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Investigation of Biopipe System Performance Using Numerical Model

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Abstract. Biopipe system is the first biological wastewater treatment system in which removal processes of carbonaceous and nitrogenous compounds are supposed to take place entirely inside a pipe. In this study a Biopipe system model, a labeled as BPSM, for investigating Biopipe system performance (in terms of soluble substrate removal) and in treating municipal wastewater has been developed. BPSM is based on solving the one-dimensional advection-dispersion equation for multiphase pipe flow (air-wastewater) under pressure in a pipeline including the representation of all biological processes affecting the concentrations of carbonaceous and nitrogenous compounds by Activated Sludge Model Number3(ASM3). The model was applied on Biopipe system with the inclusive of recirculation with and without the use of final sedimentation unit. The most important findings of BPSM application revealed that the existence of a final sedimentation unit after the Biopipe system is crucial for the effective removal of biodegradable organics. Where, the removal efficiency of readily biodegradable substrate varied on the ranges (43.3-99) and (14.8-21.3) % when final sedimentation unit is used and unused, respectively. In addition, it was found that the removal efficiency of biodegradable organics can be enhanced in case of final sedimentation absent if very long Biopipe system is used.

INTRODUCTION

Land cost beside construction, operation and maintenance costs are contribute to the high cost of wastewater treatment plants. In addition, wastewater treatment plants necessitate an advanced operating and management staff with extensive expertise and high versatility in order to keep them running in a good condition. As a result, finding an effective and low-cost wastewater treatment system, such as the type considered in this study (Biopipe system) is an important issue. Biopipe system is the first biological wastewater treatment system in which removal processes of carbonaceous and nitrogenous compounds take place entirely inside a pipe. The complement facilities of Biopipe system include [1]; (1) screenings removal unit, (2) grit removal unit (applied for large wastewater treatment plants), (3) equalization tank, (4) Biopipe, (5) air injector by which air is vacuumed due to pressure difference, (6) recirculation pump, (7) cartridge filter, and (8) Ultra violet disinfection unit.

Biopipe system was invented by E. Misirli and E. Kutluca and lunched in 2013[2]. Misirli pointed out that Biopipe system can be implemented to treat municipal wastewater in various scales including small houses, apartments, residential houses compounds, hospitals, universities, and hotels and the final effluent can be used or irrigation purposes for the same facilities. The study mentioned that till the year 2016, over 40 Biopipe systems were installed in Dubai, Oman, Turkey, Qatar, and other places around the world. The company of Biopipe system manufacturing indicated that the system is odor free and produces no sludge and its final effluent has characteristics better than those specified by the European Union (EU) Standards [3]. In Iraq, the need for such treatment system is argent especially for public buildings like universities, hospitals, and the residential compounds constructed in the recent years. The sites of these buildings and compounds usually include green areas, thus, the application of Biopipe system for them can preserve clean environment and satisfy the need of irrigation water.

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In spite of the aforementioned characteristics of Biopipe system, no of the previous studies, conducted on biological wastewater treatment, have considered the design parameters of Biopipe system or the operating factors that affect its performance, except for the brief descriptions provided by its innovators and manufacturer for its marketing purposes. That was the motivation for conducting this study. Thus, the present study aims to develop a numerical model for simulating the performance of Biopipe system in treating municipal wastewater. The model is essential for obtaining a quantitative and detailed understanding of Biopipe system, which is needed for extending the circle of system design data (beyond that of innovators) and controlling its operating parameters.

CONCEPT BACKGROUND OF WASTEWATER TREATMENT IN BIOPIPE SYSTEM

Although, there are no previous studies revealing Biopipe system performance, the conceptual roots of treating domestic wastewater into a pipe can be found in studies conducted by researchers dealt with the biodegradation of organic matter in sewers. Nielsen et al. [4] reviewed a number of studies conducted on transformation processes affecting the concentrations of many components, including organic matter and DO, in gravity and pressure sewers. One of these studies was conducted by Boon et al. In this study oxygen injected into a pressure sewer and showed that the ratios of BOD removed to DO consumed were 0.7 and 1.4 (g BOD/g DO) for temperature values varied on the ranges (11-14) and (20-25) ˚C, respectively. Garsdal et al. [5] developed a model for simulating the biodegradation processes of organic matter in gravity sewers under aerobic conditions and showed that the dissolved (suspended) COD fractions decreased (increased) towards the sewer end and that indicated the removal of soluble substrate (SS) and growth of biomass. Özer and Kasirga [6] investigated the COD removal potential in a long gravity sewer flowing half full. Table used to relate the sewer length required to obtain specific COD removal efficiency for different sewer diameters assuming influent COD of 170mg/l. They showed that the COD removal efficiency is directly proportional to the sewer length and influent substrate concentration. For example, the study indicated that the sewer lengths required to get 94% COD removal efficiency were 14.3 and 62.1 km for sewer diameters of 200 and 2000mm, respectively, and the application of sewers as a treatment facility required adequate pipe length with provisions for maintaining aerobic conditions. Tanaka and Takenaka [7] investigated, experimentally, the effect of air injection into an upward sloped force main of 350mm diameter and 3462m length on BOD values in wastewater. The study shows that air injection can reduce the BOD at a percentage varied on the range (25-70) % when the wastewater temperature and retention time were 25˚C and 6 to 7 hrs., respectively. Seidl et al. [8] studied the biodegradability of organic matter in a combined sewer system and showed that organic matter biodegradability decreased along with the sewer system. Hvitved-Jacobsen, et al. [9] developed a conceptual model for biodegradation of organic carbon in gravity sewers under aerobic conditions. The study pointed out that the transformation processes of organic matter in a sewer and in a wastewater treatment plant are identical concerning the predominant microbial processes and thus, the concept of modeling a microbial wastewater system using ASMs can be applied to the microbial wastewater system in a sewer too. Hvitved-Jacobsen et al. [10] studied the biodegradability of organic matter in combined sewers using a conceptual model of aerobic transformations and found that the biodegradability of slow settling organic fraction is greater than that of fast settling organic fraction, i.e., the biodegradation of suspended organics is greater than of settled organics. Tanaka and Hvitved-Jacobsen [11] combined Activated Sludge Model No.2 (ASM2) and a conceptual model for simulating the biodegradation of organic matter in gravity sewers under changing aerobic-anaerobic conditions. Almeida et al. [12] developed a model for simulating the one-dimensional transport of wastewater and transformation processes in gravity sewer under aerobic conditions (free surface flows). The model incorporated the processes described by activated sludge model number 1(ASM1) in addition to the reaeration process through the liquid surface and at locations of drops and changes in the flow direction. Tanaka et al. [13] developed aerobic–anaerobic process model for simulating the transformation processes affecting the concentrations of COD fractions, dissolved oxygen (DO), and sulfide in a pressure sewer (force main) injected by air. The study indicated that the injection of adequate air quantity into a force main transports wastewater to a treatment plant can remove SS and produce aerobic biomass and thus less biodegradable fractions will reach the treatment plant which may eliminate the need for a biological treatment unit. Also, they pointed out that the S_S removal started within 1 hour after air injection. Huisman and Gujer [14] simulated the transformation processes in a gravity sewer using a model developed based on ASM3 In this study calibration of the ASM3 parameter was used in laboratory and field data to show that the model can represent the microbiological processes in sewers. Hvitved-Jacobsen et al. [15] investigated the chemical and microbial transformation processes in sewers under dry weather conditions. The study pointed out that the sewer behaves as a chemical and biological treatment system and if aerobic condition is preserved, the activity of heterotrophic bacteria will be high which may lead to organic matter removal and production of biomass. Tanaka and Hvitved-Jacobsen

[16] applied a sewer process model based on ASM, for simulating the transformation processes in a pressure sewer and showed that the calibrated model results agreed with measured ones. Jiang et al. [17] applied ASM3 to simulate pollutant transformation processes in a sewer and developed a method based on a genetic algorithm for obtaining the values of ASM3 kinetic and stoichiometric parameters. In this study the ASM3 results obtained using the determined parameters were in good agreement with experimental data of nitrogenous compounds and DO utilization rate and with real DO data obtained from an existing sewer. Pai et al. [18] investigated wastewater quality changes in a trunk sewer and pointed out that organic matter decay, nitrification, and denitrification processes occurred in the sewer. Hvitved-Jacobsen et al. [19] indicated the similarity between biodegradation processes in sewers and in biological treatment plants and compared the representation of transformation processes of organic matter by ASM2 with those occurring in gravity sewers. Ilie et al. [20] developed a numerical model for simulating the biodegradation of organic matter in a gravity sewer and showed that the percentage of BOD5 removal by microbiological activity in a sewer of 4900m length was 35.44%. Zhao et al. [21] simulated wastewater quality changes in a gravity sewer using a modified ASM in which anaerobic fermentation was incorporated.

