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Numerical simulation of dissolved oxygen, algal biomass, nitrate, organic nitrogen, ammonia, and dissolved phosphorus in waste stabilization ponds

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ABSTRACT

Nowadays, throughout the world industrial communities have caused enormous difficulties for the inhabitants by unsuitable way of using water, soil, and energy sources. Water as a source of life is being used in different sections of civil life and is essential for civilization. With most regret, this natural source is being vastly polluted by municipal, industrial and commercial waste. Thus, selecting suitable methods for wastewater treatment is very important. Unfortunately, these troubles are more common in the developing countries where they do not have enough financial supports for the wastewater treatment. The best option for these communities which are generally located in warm regions, is through the usage of waste stabilization ponds. Application of modeling techniques is a common way to avoid expensive and time-consuming experiments. In this research, an implicit scheme known as backward time backward central space (BTBCS) was used to solve the advection-diffusion equations along the sources and sinks to predict the critical conditions. Various concentrations in the maturation pond were simulated, namely, dissolved oxygen, organic nitrogen, ammonia, nitrate, algae, and phosphate. Results proved that the average accuracy of model outputs was more than 97%.

Keywords: Modeling; Simulation; Waste stabilization pond; Dissolved oxygen; Organic nitrogen; Ammonia; Nitrate; Algae; Phosphate

1. Introduction

Nowadays, the use of conventional wastewater treatment systems in countries with low GDP is restricted because of high cost and technological complexity. Throughout the world, there is a continuous favor in algal-based waste stabilization pond (WSP) systems that are inexpensive and are popular for their ability to reach a good removal rate of pathogens and organic pollutants [1–13]. They are particularly appropriate for urban areas with the population ranging from 5,000 to 450,000 [14].

Fundamentally, stabilization pond is an ecosystem which includes actions and interactions between various groups of bacteria, protozoa, algae, fungi, rotifers, and crustacean larvae which co-exist and compete for food to survive [15]. Bacteria decompose the complex organic substances into simple substances such as CO_2, ammonia, phosphate, etc., which in turn are absorbed by autotrophs like algae as source of nutrients, synthesizing fresh biomass through the photosynthetic process. In photosynthesis, the oxygen which is released by algae is consumed by bacteria to perform the oxidation of organic matter. Therefore an algal–bacterial cycle is fulfilled [16,17]. After retention time of several days (instead of several hours in conventional treatment processes), a well-treated stream is discharged. WSP systems consists of a series of ponds namely, anaerobic, facultative and maturation ponds. In sunshine hours and also a few hours after sunset, these ponds are generally aerobic, while in the remaining hours the bottom of the ponds are utterly anaerobic which makes a vertical stratification [18–20]. The most recent developments in research

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on WSP show the interest to incorporate a reservoir for irrigation uses [21,22]. The pond efficiency relies on climate conditions such as light, temperature, rain, wind and the wastewater quality [17]. Nutrient removal by means of algae has shown good results [23–25]. Additionally, some cyanobacteria and algae can eliminate xenobiotics by sorption, transformation and degradation [26].

The advantages of WSP systems particularly for tropical regions and developing countries are: (i) low cost (ii) simplicity (iii) high efficiency (iv) robustness (v) reliability [27]. Major restrictions of these systems are the high concentration of total suspended solids (TSS) in the discharge that is mostly caused by large amount of algal cells, and also high footprint [14,28].

Oxygen transfer in WSPs is a significant parameter that demonstrates a considerable variation during a day [29,30]. There are two ways of oxygen transfer into the natural systems including (a) oxygen transfer across the air–water surface, and (b) oxygen transfer which is produced while the photosynthesis process is done by aquatic plants such as algae [31]. The rate of oxygen production mostly depends on the concentration of algae.

Laborious experiments are usually time-consuming and expensive. Thus, engineering and scientific phenomena are mostly studied by means of mathematical modeling which facilitate the simulation of complex processes [32,33].

The aim of this paper is to study the changes of major constituents' concentrations such as, dissolved oxygen, algal biomass, nitrate, organic nitrogen, ammonia, and phosphate in a waste stabilization pond which is quite different in comparison to a lake. The exact prediction of concentration for above mentioned constituents is a key component in the development of phytoplankton models.

2. Materials and methods

2.1. Data collection and analysis

Wastewater samples were collected to examine the various parameters. In order to avoid the errors caused by stratification, the maturation pond was chosen for sampling. The samples were taken from five points having 35 meters distance from each other. The sampling points were in the depth of 0.5 meters from the surface of the pond. The examined parameters were concentration of algae, phosphate, ammonia, nitrate, organic nitrogen, and dissolved oxygen. The analysis was carried out using appropriate water testing meters and in accordance with the standard methods [34]. In order to perform the statistical analysis, Microsoft Excel was used.

