FECAL COLIFORM MORTALITY IN WATER HYACINTHS PONDS

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Abstract
The effects of various environmental factors, sedimentation and attachment of faecal coliforms on water hyacinths, *Eichhornia crassipes,* were investigated in a pilot-scale water hyacinths pond. This investigation was conducted to evaluate the role of solar intensity, pH, dissolved oxygen, temperature, sedimentation, and attachment of faecal bacteria on *Eichhornia crassipes* on disappearance of bacteria in a water hyacinths pond. A mathematical model that used the plug flow philosophy and incorporated aforementioned factors to predict faecal coliform mortality rate was developed. The proposed multifactor model satisfactorily predicted mortality rate of faecal coliforms in a pilot-scale water hyacinths constructed wetland. The environmental factors such as solar intensity and pH were the key factors if the coverage of water hyacinths is minimum, but attachment of bacteria to water hyacinths played a major role in a wetland fully covered with water hyacinths.

***Keywords*:** Faecal coliforms, mortality rate of bacteria, water hyacinths, ponds.

1. Introduction

Water hyacinth, *Eichhornia crassipes,* is one of the rapidly growing and very productive photosynthetic plants. This aquatic macrophyte is the eighth fastest growing plant on earth (Reddy and Sutton, 1984). Its explosive growth is considered unfavorably in natural water bodies such as Lake Victoria because it restricts navigation (Lockley and Turner, 1961) and imparts undesirable taste and odour to water (Reddy and DeBusk, 1991). *Eichhornia crassipes* is also considered a health hazard because it is associated with several pathogenic organisms and vectors of diseases such as schistosomiasis, filariasis, malaria and ancephalitis (Gopal, 1987; Reddy and DeBusk, 1991) because it concentrates the microorganisms around its roots and shoots (Spira *et al*., 1981; Muyodi, 2000). Accumulation of pathogens in water hyacinths found in freshwater is undesirable because water hyacinth remains as part of the water body. However, a similar accumulation in wastewater is desirable because effluent quality will improve.

The water hyacinth, *Eichhornia crassipes*, has been extensively used for improvement of wastewater effluents from waste stabilization ponds and septic tanks (Perdomo *et al*., 1998). The capacity of water hyacinth ponds to reduce organic matter is well documented (Cooper *et al*., 1996) and mathematical models have been developed to describe the kinetics of organic degradation in these ponds (Polprasert and Khatiwada, 1997). These systems have also been used for removal of nutrients (Imaoka and Teranishi, 1988) and heavy metals (Mugasha, 1995).

However, due to lack of sufficient design criteria, it is doubtful whether water hyacinth ponds can meet present effluent standards set by many authorities without bacterial disinfection, since it is known that the plant itself accumulates pathogens around its root zone by attachment (Reed *et al*.,

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1988; Gersberg *et al*., 1989). Literature has revealed that bacterial mortality in water hyacinth ponds depends on environmental and climatological factors. Various hypotheses and explanations have been tried to explain the causes of bacterial mortality, some of which are similar to those of waste stabilization ponds, and for that matter any comprehensive model should consider them. These include temperature (Marais, 1974), effect of pH (Parhad and Rao, 1974), depletion of nutrients (Gann *et al*., 1968), biocide excretion by plants (Gersberg *et al*., 1989), microbial antagonism (Polprasert *et al*., 1983), sedimentation (Auer and Niehaus, 1993), dissolved oxygen (Curtis *et al*., 1992), solar radiation (Calkins *et al*., 1976), adsorption under aerobic conditions (Ohgaki *et al*., 1986), and attachment of bacteria to plants (Muyodi, 2000).

The primary objective of this work was to formulate a multifactor mathematical model for the mortality of faecal coliforms in water hyacinth ponds in tropical climates. Bacterial antagonism and biocide production by *Eichhornia crassipes* on mortality were assumed to be insignificant. Organic loading rates and retention time were also neglected due to the findings of Mayo and Gondwe (1989).