Conclusion from previous studies, that wastewater treatment can be achieved using a pipeline with the condition of preserving the aerobic condition which is in the gravity sewers due to the presence of a free surface or by injecting air as in force mains (pressure sewers). In addition, the transformation processes affecting the concentration of the different constituents in wastewater can be modeled using ASM3. These outcomes have been considered in developing the numerical model of Biopipe system.

METHODOLOGY

This section explains how to model the transport, dispersion and microbiological transformation processes that affecting the concentration of organic carbon compounds (COD fractions) and nitrogen compounds (nitrogen fractions) in Biopipe system. First, assumptions about modeling are presented. Second, governed equations along with their solution method are defined. Finally, all input data and parameters are displayed.

Assumptions

The current model has been developed adopting the following assumptions:

- The flow along the Biopipe system is a one-dimensional steady flow (pipe flow).
- The flow pattern is turbulent.
- The pollutant concentrations are a function of time and longitudinal distance along the Biopipe.
- The system treats settled sewage (primary sedimentation unit effluent) so sediment transport phenomena and biofilm attachment and detachment will be neglected.
- Air supply will be dispersed uniformly at the point of injection.
- The minor head losses due to bends in Biopipe system are neglected.
- Steady influent wastewater characteristics.

Governing Equations and Solution Technique

Advection-dispersion equation (Eq.1) is a well-known formula for expressing the one-dimensional concentration field of any constituent-i in flowing water as a function of longitudinal distance (x) and time (t). This equation has been adopted to simulate the transport of constituents in Biopipe system [22];

$$\frac{\partial \mathrm{C}_i}{\partial \mathrm{t}} + U\frac{\partial \mathrm{C}_i}{\partial \mathrm{x}} = \frac{\partial}{\partial \mathrm{x}}(\mathrm{D}_x\frac{\partial \mathrm{C}_i}{\partial \mathrm{x}}) + \mathrm{S}_{\mathrm{T,C}_i} \quad (1)$$

where Ci is mean concentration of constituent-i (mg/l) over the pipe cross sectional area, U is the mean flow velocity of wastewater in x-direction (m/sec), Dx is dispersion coefficient in x-direction, and $\mathrm{S}_{\mathrm{T,C}_i}$ is the sink/source term that represents all transformation processes affecting constituent-i concentration.

The sink/source term in Eq.1 represents all the microbiological processes affecting the concentration of organic carbon and nitrogen compounds in wastewater. This term was represented by ASM3 developed by Henze et al. (International Waster Association task group) [23]. ASM3 simulate the interaction of 12 reaction processes affecting the concentration of 13 compounds; 7 COD fractions and 3 total nitrogen fractions, in addition to dissolved oxygen ($\mathrm{S}_{\mathrm{O}_2}$), alkalinity ($\mathrm{S}_{\mathrm{ALK}}$) and suspended solids ($\mathrm{X}_{\mathrm{SS}}$) . The COD fractions include; inert soluble organic material (S_I), readily biodegradable organic substrates (S_S), inert particulate organic material (X_I), slowly biodegradable organic substrates (X_S), heterotrophic organisms (X_H), cell internal storage product of heterotrophic organisms (X_{STO}), and nitrifying (autotrophic) organisms (X_A). Whereas, the nitrogen fractions include; ammonium-N (S_{NH_4}), dinitrogen (S_{N_2}), and nitrate plus nitrite-N (S_{NOX}).

Eq.1 was written for each of the 13 compounds. Definitions of sink/source terms for the 13 compound equations are presented in Table 1. In this Table, the reaction processes (R1 to R12) are defined in Table 2. Whereas, the last term in Eq.3 (ROS) represents the rate of oxygen supply as will be defined in Section (3.2.3). The resulting 13 partial differential equations were solved using finite difference explicit backward approach. Adopting this approach, the values of time and spatial steps (Δt and Δx) were constrained by Courant number (Eq.2) value less than unity in order to assure the solution stability [22].

$$\text{Current Number} = \frac{U\,\Delta x}{\Delta t} \quad (2)$$

TABLE 1. Definition of source/sink term for the different model components

Component	Definition of source/sink term	
S_{O_2}	$S_{T,S_{O_2}} = -0.15R_2 - 0.6R_4 - 0.8R_6 - R_8 - 18.04R_{10} - 0.8R_{11} + R_{OS}$	(3)
S_I	$S_{T,S_I} = 0$	(4)
S_S	$S_{T,S_S} = R_1 - R_2 - R_3$	(5)
S_{NH_4}	$S_{T,S_{NH_4}} = 0.01R_1 + 0.03R_2 + 0.03R_3 - 0.07R_4 - 0.07R_5 + 0.066R_6 + 0.066R_7 - 4.24R_{10} + 0.066R_{11} + 0.066R_{12}$	(6)
S_{N_2}	$S_{T,S_{N_2}} = 0.07R_3 + 0.3R_5 + 0.28R_7 + 0.35R_9 + 0.28R_{12}$	(7)
S_{NOX}	$S_{T,S_{NOX}} = -0.07R_3 - 0.3R_5 - 0.28R_7 - 0.35R_9 + 4.17R_{10} - 0.28R_{12}$	(8)
S_{ALK}	$S_{T,S_{ALK}} = 0.001R_1 + 0.002R_2 + 0.007R_3 - 0.005R_4 + 0.016R_5 + 0.005R_6 + 0.025R_7 + 0.025R_9 - 0.6R_{10} + 0.005R_{11} + 0.025R_{12}$	(9)
X_I	$S_{T,X_I} = 0.2R_6 + 0.2R_7 + 0.2R_{11} + 0.2R_{12}$	(10)
X_S	$S_{T,X_S} = -R_1$	(11)
X_H	$S_{T,X_H} = R_4 + R_5 - R_6 - R_7$	(12)
X_{STO}	$S_{T,X_{STO}} = 0.95R_2 + 0.8R_3 - 1.25R_4 - 1.54R_5 - R_8 - R_9$	(13)
X_A	$S_{T,X_A} = R_{10} - R_{11} - R_{12}$	(14)
X_{SS}	$S_{T,X_{SS}} = -0.75R_1 + 0.51R_2 + 0.48R_3 - 0.06R_4 - 0.21R_5 - 0.75R_6 - 0.75R_7 - 0.6R_8 - 0.6R_9 + 0.9R_{10} - 0.75R_{11} - 0.75R_{12}$	(15)