2.2. Approach to waste stabilization pond quality modeling

Wastewater quality changes in treatment ponds due to advection and diffusion/dispersion, biological, chemical, biochemical, and physical conversion processes. These processes in water are governed by a set of well-known equations which are introduced as [35]:

$$\frac{\partial c}{\partial t} = -u\frac{\partial c}{\partial x} - v\frac{\partial c}{\partial y} - w\frac{\partial c}{\partial z} + \frac{\partial}{\partial x}(D_x\frac{\partial c}{\partial x}) + \frac{\partial}{\partial y}(D_y\frac{\partial c}{\partial y}) + \frac{\partial}{\partial z}(D_z\frac{\partial c}{\partial z}) + r(n) \quad (1)$$

where c is n-dimensional mass concentration vector for the n state variables, t is time, x, y, and z are spatial coordinates; u, v, and w would correspond to velocity components; D_x, D_y, and D_z are the turbulent diffusion coefficients for the directions x, y and z, respectively; r is the n-dimensional vector of the rate of changes for state variables due to biological, chemical, and other conversion processes.

Eq. (1) is a partial differential equation (PDE) that can be numerically solved. Since a one-dimensional scheme is used to observe the alternation of concentrations, the prescribed equation is rewritten as Eq. (2):

$$\frac{\partial c}{\partial t} = -u\frac{\partial c}{\partial x} + \frac{\partial}{\partial x}(D_x\frac{\partial c}{\partial x}) + r(n) \quad (2)$$

Eq. (2) not only offers the basic governing equation of water quality models, but also specifies a useful framework.

2.3. Hydrodynamics and hydraulics

The hydrodynamic condition in the pond is one of the major concerns which is related to the geometric, local, physical, and environmental situations of the pond. The flow is considered to be in a steady-state. The longitudinal sections of the pond are identical and this fact would lead to a uniform flow. As a result, velocity at each section could simply be calculated by the manning's formula [36]:

$$v = \frac{1}{n}R^{\frac{2}{3}}S^{\frac{1}{2}} \quad (3)$$

where v is the velocity for each section, R is the hydraulic radius, S is the longitudinal slope of the pond, and n is the manning coefficient of the bed.

2.4. Transport process

The term convection is usually used to describe the movement of a particular mass or volume of water over time.

Diffusion is a state in which difference in concentrations would cause the motion of molecules. Development of transport equation is based on the mass balance and can be introduced as:

Accumulation = Inflow – outflow + sources – sinks

As mentioned before, the one-dimensional transport equation could be written as [35]:

$$\frac{\partial c}{\partial t} = -u\frac{\partial c}{\partial x} + \frac{\partial}{\partial x}(D_x\frac{\partial c}{\partial x}) + Sources - Sinks \quad (4)$$

Scientists have put instantaneous efforts on calculation of diffusion coefficients. One of the most important efforts in this field is the work done by [37, 38]:

$$D_x = 22.6nuD^{0.833} \quad (5)$$

where D_x is longitudinal diffusion coefficient, n is the manning roughness coefficient, u is the mean velocity, and D is the mean water depth.

2.5. Dissolved oxygen

One of the important factors influencing the aquatic life in the ponds is dissolved oxygen (DO). Sufficient amount of DO can guarantee the biological activity of different organisms. This parameter is dependent on temperature, turbulence of water body, aeration, and photosynthesis in the pond. The latter could be a great concern especially at night time, when the solar intensity diminishes.

To model the process, Eq. (6) is introduced [39]:

$$\frac{dDO}{dT} = \frac{K_l}{h}(DO_{sat} - DO) \quad (6)$$

where K_l is the aeration factor, DO_{sat} is the saturation concentration of dissolved oxygen, DO is the existing dissolved oxygen concentration, and h is the mean water depth.

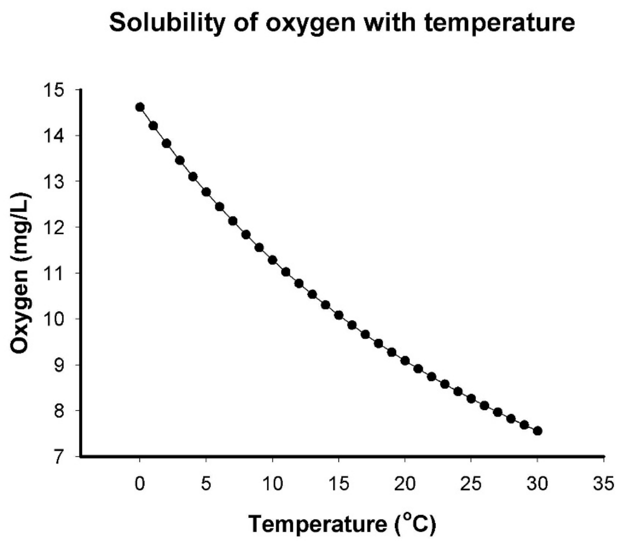

Fig. 1. Solubility variation of dissolved oxygen with temperature change.

K_l is the parameter which is determined by the Eq. (7) [39]:

$$K_l = 0.0864(8.43S_{w10}^{\frac{1}{2}} - 3.67S_{w10} + 0.43S_{w10}^2) \quad (7)$$

where S_{w10} is the wind velocity at 10 meters above the ground.

Saturation concentration of dissolved oxygen is a function of wastewater temperature and is introduced as:

$$DO_{sat} = 24.89 - 0.426T + 0.00373T^2 - 0.000033T^3 \quad (8)$$

These changes are illustrated in Fig. 1.

