DYNAMIC MODEL OF NUTRIENTS WITHDRAWAL AT THE OPEN PONDS FOR PHYTOPLANCTON BIOMASS BREEDING

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ABSTRACT
Domestic wastewater effluent after biological treatment is overloaded by nutrients and could be used as fertilizer. At the present time artificial ponds for phytoplankton biomass harvesting, used for different products manufacturing, can be considered as new potential consumer of these kinds of effluents. Sequestration of CO2 from atmosphere is another positive ecological effect. Dynamic model of phytoplankton biomass harvesting at the open pond with forced mixing is developed to study analytically the processes of nutrient consumption. The model equations are based on the principle of material balance, the law of mass action and stoichiometric relations. The necessary model parameters for unicellular green algae (*M. minutum*) are obtained by use of the published experimental data available. It enables to get assessment of annual consumption of nutrients at the pond for phytoplankton biomass harvesting in relation to the treated domestic effluent composition under different climatic conditions of illumination.

Keywords dynamic modelling, phytoplankton harvesting, nutrients, domestic effluents

INTRODUCTION

Domestic wastewaters after biological treatment are usually overloaded by nutrients (nitrogen and phosphorous compounds). Typical concentrations of nutrients in treated waste water effluent from conventional sewage treatment processes can be approximately assessed as follows: nitrogen (N) - 50 g/m^3, phosphorus (P) - 10 g/m^3. These substances may be found naturally in the environment in low concentrations, but when present in high concentrations, cause eutrophycation. That is why the discharges of biologically treated domestic effluents to the natural waters are not environmentally sound way of its utilization and these effluents can be considered as specific fertilizer.

At the present time phytoplankton biomass harvesting, used for useful products or byproducts manufacturing, can be considered as new potential consumer of this kind of effluents. Technology of phytoplankton biomass usage is now also developing due to the general understanding that petroleum resources will be earlier or later exhausted. Now experimental, semi-industrial or industrial bio-engineered systems exist for production of biodizel, methanol, dyes or other useful substances from the phytoplankton biomass, cultivated at the bio-reactors of different configurations. The specially constructed open ponds equipped by systems for the nutrients, CO_2, water supply and phytoplankton biomass extraction are investigated for the phytoplankton biomass harvesting because of their relative low cost (Benemann, Oswald, 1996).

The aim of this article is to present some analytical results on the nutrients (N, P) consumption by phytoplankton in the open pond in relation to the nutrient content in the biologically treated domestic effluents. To get this aim the dynamic model was developed taking into account the specific properties of phytoplankton biomass harvesting processes in the open ponds with forced mixing of water.

MATERIALS AND METODS

Experimental data

According to the publication (Suzdanoff, 2006) that contains useful and sufficiently complete set of necessary experimental data, the farm for the phytoplankton biomass harvesting can be constructed as the set of operational modules, each of them being the open pond presented schematically on the figure 1 below. The experimental data for this unit were obtained by National Renewable Energy Laboratory (USA) at the Outdoor Test Facility (OTF) pond in Roswell, New Mexico.

The general pond parameters are:

- depth is 20 cm
- volume of 200 m^3
- water surface area of 1000 m^2
- average water loss of 6.2 m^3 per day
- minimum average UV radiation of 3 kWh/m^2/day in December
- maximum average UV radiation of 8.5 kWh/m^2/day in June

Many ponds of this size would be fit into a small area along with larger settling ponds and a pumping centrifuge station in order to produce algae on a large scale.

The high phytoplankton growth rates are achieved because the pond is constantly mixed by the paddle wheel and it is infused with an ample amount of CO_2 and fertilizer. The paddle wheel rotates providing intensive mixing of dissolved and suspended substances. The mixing is required to ensure that all of the algae receive the necessary amounts of solar radiation, CO_2, and fertilizer required for growth of cells.