TABLE 2. Definition of ASM3 reaction processes

j	Process (R_j)	Equation	
1	Hydrolysis	$R_1 = k_H \cdot \frac{X_S/X_H}{K_X + X_S/X_H} \cdot X_H$	(16)
	Heterotrophic organisms; aerobic and denitrifying activities		
2	Aerobic storage of S_S	$R_2 = k_{STO} \cdot \frac{S_{O_2}}{K_{O_2}+S_{O_2}} \cdot \frac{S_S}{K_S+S_S} \cdot X_H$	(17)
3	Anoxic storage of S_S	$R_3 = k_{STO} \cdot \eta_{NOX} \cdot \frac{K_{O_2}}{K_{O_2}+S_{O_2}} \cdot \frac{S_{NOX}}{K_{NOX}+S_{NOX}} \cdot \frac{S_S}{K_S+S_S} \cdot X_H$	(18)
4	Aerobic growth of X_H	$R_4 = \mu_H \cdot \frac{S_{O_2}}{K_{O_2}+S_{O_2}} \cdot \frac{S_{NH_4}}{K_{NH_4}+S_{NH_4}} \cdot \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \cdot \frac{X_{STO}/X_H}{K_{STO}+X_{STO}/X_H} \cdot X_H$	(19)
5	Anoxic growth (denitrification)	$R_5 = \mu_H \cdot \eta_{NOX} \cdot \frac{K_{O_2}}{K_{O_2}+S_{O_2}} \cdot \frac{S_{NOX}}{K_{NOX}+S_{NOX}} \cdot \frac{S_{NH_4}}{K_{NH_4}+S_{NH_4}} \cdot \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \cdot \frac{X_{STO}/X_H}{K_{STO}+X_{STO}/X_H} \cdot X_H$	(20)
6	Aerobic endogenous respiration	$R_6 = b_{H,O_2} \cdot \frac{S_{O_2}}{K_{O_2}+S_{O_2}} \cdot X_H$	(21)
7	Anoxic endogenous respiration	$R_7 = b_{H,NOX} \cdot \frac{K_{O_2}}{K_{O_2}+S_{O_2}} \cdot \frac{S_{NOX}}{K_{NOX}+S_{NOX}} \cdot X_H$	(22)
8	Aerobic respiration of X_{STO}	$R_8 = b_{STO,O_2} \cdot \frac{S_{O_2}}{K_{O_2}+S_{O_2}} \cdot X_{STO}$	(23)
9	Anoxic respiration of X_{STO}	$R_9 = b_{STO,NOX} \cdot \frac{K_{O_2}}{K_{O_2}+S_{O_2}} \cdot \frac{S_{NOX}}{K_{NOX}+S_{NOX}} \cdot X_{STO}$	(24)
	Autotrophic organisms; nitrifying activity		
10	Aerobic growth of XA	$R_{10} = \mu_A \cdot \frac{S_{O_2}}{K_{A,O_2}+S_{O_2}} \cdot \frac{S_{NH_4}}{K_{A,NH_4}+S_{NH_4}} \cdot \frac{S_{ALK}}{K_{A,ALK}+S_{ALK}} \cdot X_A$	(25)
11	Aerobic endogenous respiration	$R_{11} = b_{A,O_2} \cdot \frac{S_{O_2}}{K_{A,O_2}+S_{O_2}} \cdot X_A$	(26)
12	Anoxic endogenous respiration	$R_{12} = b_{A,NOX} \cdot \frac{K_{A,O_2}}{K_{A,O_2}+S_{O_2}} \cdot \frac{S_{NOX}}{K_{A,NOX}+S_{NOX}} \cdot X_A$	(27)

Mean flow velocity determination

To maintain aerobic condition into Biopipe system, air is injected and thus the flow in the system will be of multiphase type due to simultaneous occurrence of gas (air) and liquid (wastewater). One of the important liquid-gas flow properties is the void fraction (α) that can be defined as the ratio of pipe area occupied by gas (air) and the total area of pipe [24]. For specific pipe length and time duration, α is defined as;

$$\alpha = \frac{Q_{air}}{Q_{air}+Q_w} \tag{28}$$

where Q_{air} and Q_w are the flowrate of injected air and wastewater, respectively. On the other hand, the liquid holdup (H_L) is the fraction of the pipe volume occupied by the liquid phase. Accordingly;

$$H_L = 1 - \alpha = \frac{A_w}{A} \tag{29}$$

where A_w is pipe cross sectional area occupied by wastewater and A is pipe cross sectional area. The mean wastewater flow velocity (U) is calculated as;

$$U = \frac{Q_W}{A_W} \tag{30}$$

Considering oxygen content in air is 0.232 (kg O_2/kg air) and air density is 1.2 kg/m^3, Q_{air} is obtained as;

$$Q_{air} = \frac{R_O}{0.232\times 1.2} \tag{31}$$

where R_O is theoretical oxygen requirement (kg/d) and it is calculated as [25];

$$R_O = Q(S_0 - S) - 1.42P_{X,bio} \tag{32}$$

where $P_{X,bio}$ is the biomass as VSS wasted per day (kg/d).

Dispersion coefficient determination

Longitudinal dispersion in pipes flow defines the spreading of a solute transports along the longitudinal axis of flow relative to the mean flow velocity in the axial direction [26]. The value of longitudinal dispersion coefficient (Dx) is dependent mainly on Reynolds number (Re) [27, 28, 21]. However, Hart et al. [28] showed that the dependency of Dx on Re is insignificant when Re > 20,000 and indicated that when Re < 20,000, Dx increases significantly until its value at Re ≈ 2000 is 25 times that at Re > 20,000. Hart et al. [28] developed the following formula for Dx determination when Re varied on the range (3,000-50,000);

$$\frac{DX}{Ud} = 1.17 \times 10^9 R_e{}^{-2.5} + 0.41 \tag{33}$$

Veliskova and Sokac [26] estimated Dx values from field tracer experiments in straight and non-straight sewers. They found that for non-straight sewers (like the case of Biopipe system), the Dx values varied on the range (0.02-0.24) with an average value of 0.1 m/sec^2. In this study, all the numerical experiments conducted on Biopipe system were under turbulent flow condition. When Eq.33 was adopted for Dx determination, the obtained Dx values were within the rang presented by Veliskova and Sokac. Thus, all the model runs of Biopipe system performance were conducted adopting an average Dx value of 0.1 m/sec^2.

Oxygen supply rate

The processes describing the mechanism of oxygen transfer from gaseous phase to liquid phase is an important part related to biological wastewater treatment. Many researchers investigated air transfer from gas phase to liquid phase in sewers (gravity and force mains). Tanaka et al. [13] presented two equations for modelling air supply in force main (pressurized) sewer; one for a down grade force main and the other for an upgrade force main or pipe in horizontal position. Garcia et al. [29] constructed scale model to quantify dissolved oxygen transfer to force main pipe located in two different locations in southeast of Spain. The study presented two fitted model depending on slope of pipe and showed good agreement with field data. Tanaka and Takenaka [7] presented an experimental equation to get the air volume injected inside a force main. Yin et al [30] presented a model for DO increase in a horizontal pipe flow by air injection and validated the model against experimental data.