All the conversion processes affecting the dissolved oxygen concentration are well defined through Fig. 2. Relative sources and sinks with their correlated equations can be summarized in Table 1.

F_{NH_3} is the preference factor for ammonia. Ammonia is a preferred energy source of nitrogen for plants. Preference among nitrate and ammonia in the pond is varied between 0 and 1.

F_{nitr} is the nitrification inhibitor factor which is a function of dissolved oxygen concentration and is defined as [41]:

$$F_{nitr} = 1 - e^{-0.6(DO)} \quad (9)$$

Now the terms described in Table 1 will be introduced.

F (L, N, P) is the algal growth limitation factor, which is consisted of 3 terms. L, stands for light intensity, N is the nitrogen supply, and P is the phosphorus concentration. According to [42]:

$$F(L) = I_x / (I_x^2 + K_L^2)^{\frac{1}{2}} \quad (10)$$

where I_x is the light intensity and is equal to:

$$I_x = 875(1 + \cos 2\pi t / \lambda) \quad (11)$$

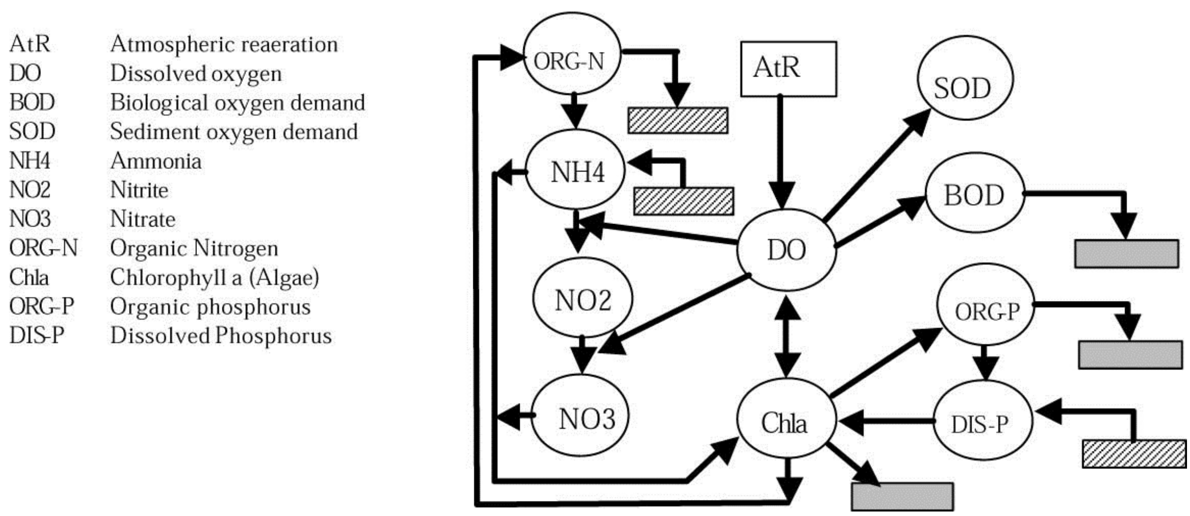

Fig. 2. Schematic description of the quality mode.

Table 1
Biochemical and physical processes of the quality model [40]

No.	Component	1	2	3	4	5	6	7	Process Rate
	Process	D.O.	BOD	Algae	Organic nitrogen	NH_3	NO_3	P	$M\ L^{-3}\ T^{-1}$
1	Rearation	1							$K_2(DO_{sat}\text{-}DO)$
2	Biodegradation	–1	–1						K_1BOD
3	BOD Sediment		–1						K_3BOD
4	Sediment DO Demand	–1							$\frac{k_4}{h}$
5	Photosynthesis	A		1		$-0.07FNH_3$	$-0.07(1-F_{NH3})$	–0.01	μ_{max}.Algae.f(L,N,P)
6	Respiration	–B		–1	0.07				$\gamma \cdot Algae$
7	Algae Sedimentation			–1					$\frac{\sigma_1}{h} \cdot Algae$
8	Nitrogen Hydrolysis				–1	1			$\beta_3 \cdot OrgN$
9	Nitrification	–4.57				–1			$\beta_1 \cdot NH_3 \cdot f(nitr)$
10	N Sedimentation				–1				$\sigma_4 \cdot NH_3$
11	N Sediment Release					1			$\frac{\sigma_3}{h}$
12	P Hydrolysis							1	$\beta_4 \cdot OrgP$
13	P Sediment Release							1	$\frac{\sigma_2}{h}$

where t is the selected time between ±0.5λ and λ is the total hours of sunlight over the day. F (N) and F (P) are both identified as [39]:

$$F(P) = \frac{P}{k_P + P} \tag{12}$$

$$F(N) = \frac{N}{k_N + N} \tag{13}$$

where K_p and K_N are the half-saturation index for phosphorus and nitrogen, respectively.

2.6. Algal biomass fraction and stoichiometry

Algae convert simple inorganic nutrients into more complex organic molecules for cell growth by photosynthesis. Respiration is the reverse process in which biomass undergoes hydrolysis and oxidation. Nitrogen and phosphorus, as well as carbon and other elements, are consumed during algal cell synthesis. Carbon, nitrogen, and phosphorus are found as a result of algal biomass fraction. Similar to oxygen consumption during nitrification, stoichiometric relationships are used to relate algal biomass and oxygen production and consumption for photosynthesis and respiration, respectively.