2. Materials and Methods

2.1. Description of the pilot water hyacinth pond system

The pilot water hyacinths pond is located at Longitude $39^{o}13^{/}$E and Latitude $6^{o}48^{/}$S approximately, close to mean sea level with a mean monthly temperature range of 23 ^{o}C to 28 ^{o}C. The water hyacinths pond had a hydraulic retention time of 10 days and a flow rate of 1 m^3/day, which was discharged from the University of Dar es Salaam primary facultative pond. The influent wastewater is predominantly domestic in nature.

Figure 1 depicts the layout of the system. Wastewater was supplied to the water hyacinths pond by directing it in a 75 mm HDPE pipe fixed with a gate valve to control flow rate. A constant head of wastewater was maintained in a chamber upstream of the pond unit. Flushing out of sediments in case of blockage in the chamber was done through a 50 mm pipe. Wastewater was evenly distributed in a water hyacinth unit through an inlet gutter from a 12 mm influent.

Effluent sampling of wastewater was conducted through an outlet pipe connected to a vertically placed 38 mm pipe that maintained a water column of 0.9 m in the wetland unit. Outlet washout next to outlet pipe was put in place during construction for purposes of flashing out sediments in case of blockage. Side sampling was done from globe gate valves installed on the sides.

2.2. Sampling and analysis

To assess the mortality of faecal coliforms in water hyacinth ponds, the water hyacinth biomass was planted after construction. Water hyacinth biomass multiplied at a rate of 0.23 m^2/day. The wetland area covered by the water hyacinth per unit time of growth was obtained with the aid of quadrant's technique. Grab samples were collected from the influent and effluent of water hyacinths unit between 9:00 am and 10:00 am for every day of sampling and examination of samples was done immediately. A number of researchers have used these types of samples, especially for wastewater analysis (Mayo, 1989; Cooper *et al.*, 1996) and they have yielded reliable results.

Dissolved oxygen, pH and temperature were measured *in-situ*. Temperature and pH of the samples were measured using a pH meter (Metrohm, model 704) equipped with a thermometer. Dissolved oxygen of the samples was measured using a DO meter (YSI Incorporated, model 50B). Solar intensity was measured using a mounted sensor at the Department of Physics, University of Dar es Salaam. The data recorded by the sensor was automatically stored in the computer installed at the center.

Faecal coliforms were enumerated in accordance with *Standard methods* (APHA, 1992) using M-FC agar base as the medium. The agar was prepared in accordance with manufacturer's specifications. The mixture of agar and wastewater sample on the petri dishes was carefully and uniformly spread to avoid trapping air bubbles. The cultured petri dishes were inverted and incubated at 44.5 ^{o}C for 24 hours. The colonies produced by faecal coliforms were then counted and reported in colony forming units per 100 ml of wastewater sample.