In this study, air is injected into Biopipe system to supply the oxygen necessary for maintaining the aerobic condition and subsequently the aerobic biodegradation processes. Since the Biopipe system is composed of horizontal pipe at pressurized flow condition, the reaeration rate was represented using the equation put by Yin et al. [30];

$$R_{OS} = K_{L,B}a_B(S_{O_2}sw - S_{O_2}) \tag{34}$$

where $K_{L,B}a_B$ is bubble transfer coefficient, $K_{L,B}$ is liquid film mass transfer coefficient, and a_B is specific interfacial bubble area, and $S_{O_2}sw$ is oxygen saturation concentration of wastewater. $K_{L,B}$ is defined by Eq.35 which was developed by Wilkinson and Haringa [31] and applied by Yin et al. [30];

$$K_{L,B} = max\left\{0.4\left(\frac{v}{D_m}\right)^{-0.5}(v\epsilon)^{0.25}, \frac{D_m P^{0.5}}{R_b\sqrt{\pi}} \times \left[1 - \frac{2}{3}\left(1 + 0.09R_b^{2/3}\right)^{-3/4}\right]\right\} \tag{35}$$

where ν is kinematic viscosity of wastewater (cm^2/sec), Dm is oxygen molecular diffusion coefficient which is dependent on temperature and it equals 2.01×10-5 cm^2/sec at 20 ˚C [32], ϵ is turbulence dissipation rate (cm^2/sec^3) defined by the following simplified formula [33];

$$\epsilon = 0.16{R_e}^{2.75}v^3/D^4 \tag{36}$$

and P is Peclet number defined as [30];

$$P = 2|\overrightarrow{u_s}|R_b/D_m \tag{37}$$

Where: Re is Reynolds number for single-phase (wastewater) pipe flow and us is slip velocity (relative velocity of air and wastewater) which is the difference between air and wastewater velocities. Specific interfacial bubble area (a_B) is defined as the contact area between air and wastewater per volume of air-wastewater mixture. It is calculated as;

$$a_B = 3\alpha/R_b \tag{38}$$

In Eqs. 35, 37 and 38, Rb is the radius of air bubbles which can be obtained as;

$$R_b = 1.5\, g^{-0.44}\sigma^{0.34}\mu_w^{0.22}\rho_w^{-0.45}\rho_a^{-0.11}U_a^{-0.02} \tag{39}$$

where g is gravitational acceleration (m/sec^2), σ = surface tension (N/m), μ_w is dynamic viscosity of wastewater ($N.sec/m^2$), ρ_a and ρ_w are densities of air bubbles and wastewater (kg/m^3), respectively, and U_a is superficial velocity of air (m/sec) defined as the ratio of air flow rate and pipe cross sectional area. σ (in N/m) is calculated using a formula relating it to water temperature (in ˚K) developed by Vargaftik et al. [34];

$$\sigma = 0.2358\left[\frac{647.15-T}{647.15}\right]^{1.256}\left[1 - 0.625\left(\frac{647.15-T}{647.15}\right)\right] \tag{40}$$

Oxygen Saturation Concentration

Oxygen saturation concentration in water is dependent on; temperature, pressure, and total dissolved solids (TDS). The molar solubility of oxygen in water, C_{aq} (mole O_2/kg water), as a function of its partial pressure, P_{O_2} (atm), and temperature, T (˚K), is obtained as [35];

$$C_{aq} = P_{O_2}.\exp\left(\frac{0.046T^2 + 203.35Tln(T/298) - (299.378 + 0.092T)(T-298) - 20.591\times10^3}{8.3144T}\right) \tag{41}$$

According to Dalton’s law, the partial pressure of oxygen is obtained as;

$$P_{O_2} = 0.21P_{air} \tag{42}$$

where P_{air} is air pressure (atm), which is taken to be equal to that of the multiphase flow at specific location along the Biopipe system, and the constant (0.21) represents the mole fraction of oxygen in air (21 mole oxygen per 100 mole of air). The pressure drop of the multiphase flow along the pipe is calculated using a methodology proposed by Shannak [33] as outlined in the following equations;

$$\Delta p_{(2ph)} = f_{(2ph)}\frac{L}{D}\frac{m_{(2ph)}^2}{2\rho_{(2ph)}} \tag{43}$$

$$\frac{1}{\sqrt{f_{(2ph)}}} = -2\log\left[\frac{1}{3.7065}\frac{e}{D} - \frac{5.0452}{Re_{(2ph)}}\log\left(\frac{1}{2.8257}\left(\frac{e}{d}\right)^{1.1098} + \frac{5.8506}{{Re_{(2ph)}}^{0.8981}}\right)\right] \tag{44}$$

$$\frac{1}{\rho_{(2ph)}} = \frac{x}{\rho_a} + \frac{(1-x)}{\rho_w} \tag{45}$$

$$x = \frac{m_a}{m_a + m_w} = \frac{m_a}{m_{(2ph)}} \tag{46}$$

$$m_w = \rho_w\ \mathrm{v}_w \tag{47}$$

$$m_a = \rho_a \ \mathrm{v}_a \tag{48}$$

$$Re_{(2ph)} = \frac{m_{(2ph)} d[x^2+(1-x)^2(\rho_a/\rho_w)]}{\mu_a x+\mu_w(1-x)(\rho_a/\rho_w)} \tag{49}$$

In Eqs. 43-49; D, L, and are diameter (m), length (m) and pipe wall roughness (m) of Biopipe system, respectively, f is friction factor, m is mass flux (kg/m^2.s), Δp is pressure drop along the Biopipe system (Pa), Re is Reynolds number, v is flow velocities (m/sec), μ is dynamic viscosity (Pa.sec), and the subscripts w, a, and 2_{ph} denote wastewater, air and multiphase flow, respectively. Considering a PVC pipe, the pipe wall roughness was taken to be 0.0015mm [34].

Adopting oxygen molar weight of 32g, the oxygen saturation concentration for freshwater, $S_{O_2}sf$ (mg/l), is obtained as;

$$S_{O_2}sf = 32000C_{aq} \tag{50}$$

To account for the effect of wastewater impurities on oxygen saturation concentration, S_{O_2SF} is corrected as;

$$S_{O_2}sw = \beta \times S_{O_2}sf \tag{51}$$

where $S_{O_2}sw$ is oxygen saturation concentration of wastewater. The correction factor (β) is expressed as [35];

$$\beta = 1 - 5.7 \times 10^{-6} \times TDS \tag{52}$$

Input Data

The data required to run the numerical model developed to simulate the performance of Biopipe system along with their values are presented in Table 3. In this Table, the influent flowrate values are derived from those of small to middle volume of wastewater treatment plants, while the influent COD and TN are the most frequent measured values of settled sewage in Al-Barakia sewage treatment plant in Najaf Governorate, middle of Iraq. The kinetic and stoichiometric parameters of ASM3 are at a temperature of 20 ˚C as obtained from Henze et al. [23]. The values of Biopipe system length, diameter and recirculation ratios are examined values for studying the system performance under different conditions.

In order to adopt ASM3 model for simulating the microbiological transformation processes in Biopipe system, the influent COD and TN are needed to be fractioned. The fractions of COD an TN are founded by ordinary fraction principle.

TABLE 3. Input data of Biopipe system model

Characteristic	Unit	Value
Influent flowrate, Q_w	m^3/d	Varied on the range (5-75)
Influent COD	mg/l	450
Influent BOD	mg/l	350
Influent TN	mg/l	25
Length of Biopipe system, L	M	Varied on the range (70-4000)
Diameter of Biopipe system, D	M	Varied on the range (0.0508 - 0.152)
Recirculation ratio	-	Varied on the range (1-5)
Temperature, T	$^\circ C$	20
Pump head, H	m	20
Wastewater mass density, ρ_w	kg/m^3	1000
Kinematic viscosity of wastewater, v	cm^2/sec	0.01
Air density, ρ_{air}	kg/m^3	1.2
Pipe roughness, e	mm	0.0015
Hydrolysis rate constant, K_H	$(g\ COD_{X_S}.(g\ COD_{X_H})^{-1}/d)$	3
Hydrolysis saturation constant, K_x	$(g\ COD_{X_S}.(g\ COD_{X_H})^{-1}$	1
Storage rate constant, k_{STO}	$(g\ COD_{S_S}.(g\ COD_{X_H})^{-1}/d)$	6.5
Anoxic reduction factor, η_{NOX}	-	0.6
Saturation constant for S_{NO2}, K_{O2}	$(g\ O_2/m^3)$	0.2
Saturation constant for S_{NOX}, K_{NOX}	$(g\ NO_3^- - \mathrm{N}/m^3)$	0.5
Saturation constant for substrate S_S, K_S	$(g\ COD_{S_S}/m^3)$	2
Saturation constant for X_{STO}, K_{STO}	$g\ COD_{X_{STO}}(g\ COD_{X_H})^{-1}$	1
Heterotrophic max. growth rate of X_H, μ_H	(1/d)	12
Saturation constant for ammonium S_{NH_4}, K_{NH_4}	$(g\ \mathrm{N}/m^3)$	0.01