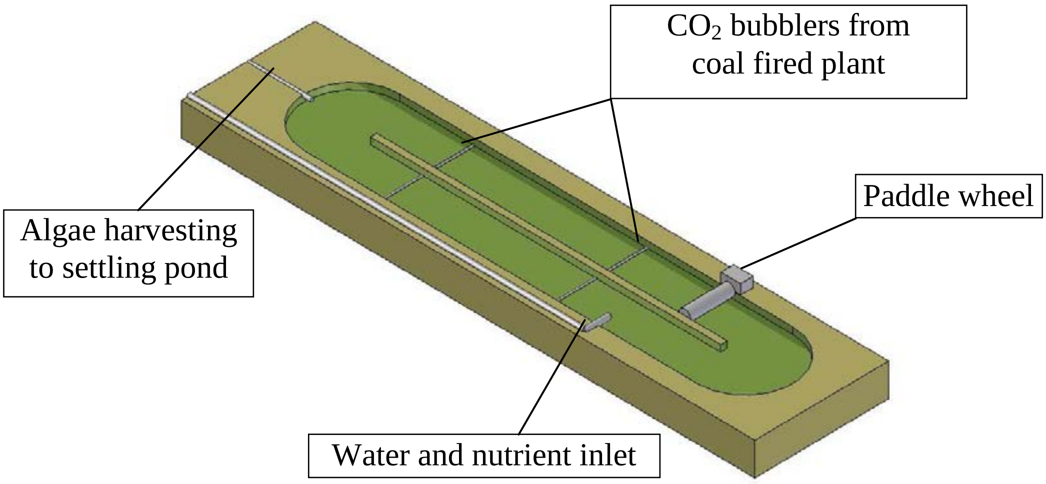

Figure 1. Scheme of algae breeding pond, (Suzdanoff, 2006)

The unicellular green algae called *Monoraphidium minutum* (*M. minutum*) was used to study the productivity of the phytoplankton biomass breeding under the real conditions. The nitrogen is in the form of ammonia or nitrate and must compose 0.8% of the volume of the pond solution to ensure maximum algae production. Likewise phosphorus is in the form of phosphate and must compose 0.6% of the pond. The corresponding ratio of the dry weight of the *M. minutum* algae to nitrogen and phosphorous is approximately 1:0.008:0.006.

Algae pond operations are simple. At the breeding phase the algae are introduced into the pond and allowed to grow until they occupy 1% of the volume of the pond (about 1000 mg/l of the dry weight). This concentration of algae is high enough that light does not penetrate through the water. Then water discharge of certain rate from the pond is maintained to harvest algae leaving the remaining algae space to grow. Time-averaged experimental data available to relate algae productivity with UV radiation are given in table 1.

Table 1. Long Term OTF Results (after: Suzdanoff, 2006), (gm/afdw/m^2/d: grams of ash-free dry mass per square meter per day)

Dates	Solar Radiation I_0 (kWh/m^2/day)	Productivity P (gm afdw/m^2/day)
10/1/89 - 9/30/90	5.75	10.5
5/1/90 - 9/30/90	7.75	18

Dynamic model

To describe the algae harvesting process analytically the following assumptions are made:

- forced mixing of water makes the distribution of all dissolved and suspended materials in the water to be homogeneous
- light is the only factor, limiting the photosynthesis
- the light attenuation coefficient in the water depends only on the concentration of algae cells
- the water volume of pond is constant
- the harvesting biomass concentration is maintained at the constant level

Accordingly, the lumped model of algae biomass dynamics at the pond is taken as following:

$$\frac{dX}{dt} = \mu \frac{I_0}{kh} \left[1 - \exp(-khX)\right] - rX - \frac{QX}{V} \qquad (1)$$

X = algae biomass concentration (g/m^3)
I_0 = light flux density on water surface (kWh/m^2/day)
V = volume of pond (m^3)
Q = water discharge rate (m^3/day)
h = depth of pond water (m)
k = light attenuation coefficient (m^2/g)
μ = photosynthesis rate coefficient (m^2/kWh)
r = respiration rate coefficient (1/day)
t = time (day)