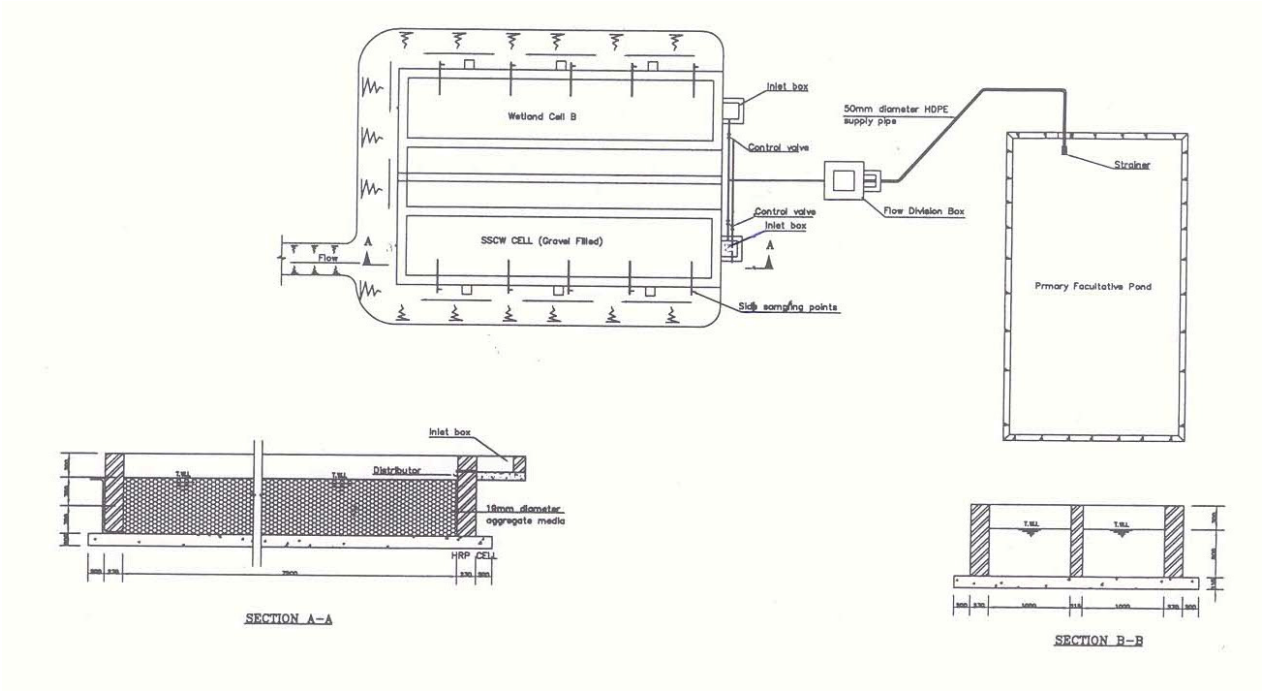


Fig. 1: Layout of experimental wetlands

3. Development of a mathematical model

3.1. Hydraulic Considerations

A dispersed flow regime has been considered to represent pond hydraulic regime by many researchers (Polprasert *et al*., 1983; Agunwamba *et al*., 1992). However, application of dispersed flow model is limited by difficulties in prediction of the pond dispersion number. For simplicity many researchers have applied either completely mixed flow regime (Marais, 1974; Mills *et al*., 1992) or plug flow regime (Mayo, 1995; Sarikaya and Saatci, 1987). Thirumurthi (1969) concluded that ponds are seldom completely mixed, but operate near plug flow conditions. To simulate conditions close to plug flow regime, the length to width ratio of the pond was kept above 5 as recommended by Cooper *et al.* (1996). Research studies have confirmed that planting the ponds with water hyacinths is not expected to change the hydraulic regime (Alvaer, 1995). Therefore the faecal coliform mortality rate was calculated from Chick's (1908) law as shown by equation (1).

$$N_e / N_i = \exp(-k \times t) \quad \text{.....(1)}$$

in which N_i= influent number of faecal coliforms (cfu/100 ml), N_e= effluent number of faecal coliforms (cfu/100 ml), t = hydraulic retention time in days, and k = first-order faecal coliform mortality rate constant (d^{-1}).

3.2. Conceptual Model

To develop a mathematical model that engulfs the major aforementioned factors leading to faecal coliform mortality in water hyacinth ponds, it is considered necessary to take into consideration the effects of environmental factors and sedimentation. Several studies in recent years have shown the importance of biofilm in wastewater purification (Polprasert and Agarwalla, 1994; Polprasert and Khatiwada, 1997) and this factor was also incorporated in the model. A conceptual illustration of faecal coliform mortality/biomass balance for the water hyacinths pond is shown in Fig. 2.