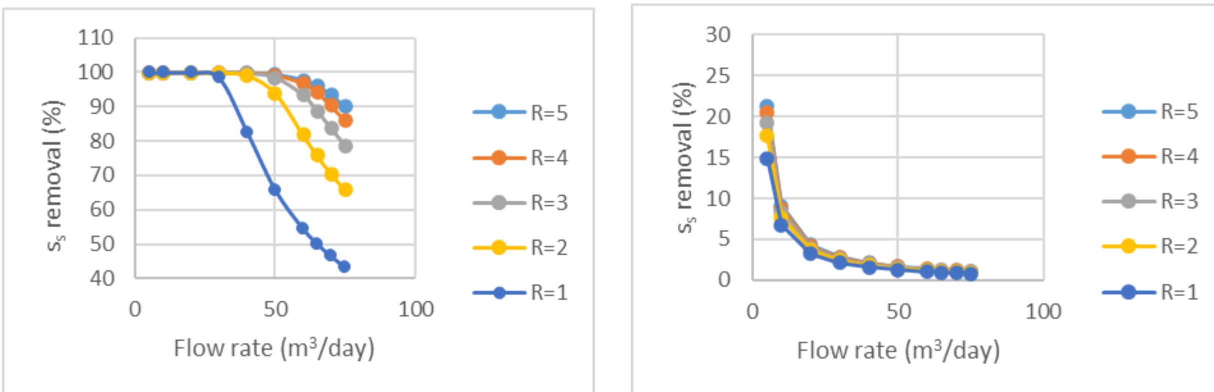
Saturation constant for alkalinity for X_H, K_{ALK}	$(mole \frac{HCO_3^-}{m^3})$	0.1
Aerobic endogenous respiration rate of X_H, b_{H,O_2}	(1/d)	0.2
Aerobic endogenous respiration rate of X_H, $b_{H,NOX}$	(1/d)	0.1
Aerobic respiration rate for X_{STO} , b_{STO,O_2}	-	0.2
Anoxic respiration rate for X_{STO} , $b_{STO,NOX}$	-	0.1
Autotrophic max. growth rate of X_A , μ_A	(1/d)	2.5
Ammonium substrate saturation for X_A , K_{A,NH_4}	$(g\ N/m^3)$	1
Oxygen saturation for nitrifiers , K_{A,O_2}	$(g\ O_2/m^3)$	0.5
Bicarbonate saturation for nitrifiers , $K_{A,ALK}$	$(mole\ HCO_3^-/m^3)$	0.5
Aerobic endogenous respiration rate of X_A , b_{A,O_2}	(1/d)	0.15
Anoxic endogenous respiration rate of X_A, $b_{A,NOX}$	(1/d)	0.05
Production of S_I in hydrolysis, f_{S_I}	$(g\ COD_{S_I}.(g\ COD_{X_S})^{-1})$	0
Aerobic yield of stored product per S_S ,Y_{STO,O_2}	$(g\ COD_{X_{STO}}.(g\ COD_{S_S})^{-1})$	0.85
Anoxic yield of stored product per S_S,	$Y_{STO,NOX}(g\ COD_{X_{STO}}.(g\ COD_{S_S})^{-1})$	0.8
Aerobic yield of heterotrophic biomass, Y_{H,O_2}	$(g\ COD_{X_H}.(g\ COD_{X_{STO}})^{-1})$	0.63
Anoxic yield of heterotrophic biomass, $Y_{H,NOX}$	$(g\ COD_{X_H}.(g\ COD_{X_{STO}})^{-1})$	0.54
Yield of autotrophic biomass per $NO3_3^-$-N, Y_A	$(g\ COD_{X_A}.(g\ N_{S_{NOX}})^{-1})$	0.24
Production of X_I in endog. respiration, f_{X_I}	$(g\ COD_{X_I}.(g\ COD_{X_{BM}})^{-1})$	0.2
N content of S_I , i_{N,S_I}	$(g\ N.(g\ COD_{S_I})^{-1})$	0.01
N content of S_S , i_{N,S_S}	$(g\ N.(g\ COD_{S_S})^{-1})$	0.03
N content of X_I , i_{N,X_I}	$(g\ N.(g\ COD_{X_I})^{-1})$	0.02
N content of X_S , i_{N,X_S}	$(g\ N.(g\ COD_{X_S})^{-1})$	0.04
N content of biomass , X_H, X_A , $i_{N,BM}$	$(g\ N.(g\ COD_{X_{BM}})^{-1})$	0.07
S_S to COD ratio for X_I, i_{SS,X_I}	$(g\ SS.(g\ COD_{X_I})^{-1})$	0.75
S_S to COD ratio for X_S, i_{SS,X_S}	$(g\ SS.(g\ COD_{X_S})^{-1})$	0.75
S_S to COD ratio for X_H, X_A , $i_{SS,BM}$	$(g\ SS.(g\ COD_{X_{BM}})^{-1})$	0.9

RESULTS AND DISCUSSION

A program package was written for the developed numerical model of Biopipe system, labelled as BPSM, using MATLAP R2015a software. BPSM has been applied to simulate the performance of Biopipe system considering different values of influent flowrates (Q_I), pipe diameter, pipe length and recirculation ratio (R) with the adoption of two scenarios (with and without sedimentation). In the first scenario, a final sedimentation unit is placed after the Biopipe system and settled activated sludge is recirculated. While, in the second scenario, it is assumed that the final effluent of Biopipe system is recirculated without the implementation of final sedimentation unit. This is the case of the invented Biopipe system where the recirculation is achieved using the system effluent and the final effluent of Biopipe system is then passed through a cartridge filter for the intent of removing the produced biomass. Herein, all the presented results are those obtained by running the model for simulating the Biopipe system performance after continuous operation of 15 days. The focus will be on Biopipe system performance in removing readily and slowly biodegradable organic substrates (S_S and X_S).