During phase of algae biomass breeding the water discharge is absent until the harvesting biomass concentration will be reached. Thereafter, water discharge rate is maintained in that way to provide for the constant level of algae biomass:

$$Q(t) = \frac{\mu A R}{k X_{max}} I_0(t) - rV \qquad (2)$$

$$R = \left[1 - \exp(-khX_{max})\right] \qquad (3)$$

R = light absorption coefficient (1)
X_{max} = harvesting biomass concentration (g/m^3)

A = water surface area (m^2)

Then phytoplankton productivity *P(t)* (g/m2/day) can be assessed as following:

$$P(t) = \frac{Q(t) X_{\max}}{A} = \mu \frac{R I_0(t)}{k} - rhX_{max} \qquad (4)$$

Growing algae consume correspondent quantity of nitrogen $P_N(t)$ (gN/m2/day) and phosphorous $P_{NP}(t)$ (gP/m2/day) from the water:

$$P_N(t) = \beta_N P(t) \qquad (5)$$

$$P_{Ph}(t) = \beta_{Ph} P(t) \qquad (6)$$

β_N = ratio of nitrogen to algae biomass (gN/g)
β_{Ph} = ratio of phosphorous to algae biomass (gP/g)

To eliminate the deficit of nutrients, the appropriate quantities of fertilizers or biologically treated domestic effluent or both should be added to the pond. Besides, the water losses through evaporation also should be compensated by adding fresh water to maintain water volume at desirable level.

$$Q(t)_{fresh} = Q(t)_{evap} \qquad (7)$$

Due to linearity, all above-mentioned dependencies for the harvesting phase of pond operations conserve their forms, being averaged on any time span *T*. Upper-line marked variables in the following relationships mean time-averaged values.

$$\bar{P} = \mu \frac{R \bar{I}_0}{k} - rhX_{max} \qquad (8)$$

$$\bar{Q} = \frac{\mu A R}{k X_{max}} \bar{I}_0 - rV \qquad (9)$$

$$\bar{P}_N = \beta_N \bar{P} \qquad (10)$$

$$\bar{P}_{Ph} = \beta_{Ph} \bar{P} \qquad (11)$$

$$\bar{Q}_{fresh} = \bar{Q}_{evap} \qquad (12)$$

Model calibration

The data, presented in the previous section and taken from (Suzdanoff, 2006), enable to assess easily the properties of phytoplankton population, that was used at the OTF pond in Roswell, New Mexico. We assume:

h = 0.2 m
$X_{\max}$ = 1000 g/m^3
R = 0.99

P = 10.5 (g/m^2/day), if $\overline{I_0}$ = 5.75 (kWh/m^2/day)
P = 18 (g/m^2/day), if $\overline{I_0}$ = 7.75 (kWh/m^2/day)
$\bar{Q}_{evap}$ = 6.2 m^3/day

Then equations below can be used for the estimation of unknown model parameters.

$$R=\left[1-\exp\left(-khX_{max}\right)\right]=0.99 \qquad (13)$$

$$10.5=5.75\cdot\mu\frac{R}{k}-rhX_{max} \qquad (14)$$

$$18=7.75\cdot\mu\frac{R}{k}-rhX_{max} \qquad (15)$$

The following figures, characterizing approximately absorption, photosynthetic and respiration abilities of *M. minutum*, were obtained:

k = 0.023 m^2/g
μ = 0.087 m^2/kWh
r = 0.055 1/day

RESULTS AND DISCUSSION

Algae breeding dynamics

During the breeding phase of pond operation the uptake of algae from the pond is absent, so that dynamics of algae biomass is governed by the processes of photosynthesis and respiration only. Two different dynamics of the algae biomass development under the constant light illumination and initial biomass concentration $X(0)$ = 0.1 g/m^3 are shown on the Figure 2.