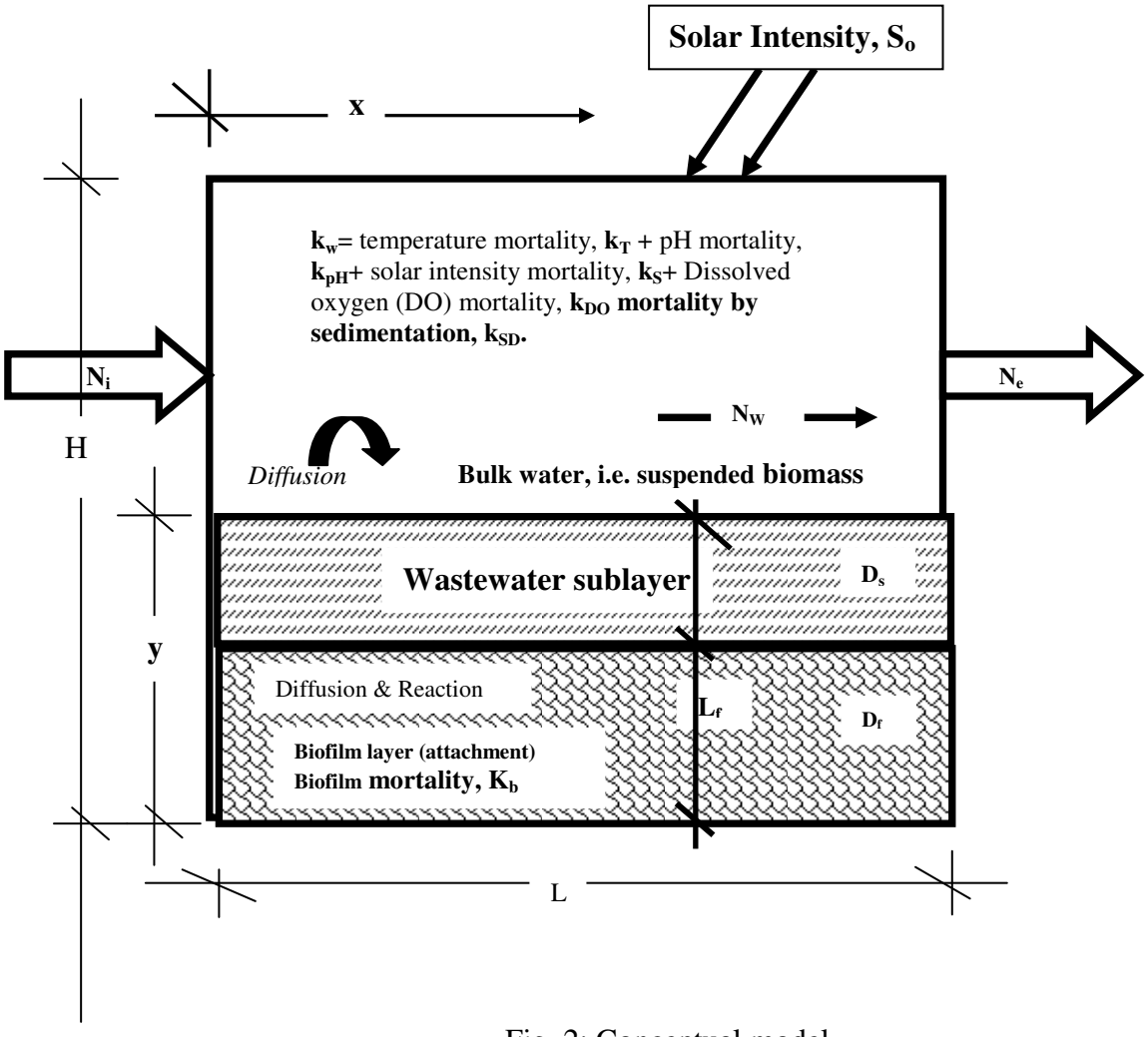


Fig. 2: Conceptual model

From earlier discussion, the conceptual model was designed to incorporate the effects of environmental factors and pond characteristics such as temperature, solar intensity, pond depth, pH and dissolved oxygen concentration. The overall faecal coliform mortality rate constant, k, also

takes into account the effects of sedimentation, attachment of microorganisms on the cell walls and roots of water hyacinths (equation 2).

$$k = k_{envir} + k_{biofilm} + k_{sed} \quad \text{.....(2)}$$

in which k_{envir} = the overall mortality rate constant in wastewater due to environmental factors (d^{-1}), $k_{biofilm}$ = first order rate constant due to attachment of bacteria on the plants (d^{-1}), and k_{sed} = mortality rate constant due to sedimentation (d^{-1}).