2.6.1. Algal biomass fraction

The composition of organic matter in plankton is $C_{106}H_{263}O_{110}N_{16}P_1$. Nitrogen and phosphorus fractions of algal biomass are approximately 7.2 and 1.0 percent, based on dry weight. Estimates may vary with algal species. Nitrogen content of algae ranges from 7 to 10 percent by weight, while nitrogen content of attached algae ranges from 2 to 4 percent by weight.

2.6.2. Algal stoichiometry

Several models are available for cell synthesis. When ammonia is the primary source of nitrogen cell, synthesis may be represented by [43]:

$$106CO_2 + 16NH_4^+ + HPO_4^{2-} + 108H_2O \rightarrow 14H^+ + C_{106}H_{263}O_{110}N_{16}P_1 + 107H_2O \tag{14}$$

and for nitrate as the primary nitrogen source as [43]:

$$106CO_2 + 16NO_3^- + HPO_4^{-2} + 18H^+ \rightarrow C_{106}H_{263}O_{110}N_{16}P_1 + 138O_2 \tag{15}$$

When ammonia and nitrate are the primary nitrogen sources, different formulations can be presented [41]:

$$132CO_2 + 16NH_4^+ + H_3PO_4 + \frac{177}{2}H_2O \rightarrow C_{132}H_{228}O_{58}N_{16}P_1 + \frac{597}{4}O_2 + 16H^+ \tag{16}$$

$$132CO_2 + 16HNO_3 + H_3PO_4 + \frac{209}{2}H_2O \rightarrow C_{132}H_{228}O_{58}N_{16}P_1 + \frac{725}{4}O_2 \tag{17}$$

All models illustrate the importance of phosphate in aquatic systems. For example, Eq. (14) illustrates that each atom of phosphorus (as phosphate) added to an aquatic system can result in the fixation of about 106 atoms of carbon in organic matter. Furthermore, Eq. (15) shows that by decomposition of organic matter produced from one atom of phosphorus138 molecules of oxygen could be consumed.

Respiration yields carbon as CO_2, nitrogen as NO_3^-, and phosphorus as HPO_4^{-2}. In other words, respiration is presented as [41]:

$$C_{106}H_{263}O_{110}N_{16}P_1 + 138O_2 \rightarrow 106CO_2 + 16NO_3^- + HPO_4^{2-} + 122H_2O + 18H^+ \quad (18)$$

$$C_{132}H_{228}O_{58}N_{16}P_1 + \frac{725}{4}O_2 \rightarrow 132CO_2 + 16HNO_3 + H_3PO_4 + \frac{209}{2}H_2O \quad (19)$$

These inorganic forms of nitrogen and phosphorus can be readily used by plants. The release of CO_2 can decrease pH. When oxygen is not available, decay of organic matter will continue under anoxic conditions. Some of the most important reactions are denitrification, deaminization of amino acids, sulfate reduction, and fermentation.

If ammonia is the nitrogen source, the stoichiometric relationship for produced oxygen during photosynthesis can be obtained from Eq. (14):

Algal biomass (A): $C_{106}H_{263}O_{110}N_{16}P_1$ = 3,550 gram

Produced oxygen: 107*(2*16) = 3,424 gram

Stoichiometric ratio of produced oxygen to algal biomass:

3,424/3,550 = 0.96 gram oxygen/gram algae

Similarly, stoichiometric ratios for Eq. (15), Eq. (16), and Eq. (17) are 1.24, 1.59, and 1.94 grams of produced oxygen per gram of algal biomass, respectively. Stoichiometric ratios for respiration represented in Eq. (18) and Eq. (19) are 0.96 and 1.59 grams of consumed oxygen per gram of algal biomass, respectively. Other used parameters are introduced in Table 2.

2.7. Model development

Partial differential equations should be solved simultaneously to obtain a suitable answer, an important issue that cannot be done analytically. Therefore, scientists have been using programming software to solve these equations by a process of trial & error.

There are numerous ways to discretize the partial differential equations.

Implicit and explicit schemes are the two main methods for solving these equations.

Implicit scheme tends to be more stable than explicit ones, so the method used in this research is backward finite difference method over time and central discretization over space known as backward time backward central space (BTBCS.

So the common advection-diffusion equation can be written as Eq. (20),

$$\left(-D_x\frac{\Delta t}{\Delta x^2} - v\frac{\Delta t}{\Delta x}\right)u_{i-1}^{\;n+1} + \left(1 + 2D_x\frac{\Delta t}{(\Delta x)^2} + v\frac{\Delta t}{\Delta x}\right)u_i^{\;n+1} - \left(D_x\frac{\Delta t}{\Delta x^2}\right)u_{i+1}^{n+1} = u_i^n \quad (20)$$

where D_x is the diffusion coefficient, Δt is the time interval, Δx is the ratio of the displacement that occurs during a particular time interval, and u is the flow velocity.

Number of unknown parameters in this equation are far more than the known ones, so the equations are set as a tridiagonal matrix form and solved using the Thomas Algorithm.