Recirculation Ratio Impact on S_S Removal Efficiency

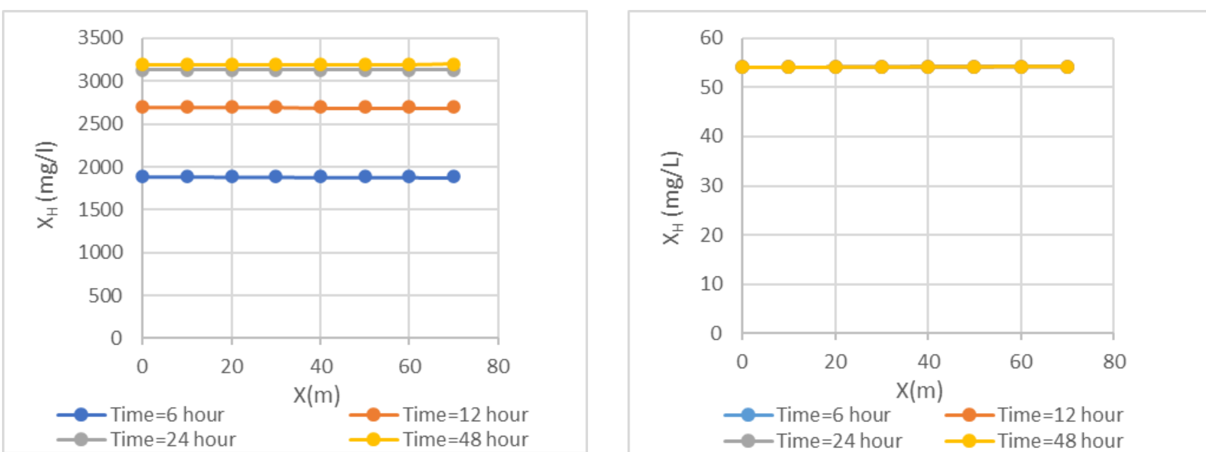
BPSM was run adopting pipe diameter and length of 100mm and 70m, respectively. The results of S_S removal percentages are shown in Fig. 1 as a function of influent flowrate at different recirculation ratios with and without sedimentation (a and b). Figure 1 shows that the percentage of S_S removal increases with the increase of recirculation ratio and decrease of influent flow rate (increase hydraulic retention time, HRT) in both scenarios of with and without sedimentation. This is a fact in biological treatment of wastewater, however, the impact of recirculation ratio in case of applying sedimentation is significant especially at high influent flowrates (low HRTs), while, it is insignificant in case of sedimentation absence. Figure 2a shows that the S_S removal efficiency of Biopipe system at influent flowrates not exceeding 30m3/day (HRT ≥ 0.44 hr.) is about 99% for all recirculation ratio(R) values, while, at higher flowrates, the S_S removal efficiency varied on the ranges (43.3-98), (65.8-99), (78.6-99), (86.0-99), and (90.1-99) for R values of 1, 2, 3, 4, and 5, respectively. Thus, regardless of HRT value, to get maximum SS removal efficiency, the R value must not be less than 5. Figure 2b shows that for a Biopipe system of 70 m length, the S_S removal efficiency may be as low as 0.84% when R equal 1 and the increase of R can slightly increase the removal efficiency at low flowrates (high HRT). At very low flowrate, the removal efficiency values were 14.8, 17.6, 19.3, 20.4, and 21.3 for R values of 1, 2, 3, 4, and 5, respectively.



(a) (b)

FIGURE 1. Recirculation ratio impact on ss removal efficiency; (a) with final sedimentation unit, (b) without final sedimentation unit

The high S_S removal efficiency obtained in case of final sedimentation implementation can be attributed to the excessive growth of heterotrophic bacteria X_H as shown in Fig. 2. This Figure shows the impact of using final sedimentation on longitudinal X_H distribution, after operating the Biopipe system for durations of 6, 12, 24, and 48 hours. Figure 2a shows that the X_H values increased with the increase of system operation time and they are uniformly distributed along the Biopipe length. The X_H values were 1887, 2700, 3133, and 3202 mg/L for Biopipe system operation durations of 6, 12, 24, and 48 hours, respectively, and the steady state X_H value is 3202 mg/L which was obtained after running BPSM for a duration of 15 days. While Figure 2b shows that, in case of final sedimentation absence, the increase of system operation time would not increase the X_H value which was about 54 mg/l and uniformly distributed along the system length.

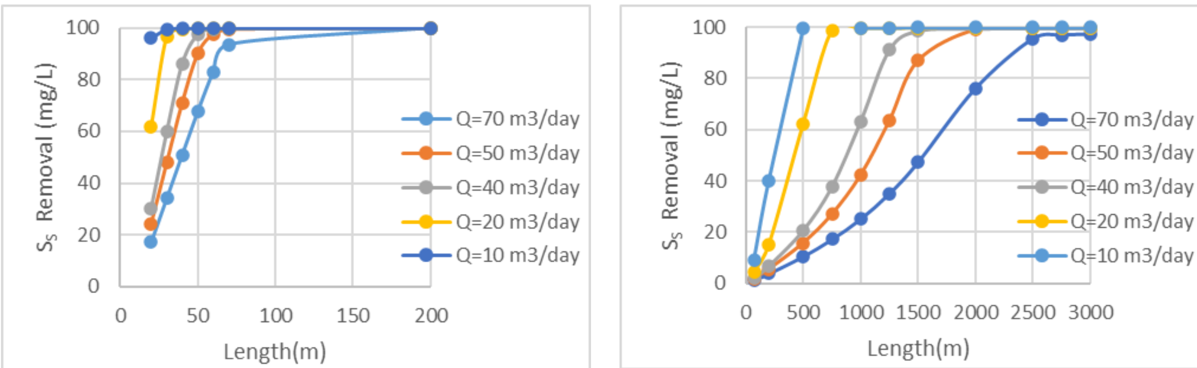


a) b)

FIGURE 2. Longitudinal distribution of X_H (a) with final sedimentation unit, (b) without final sedimentation unit

Biopipe System Length Impact on S_S Removal Efficiency

To study the impact of Biopipe system length on S_S removal efficiency at influent flowrates varied on the range (10-70) m^3/day, BPSM was run adopting the best recirculation ratio (R=5) and a system diameter of 100 mm. The results are shown in Fig. 3 for the two scenarios; with and without final sedimentation. Figure 3a shows that when the Biopipe length was 70 m, the S_S removal efficiency values exceeded 93.4% and a further increase in pipe length has slightly increased the removal efficiency at the maximum influent flowrate value. While Figure 3b shows that the SS removal efficiency exceeded 90% when pipe length exceeded 500 m based on influent flowrate. For example, if the influent flowrate is 70 m^3/day, the required length to get high S_S removal efficiency is 2300 m. This result agreed with that of Özer and Kasirga [6] who showed that the COD removal efficiency can exceed 90% in a gravity sewer has length in km order of magnitude. Thus, the absence of final sedimentation unit requires a longer Biopipe system as compared with the case of using final sedimentation.



a b

FIGURE 3. Biopipe length impact on S_S removal efficiency (a) with final sedimentation unit, (b) without final sedimentation unit

Biopipe System Diameter Impact on S_S Removal Efficiency

The impact of Biopipe system diameter on S_S removal efficiency was assessed at different influent flowrates using Biopipe of 70 m length. The obtained results are presented in Fig. 4 with and without sedimentation. If sedimentation is adopted, Figure 4a shows that the increase in pipe diameter up to 100mm can enhance S_S removal efficiency which reached its maximum value. Within the applied influent flowrates (20 to 60 m^3/day) a diameter of 100 mm is recommended if final sedimentation unit is adopted. At the absence of sedimentation, Figure 4b shows that the impact of pipe diameter on S_S removal efficiency is insignificant at influent flowrates greater than 20 m^3/day. Thus, low influent flowrate values were adopted and it was found that at influent flowrate of 4 m^3/day, the removal efficiency can be 74% when the diameter is 150 mm.

