving-Bed Biofilm Sequencing Batch Reactor | Organic Matter (BOD) | 1.856 | 83.158 | 0.9901 | | [21] |
| | **Up-Flow Submerged Biofiter Reactor (Nitrification)** | **$NH_4$-N** | **0.007** | **0.0025** | **0.9273** | | **This study** |
| Grau second-order kinetic model | | | $a$ | $B$ | $k_2$ | $R^2$ | |
| | Upflow Anaerobic Sludge Blanket Reactor | COD | 0.0291 | 0.0113 | 0.26 | 0.942 | [30] |
| | Upflow Anaerobic Sludge Blanket Reactor | Textile Wastewater (COD) | 0.562 | 1.095 | 0.337 | 0.995 | [28] |
| | Internal-Loop Airlift Bio-Particle Reactor (PN-Anammox) | $NH_4$-N | 1.0852 | 0.015 | 2.064 | 0.9954 | [18] |
| | Partially packed upflow anaerobic fixed film reactor | low-strength synthetic rubber wastewater | 0.918 | 0.962 | 105 | 0.999 | [15] |
| | UASB-Anammox | $NH_4$-N<br>$NO_2$-N | −0.087<br>0.051 | 1.13<br>1.14 | -<br>- | 0.93<br>0.98 | [40] |
| | Aerated submerged fixed-film Bioreactor | BOD | 0.0715 | 0.8475 | 0.4910 | 0.98 | [35] |
| | **Up-Flow Submerged Biofiter Reactor (Nitrification)** | **$NH_4$-N** | **1.141** | **0.676** | **0.0125** | **0.9736** | **This study** |

biofilm reactors, the substrate removal rate constant ($k_2$) of the Grau second-order kinetic model is lower than that determined in other studies. The $k_2$ value depends on the influent, substrate concentration, and biomass concentration in the reactor and increases with the increase in substrate removal efficiency [23]. Işık and Sponza (2005) and Borghei et al. (2008) attributed high $k_2$ values to the increase in substrate removal rate depending on the influent substrate and the microorganism concentration in the reactor.

The $k$ value is low for the first-order kinetics, and the higher the $k$ value is, the higher the degradation capacity of the microorganism [31].

The ammonium removal efficiencies and the effluent ammonium concentrations predicted for each model using the kinetic coefficients calculated after the kinetic coefficients were calculated are presented in Table 5. The values calculated for the Monod kinetics are not given in the table since they were found to be insignificant. As shown in Table 5, the modified Stover-Kincannon kinetic model gave the values closest to the experimentally measured values, which means that the modified Stover-Kincannon kinetic model was the most appropriate kinetic model.

## Conclusions

In this study, the nitrification process was performed in upflow biofilm reactors, and substrate consumption kinetics were studied for these reactors.

The effect of HRT and NLR on the nitrification process in upflow biofilm reactors was investigated, and it was determined that the efficiency increased from 53% to 96% along with the increase in HRT from 22 to 80 hr and the decrease in NLR from 0.165 kg/m$^3$.day to 0.044 kg/m$^3$.day. The increase in nitrification efficiency with increased HRT is considered to be associated with increased contact time between biomass and substrate.

According to the regression coefficients and kinetic constants, it was determined that the modified Stover-Kincannon model was the most appropriate kinetic model. The effluent substrate concentrations for the initial substrate concentrations of 125, 150, 175, 200 and 225 mg $NH_4$-N/L were experimentally measured as 4.5, 10.1, 19.7, 26.2 and 42.3 mg/L, respectively. Considering the effluent substrate concentrations calculated according to the kinetic constants, the modified Stover-Kincannon kinetic model was the most compatible with the experimental results of the values of 4.16, 10.71, 18.92, 28.63, and 39.51 mg $NH_4$-N/L. This result indicated that the kinetic study complied with the modified Stover-Kincannon kinetic model.

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## Disclosure statement

No potential conflict of interest was reported by the author(s).

## Data availability statement

All data used during the study are available from the corresponding author by request.

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