The faecal coliform mortality rate constant was assumed to follow first-order kinetics. Furthermore, bacteria attached to the biofilm layer were assumed to be removed from the water body and that diffusion coefficients of sublayer and biofilm as well as biofilm thickness do not vary with the length of the water hyacinth unit.

3.3. Environmental factors

The major environmental factors influencing mortality of bacteria are solar intensity, temperature, pH and dissolved oxygen. The effect of these factors can be presented mathematically by equation (3).

$$k_{envir} = \frac{k_S(\lambda_t S_O^{\ a})}{KH}(1-e^{-KH})(1-l_o) + (k_{pH})(pH) + (k_{DO})(DO) + (k_{20})(\theta)^{(T-20)} \quad \text{.....(3)}$$

Where S_o= solar intensity (cal/m^2/d), K= light attenuation coefficient (m^{-1}), k_S = solar intensity mortality rate constant (d^{-1}), l_o = surface layer effect coefficient, H= depth of water hyacinth cell (m), λ_t= solar intensity correction factor i.e. the relative area $A^{/}$ of the pond exposed to solar energy at time t, $A^{/}$ = ratio of surface area exposed to solar energy and uncovered by plants to the total area of water hyacinth pond, k_{DO}= mortality rate constant for dissolved oxygen (d^{-1}), DO = dissolved oxygen concentration, k_{pH} = mortality rate constant for pH (d^{-1}), T= water temperature (^oC), k_{20} = first-order mortality rate constant at 20^oC (d^{-1}), θ = temperature coefficient, a = coefficient.

3.3.1 Effect of Solar intensity

Solar intensity was potentially the strongest contributing factor to mortality among all the considered physical-chemical factors. However, as growth of the water hyacinth increased, the exposed area of the pond to solar energy decreased. Therefore solar intensity correction factor λ_t which ranged between 0.0 and 1.0 was applied. This factor was taking into consideration the ratio of surface area exposed to solar energy and uncovered by plants to the total area of water hyacinths pond. Therefore λ_t decreased as water hyacinths continued to spread and cover the entire pond.

The surface layer effect coefficient generally varies from 0 to 0.03 (Qin *et al*., 1991) and can therefore be neglected. The light attenuation coefficient, K, in waste stabilization ponds and wetlands vary from 6.0 to 24 m^{-1} (Sarikaya and Saatci, 1987; Calkins *et al*., 1976; Moeller and Calkins, 1980). The term KH in equation (3) will vary from 5.1 to 20.4 bearing in mind that the depth of water hyacinths unit was 0.85 m. For $KH > 4.6$, the term e^{-KH} in equation will be less than 0.01, which means neglecting e^{-KH} may cause an error of less than 1 %. Therefore the term e^{-KH} was neglected.

3.3.2. Effect of temperature

Some literature reports indicate that increase of temperature reduces density of faecal bacteria in accordance with Arrhenius equation (Klock, 1971; Marais, 1974), but others indicate that mortality of faecal bacteria is unrelated to temperature (Auer and Niehaus, 1993; Moeller and Calkins, 1980). Furthermore, a modelling study conducted in the same geographical area by Mayo (1995), showed that the contribution of the temperature term on bacterial mortality rate to the efficiency of the model he developed in waste stabilization was insignificant within a narrow temperature range. With this in mind, temperature term was omitted from the model.