2.8. Validation and calibration

In simulation and modeling, calibrating the output data is of a great importance. In other words, coefficients should be set in a way that the answers would have a good correlation with the results of the experiments. To achieve this goal, a set of real operating waste stabilization ponds which are located in the southwest of Rey-City, a suburb of Tehran, was chosen to compare the results and validate them. The treatment plant is consisted of one operating and one reserved module, each of which has three ponds namely, anaerobic, facultative, and maturation ponds. The physical characteristics of the ponds are defined in Table 2, and the feed wastewater flow rate is 250 L/s.

The site is almost flat and falls with 6.5 m/km from north to south. The predominant climate is defined as semi-arid to arid, and the temperature rarely comes below 28°C in summer.

The regional wind blows from east to west with a mean velocity of 4.7 m/s.

3. Results and discussion

The results are shown in the figures for different sections. It should be said that the distance between sections is 35 meters.

Table 2
Physical characteristics of the ponds

Type of pond	Length (m)		Width (m)		Depth (m)	Volume (m^3)
	External	Internal	External	Internal		
Anaerobic	146.4	134.4	66.7	54.7	3.4	50,000
Facultative	241	219.65	66.7	54.7	3.4	79,300
Maturation	210	201.9	66.7	58.6	2.1	49,700

3.1. Effect of time on parameters in a specific section

In this part, various concentrations in a certain section are discussed in different time hours.

3.1.1. DO concentration

Solar radiation has been found to be one of the most important variables affecting DO. The changes in solar radiation results in the variation of photosynthesis activity of living organisms such as algae. As solar radiation is intensified in the early morning, the photosynthesis activity is boosted. Hence, the concentration of DO is increased. In contrast, when solar radiation is decreased in the evening, the DO concentration is diminished. The peak DO concentration is in the afternoon at 16 where the algal growth is in the highest rate as shown in Figs. 4, 6, 8, 10, and 12.

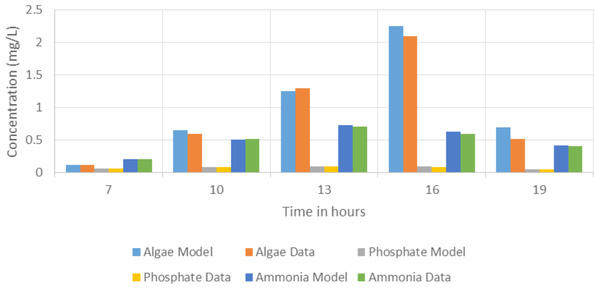

Fig. 3. Concentration of algae, ammonia, and phosphate at first section.

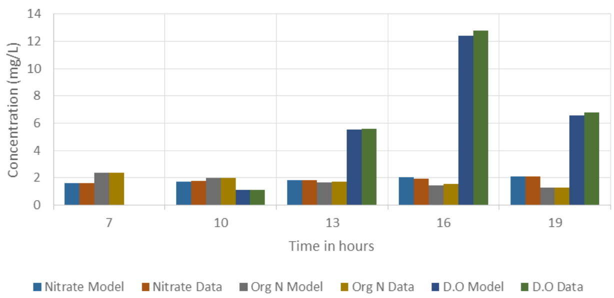

Fig. 4. Concentration of nitrate, oxygen, and organic nitrogen at first section.

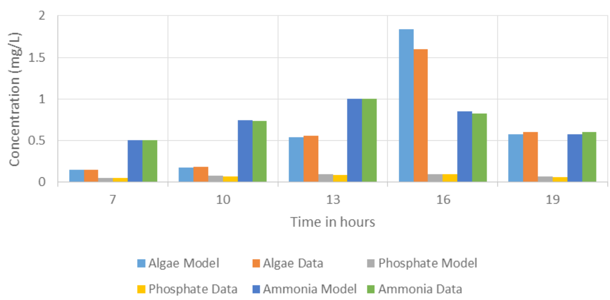

Fig. 5. Concentration of algae, ammonia, and phosphate at second section.

According to Tables 3–7, the maximum and minimum measured concentration of DO were 16.3 mg/L in the evening in the maturation pond and 0.05 mg/L in the morning in

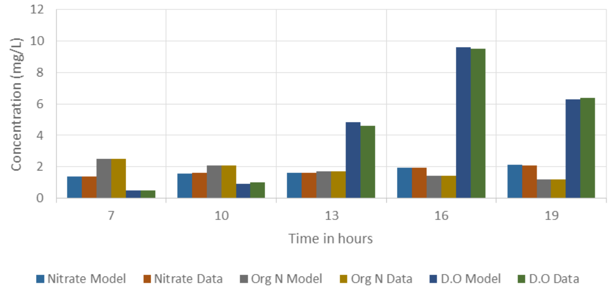

Fig. 6. Concentration of nitrate, oxygen,andOrganic nitrogen at second section.