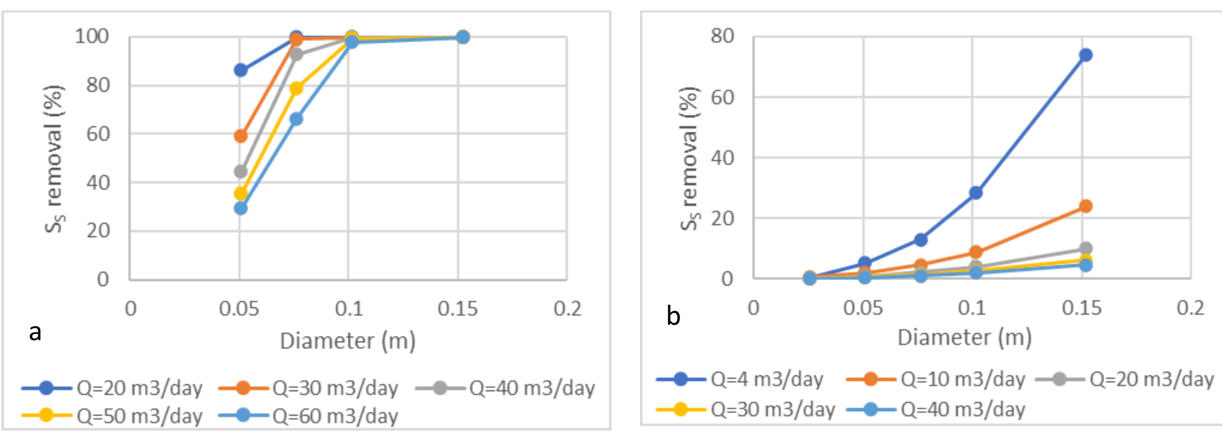
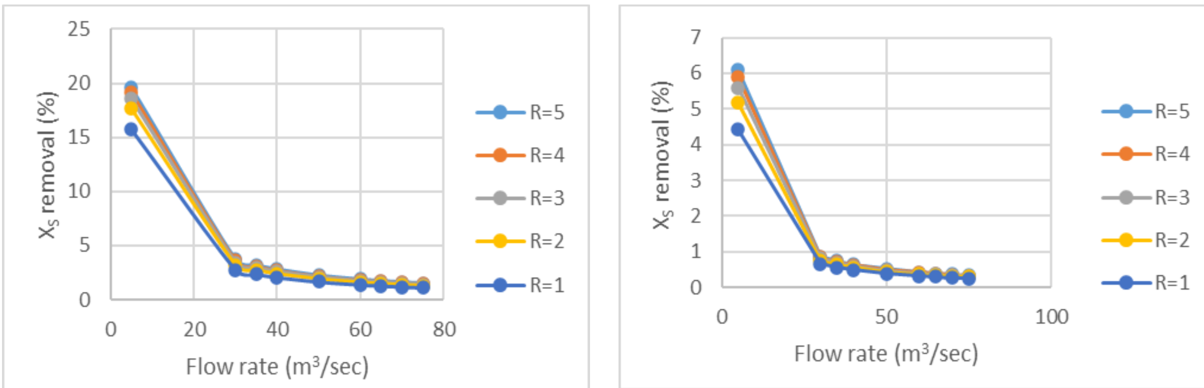


FIGURE 4. Biopipe diameter impact on S_S removal efficiency; (a) with final sedimentation unit, (b) without final sedimentation unit

Recirculation Ratio Impact on X_S Removal Efficiency

The impact of recirculation ratio on removal efficiency of X_S versus influent flowrate has been investigated applying the two scenarios with and without final sedimentation and the obtained results are shown in Fig. 5. These results are for Biopipe system of 100 mm diameter and 70 m length. Figure 5a illustrates that the X_S removal efficiency, slightly, increases with R increase when influent flowrate is less than 30 m^3/day, However, when influent flowrate is increased the impact of R on X_S removal efficiency is insignificant. This is also the case when final sedimentation is not used as shown in Fig. 5b. Generally, the maximum X_S removal efficiency values by Biopipe system were 19.2 and 6.1% for the first and second scenarios, respectively.

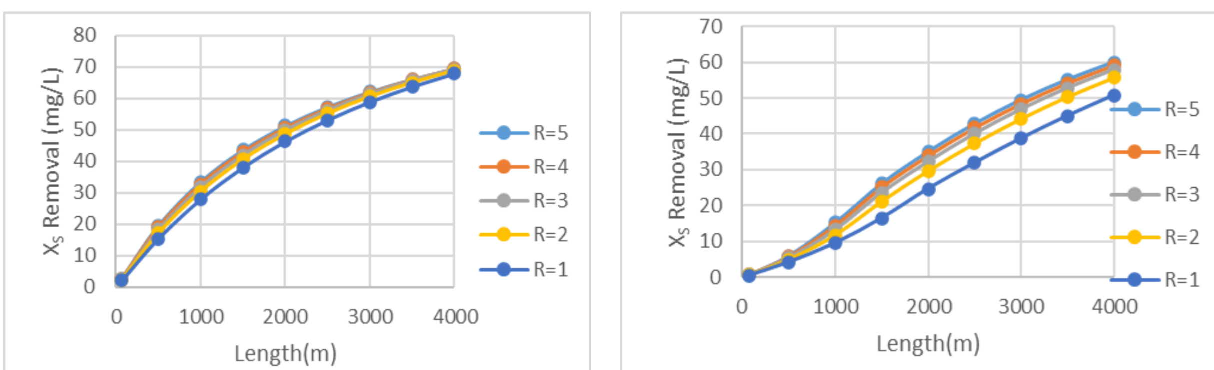


a b

FIGURE 5. Recirculation ratio impact on X_S removal efficiency (a) with final sedimentation unit, (b) without final sedimentation unit

Biopipe System Length Impact on X_S Removal Efficiency

Figure 6 illustrates X_S removal efficiency versus Biopipe length for different R values at influent flowrate and system diameter of 40 m^3/day and 100mm, respectively. It shows that the Biopipe length increase can enhance the X_S removal efficiency for both with and without final sedimentation scenarios. But this enhancement requires impractical pipe length which reached a value of 4000m to get X_S removal efficiency of 70 and 60% for the first and second scenarios, respectively.

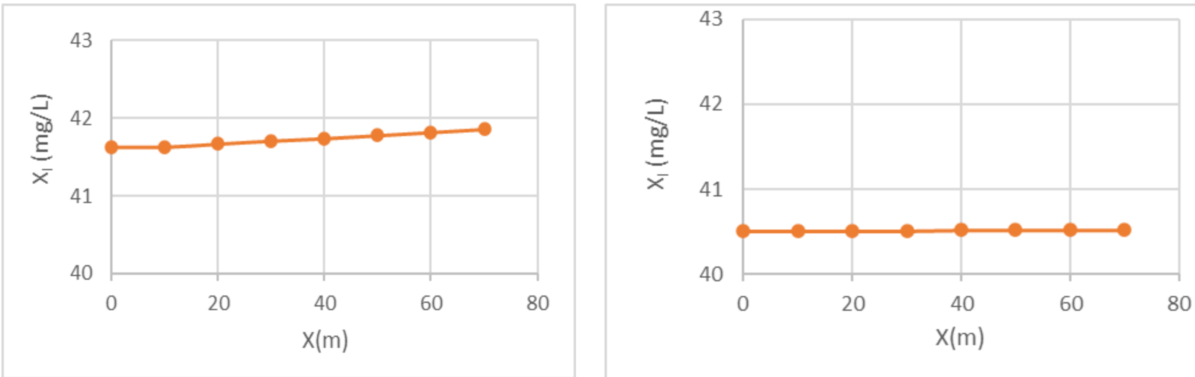


a b

FIGURE 6. Biopipe length impact on X_S removal efficiency (a) with final sedimentation unit, (b) without final sedimentation unit

Longitudinal Distribution of Other Wastewater Constituents

This section presents the fate (longitudinal distribution) of non-biodegradable compounds (S_I and X_I) and nitrogenous compounds (S_{NH_4} and S_{NO_X}) when influent flowrate of 40 m^3/day is treated using Biopipe system of 70 m length and 100 mm diameter with adopting R value of 5. The S_I value was constant along the Biopipe system and equals 54 mg/L (12% of influent COD, which is 450 mg/L). That is because the production rate of S_I by hydrolysis was considered to be zero, see Table 3. Since SI is a soluble constituent, thus, the adopting of final sedimentation has no impact on it. The longitudinal distributions of X_I with and without final sedimentation are shown in Fig. 7. Figure 7a shows that there is slightly increase in X_I, while Fig. 7b shows constant X_I value along the Biopipe. That is because X_I is produced in endogenous respiration of biomass and the biomass values during the first scenario are greater than those during the second scenario, see Fig. 2.



a B

FIGURE 7. Longitudinal distribution of X_I (a) with final sedimentation unit, (b) without final sedimentation unit

Figure 8 shows the longitudinal distribution of S_{NH_4} where it can be noticed that S_{NH_4} values for the first scenario are less than those of the second. That can be attributed to the autotrophic biomass which reached values of 216 and 0.5 mg/L when final sedimentation was present and absent, respectively, and the rate of S_{NH_4} removal is increasing with the increase of X_A aerobic growth. The contrast was shown in longitudinal distribution of S_{NO_X}, Fig. 9, where it can be noticed that S_{NO_X} values are very low and increases with longitudinal distance. That was because S_{NO_X} is reduced as a result of anoxic growth of heterotrophs and aerobic conditions are maintained during Biopipe system operation, as shown in dissolved oxygen (S_{O_2}) longitudinal distributions shown in Fig. 10. It is important to mention here that S_{O_2}values are high since the Biopipe is pressurized flow system and oxygen gas solubility increases with the pressure increase.