3.3.3. Effect of Dissolved Oxygen concentration

The concentration of dissolved oxygen in water hyacinths pond is influenced by its concentration in the influent and transportation rates in water hyacinth root density, which is estimated to vary between 0.11 g-O_2 to 3.73 g-O_2/kg/h (Moorhead and Reddy, 1988). Information in literature has conflicting opinions on the effect of dissolved oxygen on faecal coliform mortality rate. Mayo (1995) and Pearson *et al*. (1987) did not observe the effect of dissolved oxygen on bacterial mortality. However, Curtis *et al*. (1992) suggested that in the presence of humic substances, oxygen radicals such as singlet oxygen, hydrogen peroxide and superoxide were toxic to bacteria. This toxicity was reported to increase proportionally with an increase in dissolved oxygen concentration. Field data indicated that the mortality rate of faecal coliforms increased slightly with concentration of dissolved oxygen, and therefore this factor was included in the model.

3.3.4. The effect of pH

The effect of pH on faecal coliforms was more pronounced during the early stages of this work when only a portion of the system was covered by water hyacinths. During this time algae coexisted with water hyacinths and effluent pH was relatively higher than the influent pH leading to some mortality, until algae was phased out in the latter stage as a result of dominance of water hyacinths.

3.4. The sedimentation term

The effect of sedimentation on bacterial mortality rate is described by equation (4), which assumes that the collector shape is cylindrical (Bales *et al*., 1991; Logan *et al*., 1993). For simplicity, the roots of the water hyacinths were assumed to be cylindrical.

$$k_{sed} = \frac{4}{\pi}\eta\alpha\frac{u(1-p)}{d_C} \quad \text{.....(4)}$$

Where η = single collector removal efficiency, α = sticking coefficient, u = flow velocity (m/day), d_C = diameter of collector (m), and p = porosity of medium (%). The value of η was further computed from the expression of Stoke's law as given by O'Melia (1985). The values of the parameters for the model equations (4) and (5) were derived both from literature and the field as detailed below.

$$\eta = \frac{(\rho_P - \rho) g d_P^{\ 2}}{18 \mu u} \quad \text{.....(5)}$$

The velocity of flow was calculated from the influent flow rate, Q, and cross section area of the water hyacinth pond, A, and was found as $u = Q/A = 0.702$ m/day. The mean root hair diameter of water hyacinth d_C was measured and was found to be 0.068 ± 0.031 mm. This value compared well with that of Polprasert and Khatiwada (1997) who reported the mean root diameter of 0.075 ± 0.025 mm. Other researchers reported values in the same range, $0.06 \leq d_C \leq 0.3$ mm (Reddy, 1988; Gopal, 1987; Alvaer, 1995).

The mean porosity of the water hyacinths pond was obtained as 95%, which compared well with a porosity of 96.5% reported by Kim and Kim (1999). The sticking coefficient α was 0.008, which is within the range reported in the literature (Polprasert and Khatiwada, 1997). The density of sediment/colloid particles, ρ_P ranged between 1050 and 1500 kg/m^3 and the diameter of colloidal matter d_P ranged between 0.4 μm to 10 μm (Metcalf and Eddy, 1995).

The viscosity of water, μ, was considered to vary with temperature. Weast (1981) suggested that for temperatures between 20 $^oC \leq T \leq 100\ ^oC$ equation (6) is valid.

$$\log \frac{\mu}{\mu_{20}} = \frac{1.3272(20 - T) - 0.001053(T - 20)^2}{(T + 105)} \quad \text{.....(6)}$$

Where T is temperature of the effluent in ^oC, μ is the coefficient of dynamic viscosity of water in poise, μ_{20} is the coefficient of dynamic viscosity of water at 20^oC = 1.002x10^{-3} N.s/m^2 (= 1.002x10^{-2} poise). The density of water was also related to water temperature. After substitution of parameters of known values related to the sedimentation term in equation (4) the sedimentation term represented by equation (7) was obtained.