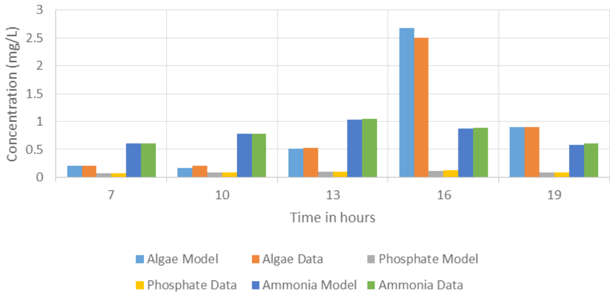

Fig. 7. Concentration of algae, ammonia, and phosphate at third section.

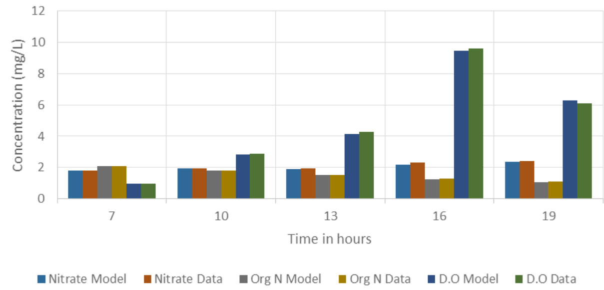

Fig. 8. Concentration of nitrate, oxygen, and Organic nitrogen at third section.

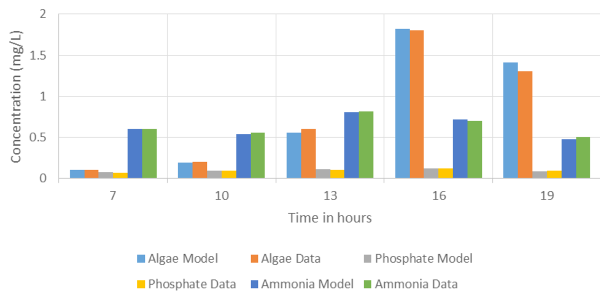

Fig. 9. Concentration of algae, ammonia, and phosphate at fourth section.

the anaerobic pond, respectively. The accuracy of model in comparison to measured data for DO concentration was more than 98%.

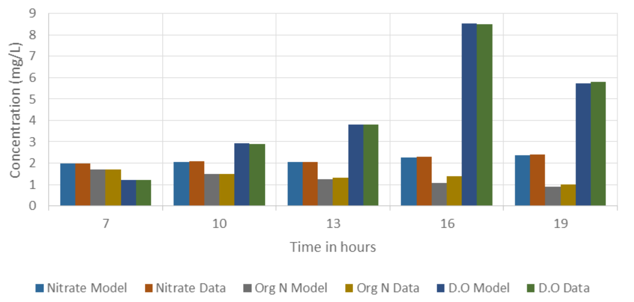

Fig. 10. Concentration of nitrate, oxygen, and organic nitrogen at fourth section.

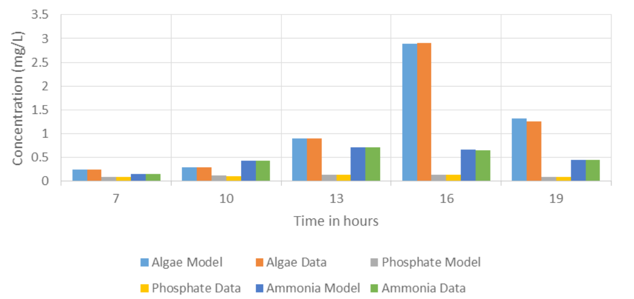

Fig. 11. Concentration of algae, ammonia, and phosphate at fifth section.

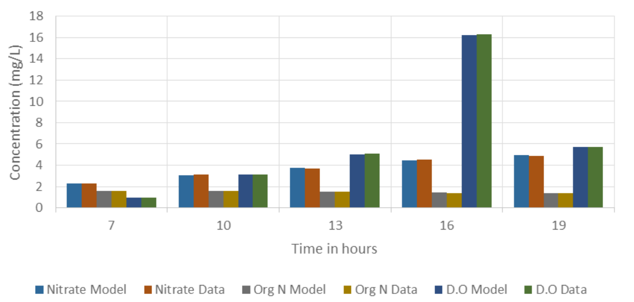

Fig. 12. Concentration of nitrate, oxygen, and organic nitrogen at fifth section.

3.1.2. Algae concentration

Solar radiation and temperature in the morning are low. But as the sun rises and solar radiation becomes available, the temperature increases so that due to photosynthesis, the concentration of algae rises to the highest point at 16 in the afternoon as illustrated in Figs. 3, 5, 7, 9, and 11. As the solar intensity and temperature decrease, the algae concentration is reduced at 19 in the evening. So, we can conclude that algal growth depends directly to the solar radiation and wastewater temperature. Based on Tables 3–7, the maximum and minimum measured algae concentration were 2.9 mg/L in the evening and 0.1 mg/L in the morning, respectively. The exactness of the model for algae concentration was more than 95%.

3.1.3. Phosphate concentration

As mentioned before, phosphate is a well-known nutrient for the algal growth and in case the phosphate concentration is not enough, it can limit the growth of algae. After sunrise, the algal growth and the biological activity rise gradually, thus, phosphate will be consumed by algae, but as the algal growth becomes maximum, the endogenous respiration rate of algae will increase. Thus, the phosphate which was in the algae cell will be released making the phosphate concentration increase. Additionally, as shown in Figs. 3, 5, 7, 9, and 11, when the photosynthesis is stopped at night, there is no need to phosphate and as a result, the concentration of phosphate is increased. It can be noticed from Tables 3–7 that the maximum and minimum measured phosphate concentration were 0.13 mg/L and 0.048 mg/L, respectively. Model results of phosphate concentration were more than 96% near to the measured data values.