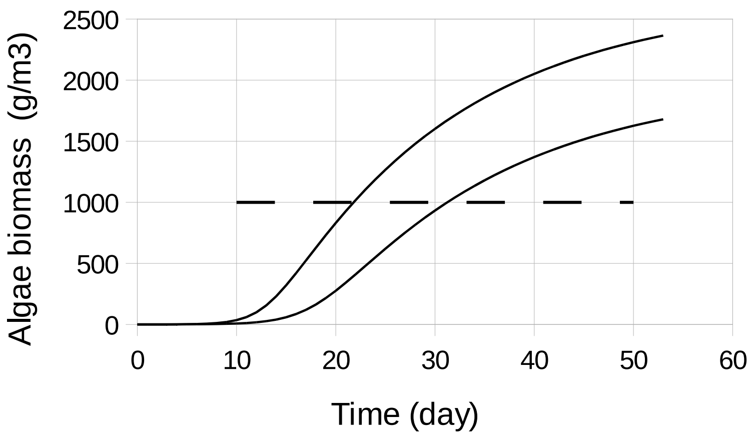

Figure 2. Algae biomass growth at the breeding phase of pond operation (upper line: at I_0 = 7.75 kWh/m^2/day, lower line: at I_0 = 5.75 kWh/m^2/day)

It is evident, the larger light illumination, the quicker harvest level (1000 g/m3) of algae biomass concentration is reached. Also, the level of algae biomass concentration for algae harvest operation lies somewhere at the end of the phytoplankton linear growth interval.

Nutrient consumption

To assess the necessity in nutrient supply for algae harvesting in relation to possible usage of effluents for this purpose, we consider hypothetical production of algae biomass at the OTF pond for one year period under the average condition of light illumination. According to (Suzdanoff, 2006), the average solar radiation at the place of Roswell is 5.92 kWh/m^2/day. Then the year yield of algae Y (g) can be calculated as:

$$Y = P \times A \times 365 = 4077 \text{ kg} \qquad (16)$$

To get this yield it would be necessary to add to this pond 32,6 kg of nitrogen (0.8%) and 24,5 kg of phosphorous (0.6%). But not all of these quantities can be introduced with domestic effluents because pond should receive the returned water after extraction of algae. The free volume for liquid domestic effluents arises through the annual loss of water due evaporation and operational losses. It is not less than $\bar{Q}_{evap} \times 365 = 2260$ m^3.

Dividing required values of nitrogen and phosphorous on the average content of nitrogen (0.05 kg/m^3) and phosphorous (0.01 g/m^3) in the treated domestic sewerage water, one can find that about 652 m^3 and 2450 m^3 of liquid effluents contain required nitrogen and phosphorous, correspondingly. That means that only 652 m^3 of effluents can be used to compensate for the losses of nutrients because nitrogen and phosphorous should be introduced to the pond in ratio that should be correspondent to algae ratio 0.008N:0.006P. Consequently, the remaining part of phosphorous (about 18 kg) should be carried in by the mineral phosphates and remaining part of the water losses should be added by fresh water (about 1608 m^3).

Nevertheless, algae farm, including 64 pond units considered, could consume approximately 40000 m^3 biologically treated domestic effluents per year.

CONCLUSIONS

The bulk model is used to describe the dynamic processes of algae breeding and harvesting in the artificial pond with forced mixing.

The procedure of calibrating of model parameters, that responsible for the simulation of light absorption, photosynthesis and respiration of algae, is proposed and implemented by use of the published experimental data available.

Some simulations are presented to show the dynamic behavior of algae used for harvesting and to assess the consumption of nutrients in relation to the nutrient content of the treated domestic effluents.

It is shown that ability of algae breeding pond to consume the biologically treated domestic sewerage water is strongly dependent, beside other factors, on the climate conditions (evaporation) and ratio N:P in the algae and domestic effluents.

Other climate (heat balance) and operational (material balance) factors could be taken into account to advance the quality and ability of the model to simulate and to predict the processes of algae breeding and harvesting under the real conditions.

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