$$k_{sed} = \frac{89.38(1 - p)\eta\alpha}{d_c} \quad \text{.....(7)}$$

3.5. The biofilm term

The effect of biofilm attachment is described by equation (8), and the values of the parameters for this model were derived both from literature and the field as detailed below.

$$k_{biofilm} = (a_S)_t \frac{\gamma\beta}{(\gamma + \beta)} \quad \text{.....(8)}$$

Where γ and β are coefficients of biofilm, and $(a_S)_t$ = Specific surface area of biofilm per unit control volume at time t (m^2/m^3). The thickness of biofilm, L_f, was 2.5x10^{-4} m, which was outside the range of $1.462\text{x}10^{-3}\ \text{m} \leq L_f \leq 1.615\text{x}10^{-3}$ m reported by Polprasert and Agarwalla (1994) probably because this study was done almost immediately after the system started operating. Therefore ample time was not given for sufficient biofilm thickness to develop.

Williamson and McCarty (1976b) found that the sublayer thickness consisted of two layers L_1 and L_2. The outer liquid sublayer (L_1) could be totally omitted with adequate mixing in the pond. The inner layer L_2 was constant; with a constant thickness of 56 μm. Rittmann and McCarty (1980)

conducted column reactor experiments and found that liquid sub-layer thickness, L_S ranged from 1.19×10^{-4} m to 2.26×10^{-4} m for superficial flow velocities between 3220 and 43000 mm/day. The flow velocity of the study was 702 mm/day, and in the absence of data, an entire range was used during parameter optimization.

Perry and Chilton (1973) and Lamotta (1976) reported a sub-layer diffusion coefficient D_S of 5.26×10^{-5} m^2/day. Furthermore, the ratio of the diffusion coefficient of biofilm D_f to diffusion coefficient of sub-layer D_s was reported to be 0.1 ~ 0.3 for aerobic conditions in a biofilm (Pavlostathis and Gilardo-Gomes, 1991) and 0.8 for anaerobic conditions in a biofilm (Williamson and McCarty, 1976a, b). Some researchers adopted D_f to be a percentage of D_S (Rittmann and McCarty, 1980; Pavlostathis and Gilardo-Gomes, 1991). Since the entire range between aerobic and anaerobic conditions is $0.1 \leq D_f/D_S \leq 0.8$ and water hyacinths ponds are usually facultative in nature, a D_f/D_S ratio of 0.4 was adopted. Therefore the diffusion coefficient of biofilm $D_f = 2.30 \times 10^{-5}$. The parameter γ was calculated from equation (9) was observed to vary from $0.233 \leq \gamma \leq 0.442$ m/d.

$$\gamma = D_s/L_s \quad \text{..... (9)}$$

Characteristic biofilm parameter ϕ and β were calculated from equations (10) and (11), respectively.

$$\phi = (k'_{fb} L_f^2 / D_f)^{1/2} \quad \text{..... (10)}$$

$$\beta = \{\tanh(\phi) * k'_{fb} * L_f/\phi\} \quad \text{..... (11)}$$

The specific surface area of biofilm per unit control volume, $(a_S)_t$ of a pond without baffles is given by $(a_S)_t = 1/H + 2/W + 2/L$, where L, W, H are pond length, width and depth, respectively, and that of attached growth system like water hyacinth, $(a_S)_t = (R_S)_t/H$, where $(R_S)_t$ is the effective root surface area per unit pond surface area at time t. $(R_S)_t$ and $(a_S)_t$ are a function of the pond area covered by the water hyacinths and time since the relative specific surface area λ_t of the pond was also varying. For simplicity, $(a_S)_t$ and/or $(R_S)_t$ were assumed to be proportional to the relative surface area A' covered by the water hyacinths in time t.

$$(R_S)_t = R_S(1 - \lambda_t) \quad \text{.....(12)}$$

$$(a_S)_t = a_S(1 - \lambda_t) \quad \text{.....(13)}$$

Where R_S = effective root surface area per unit surface area of pond at full pond coverage by water hyacinths, and a_S = specific surface area of water hyacinths at full pond coverage by the plant, which varies between 5.76 m^2/kg $\leq a_S \leq$ 20.83 m^2/kg for water hyacinths (Polprasert and Khatiwada, 1997; Kim and Kim, 1999).