3.1.4. Ammonia concentration

At the beginning of the day, ammonia concentration increases due to the oxidation process. As the concentration of the DO becomes low in the evening, the oxidation process is inhibited which makes the ammonia concentration decrease which is illustrated in Figs. 3, 5, 7, 9, and 11. The maximum and minimum measured ammonia concentration were 1.05 mg/L and 0.15 mg/L, respectively. Exactness between measured values and predicted ammonia concentration was more than 98%.

Table 3
The results of model & experiments at first section

Time (h)	Algae (mg/l)		Phosphate (mg/l)		Ammonia (mg/l)		Nitrate (mg/l)		Organic nitrogen (mg/l)		D.O. (mg/l)	
	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data
7	0.12	0.12	0.06	0.06	0.2	0.2	1.6	1.6	2.4	2.4	0.05	0.05
10	0.649	0.59	0.08	0.085	0.508	0.52	1.74	1.8	2.002	1.98	1.103	1.1
13	1.247	1.3	0.092	0.095	0.735	0.71	1.81	1.85	1.69	1.72	5.54	5.6
16	2.25	2.1	0.09	0.082	0.634	0.6	2.04	1.94	1.46	1.53	12.4	12.8
19	0.687	0.52	0.053	0.054	0.426	0.4	2.08	2.1	1.3	1.28	6.57	6.78

Table 4
The results of model & experiments at second section

Time (h)	Algae (mg/l)		Phosphate (mg/l)		Ammonia (mg/l)		Nitrate (mg/l)		Organic nitrogen (mg/l)		D.O. (mg/l)	
	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data
7	0.15	0.15	0.048	0.048	0.5	0.5	1.4	1.4	2.5	2.5	0.5	0.5
10	0.17	0.18	0.071	0.07	0.74	0.73	1.567	1.6	2.09	2.1	0.93	1
13	0.54	0.56	0.089	0.085	1.01	1	1.61	1.6	1.73	1.73	4.85	4.6
16	1.84	1.6	0.095	0.09	0.85	0.82	1.94	1.94	1.43	1.43	9.62	9.5
19	0.57	0.6	0.066	0.06	0.57	0.6	2.11	2.1	1.2	1.2	6.31	6.4

Table 5
The results of model and experiments at third section

Time (h)	Algae (mg/l)		Phosphate (mg/l)		Ammonia (mg/l)		Nitrate (mg/l)		Organic nitrogen (mg/l)		D.O. (mg/l)	
	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data
7	0.2	0.62	0.07	0.07	0.6	0.6	1.8	1.8	2.1	2.1	0.95	0.95
10	0.167	0.2	0.89	0.09	0.78	0.78	1.92	1.95	1.8	1.8	2.82	2.9
13	0.507	0.52	0.105	0.1	1.04	1.05	1.9	1.92	1.52	1.53	4.13	4.3
16	2.68	2.5	0.11	0.12	0.87	0.89	2.19	2.3	1.26	1.3	9.49	9.6
19	0.9	0.9	0.08	0.09	0.58	0.6	2.36	2.4	1.06	1.1	6.28	6.1

Table 6
The results of model and experiments at fourth section

Time (h)	Algae (mg/l)		Phosphate (mg/l)		Ammonia (mg/l)		Nitrate (mg/l)		Organic nitrogen (mg/l)		D.O. (mg/l)	
	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data
7	0.1	0.1	0.073	0.07	0.6	0.6	2	2	1.7	1.7	1.2	1.2
10	0.19	0.2	0.094	0.09	0.54	0.56	2.066	2.08	1.48	1.5	2.92	2.9
13	0.56	0.6	0.11	0.1	0.805	0.81	2.05	2.04	1.26	1.3	3.79	3.8
16	1.82	1.8	0.116	0.12	0.714	0.7	2.27	2.3	1.06	1.4	8.54	8.5
19	1.41	1.3	0.088	0.09	0.48	0.5	2.38	2.4	0.9	1	5.75	5.8

Table 7
The results of model and experiments at fifth section

Time (h)	Algae (mg/l)		Phosphate (mg/l)		Ammonia (mg/l)		Nitrate (mg/l)		Organic nitrogen (mg/l)		D.O. (mg/l)	
	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data	Model	Data
7	0.24	0.24	0.08	0.08	0.15	0.15	2.3	2.3	1.6	1.6	0.95	0.95
10	0.286	0.29	0.108	0.1	0.43	0.42	3.08	3.1	1.56	1.6	3.12	3.12
13	0.898	0.9	0.129	0.13	0.7	0.7	3.72	3.7	1.5	1.5	5.05	5.1
16	2.89	2.9	0.132	0.13	0.66	0.65	4.45	4.5	1.42	1.4	16.25	16.3
19	1.309	1.26	0.085	0.09	0.45	0.45	4.92	4.9	1.36	1.35	5.69	5.7

3.1.5. Nitrate concentration

Similar to phosphate, nitrate is a nutrient source. So, during the day when sunlight is available, nitrate is used by algae. On the other hand, after stationary phase, algae cells are oxidized in endogenous respiration phase leading to release of nitrate. Besides, when photosynthesis is stopped at night, the nitrate concentration is increased. It should be said that the nitrification process increases the nitrate concentration as well. All of these can be deduced in Figs. 4, 6, 8, 10, and 12. The maximum and minimum nitrate concentration measured values according to Tables 3–7 were 4.9 mg/L and 1.4 mg/L, respectively. Prediction of nitrate concentration was almost 99% identical to the measured values.