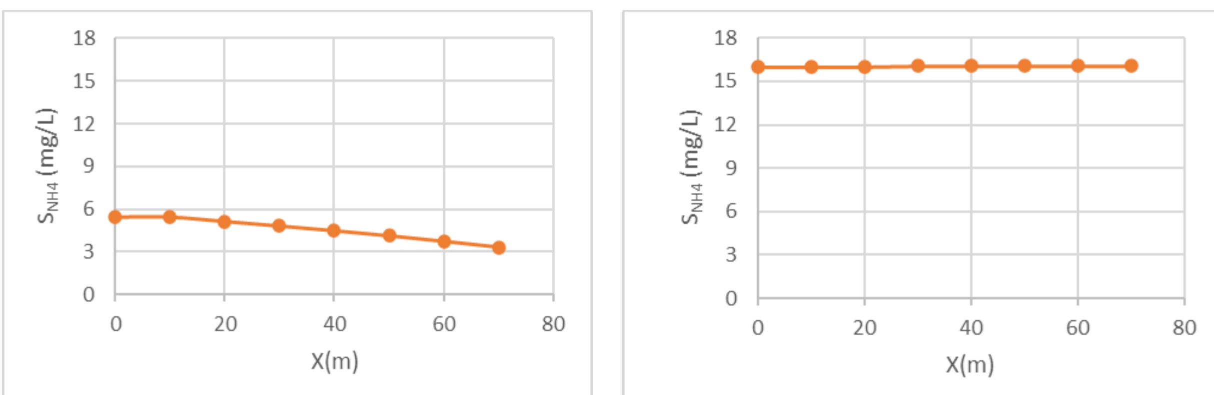


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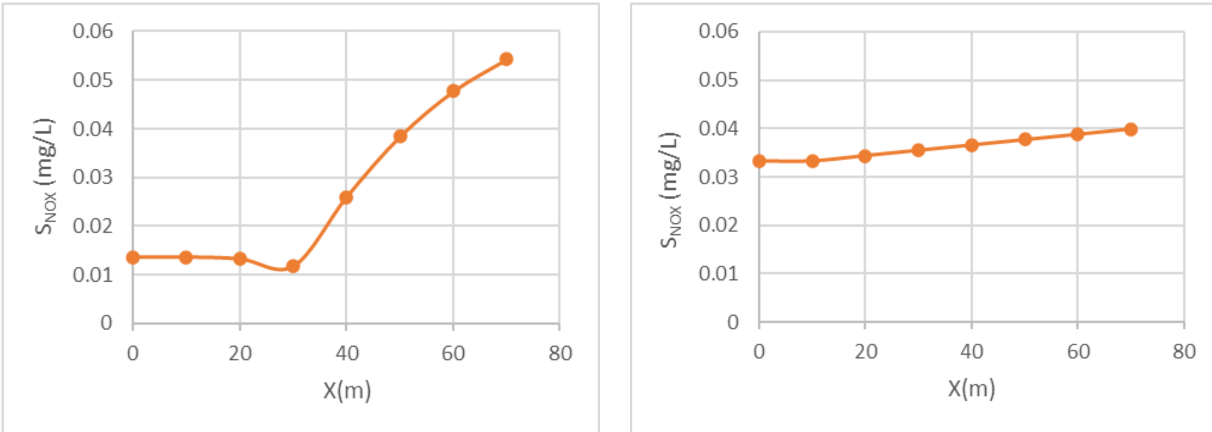
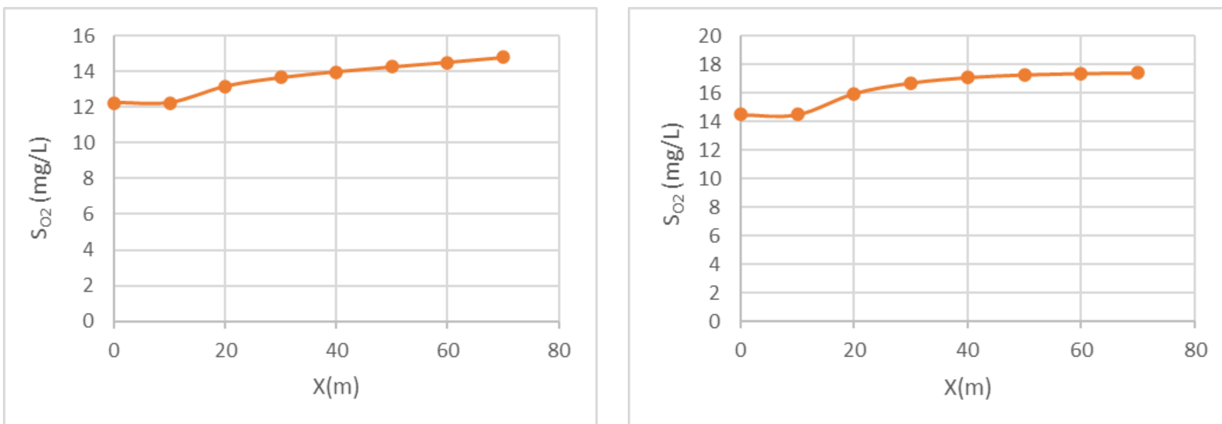
FIGURE 8. Longitudinal distribution of S_{NH_4}(a) with final sedimentation unit, (b) without final sedimentation unit



A b

FIGURE 9. Longitudinal distribution of S_{NO_x}(a) with final sedimentation unit, (b) without final sedimentation unit



a b

FIGURE 10. Longitudinal distribution of S_{O2}(a) with final sedimentation unit, (b) without final sedimentation unit

CONCLUSION

A numerical model, labeled as BPSM, has been developed to investigate the performance of Biopipe system in treating municipal wastewater. The main findings of BPSM application are:

1. The existence of a final sedimentation unit after the Biopipe system is crucial for the effective removal of SS and XS.
2. If final sedimentation unit is used, the SS removal efficiency of Biopipe system at influent flowrates not exceeding 30 m3/day (HRT≥ 0.44 hr.) is about 99% for all R values, while, at higher flowrates, the SS removal efficiency varied on the ranges (43.3-98), (65.8-99), (78.6-99), (86.0-99), and (90.1-99) for R values of 1, 2, 3, 4, and 5, respectively.
3. If final sedimentation is not used and the influent flowrate is 5 m3/day, the SS removal efficiency values were 14.8, 17.6, 19.3, 20.4, and 21.3 for R values of 1, 2, 3, 4, and 5, respectively.
4. If final sedimentation unit is not used, the required Biopipe system length to get high SS and XS removal efficiencies may reach values of 2300 and 4000 m, respectively.
5. By maintaining an aerobic condition in the Biopipe system, the concentrations of nitrogenous compounds cannot be lowered and this issue requires further investigation by studying the impact of tapered aeration on Biopipe system performance.

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