3.1.6. Organic nitrogen concentration

Throughout the day and night, as shown in Figs. 4, 6, 8, 10, and 12, the bacterial oxidation of organic matter such as organic nitrogen does not stop, making the organic nitrogen concentration decrease consecutively. Tables 3–7 present the maximum and minimum measured organic nitrogen concentration to be 2.5 mg/L and 1 mg/L, respectively. Output of simulation showed that the model values of organic nitrogen concentration were more than 97% consistent to the measured values.

3.2. Effect of time on parameters in the longitudinal profile

In this section, the concentration variation of parameters is discussed in the longitudinal profile.

3.2.1. Dissolved oxygen concentration

Oxygen is essential for microorganisms to degrade the organic matter. Degradation process is mainly performed in the beginning of the pond meaning that the oxygen consumption is high and the dissolved oxygen concentration significantly decreases. The demand for oxygen is reduced in the end sections of the pond, so the dissolved oxygen concentration is increased which is shown in Fig. 13.

3.2.2. Algae concentration

As it is illustrated in Fig. 13, microorganisms start to degrade algae in the beginning of the pond, making the algae concentration decrease. While the profile goes forward, algae tries to consume nitrogen and phosphorus as nutrient sources. In other words, the growth rate as well as concentration of algae is increased.

3.2.3. Phosphate concentration

Phosphate is a part of algae. In simple words, the variation pattern for phosphate and algae concentration is exactly the same and it can be seen in Figs. 13 and 14. Therefore, the concentration is decreased in the beginning while increasing in the rest of the pond.

3.2.4. Ammonia concentration

The microorganisms degrade the organic matter in wastewater, converting them to cell mass and waste products. By degradation of organic matter in the beginning of the pond, ammonia is produced, so the ammonia concentration is high which is shown in Fig. 14. In the rest of the pond, nitrification process gradually transforms the ammonia to other products such as nitrate, making the ammonia concentration decrease.

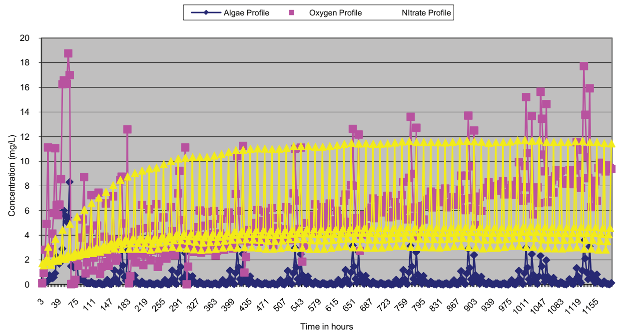

Fig. 13. Longitudinal profile of algae, oxygen,and nitrate.

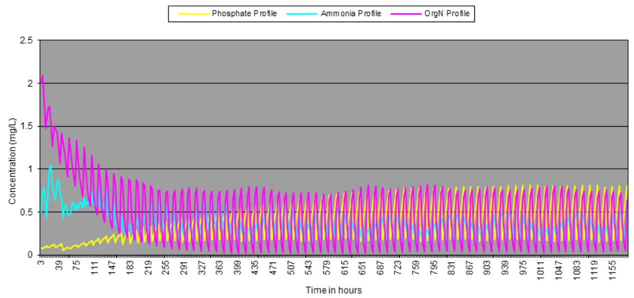

Fig. 14. Longitudinal profile of phosphate, ammonia, and organic nitrogen.

3.2.5. Nitrate concentration

Nitrate is a portion of algae body, meaning that the concentration pattern of nitrate is identical to algae concentration pattern. As a result, nitrate concentration is decreased in early sections, while in the rest of the pond, is increased. As stated above, the nitrification process in the end of the pond makes the nitrate concentration increase which can be noticed in Fig. 13.

3.2.6. Organic nitrogen concentration

Organic nitrogen is a part of algae which is an organic matter. For the degradation of organic matter, microorganisms need an adaptation period. Therefore, in the beginning of the pond, the concentration of organic nitrogen is not decreased significantly. However, microorganisms attain the ability to degrade the algae after a short time so that the concentration of organic nitrogen decreases.

4. Conclusions

In this research, several parameters such as dissolved oxygen, organic nitrogen, ammonia, nitrate, algae, and phosphate were measured along the maturation pond in different time hours. Efforts were also made to predict these parameters by means of an implicit scheme known as BTBCS to solve the one-dimensional equations. Interestingly, the outcomes of the research reported that the matching ratios between model and measured values were more than 97%.

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