4. Results and Discussion

As discussed earlier, no factor on its sufficiently predicted the mortality rate of faecal coliforms because of aforementioned reasons. Amalgamating both models to predict the overall faecal coliform mortality k provided a relatively better fit since this process phases out the shortcomings of the individual models (Fig. 3). The final mathematical model was the summation of mortality rate constant from individual models (equation 14).

$$k = \frac{k_S(\lambda_t S_O^{\ a})}{KH} + (k_{pH})(pH) + (k_{DO})(DO) + \frac{4}{\pi}\eta\alpha\frac{u(1-p)}{d_C} + (a_S)_t\frac{\gamma\beta}{(\gamma+\beta)} \quad \text{.....(14}$$

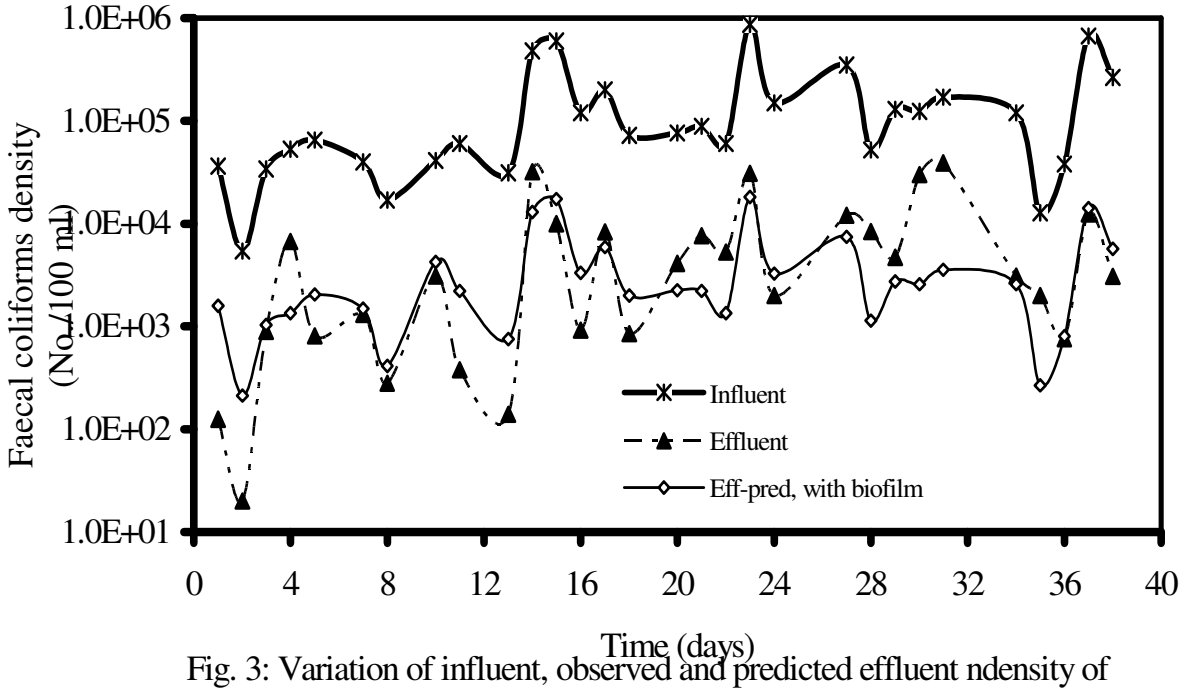


Fig. 3: Variation of influent, observed and predicted effluent ndensity of faecal coliforms with time

4.1. Effect of environmental factors

A multiple regression on a partial model that considers environmental factors such as solar intensity, pH and dissolved oxygen terms alone was tested and parameters were optimized using FORTRAN programming. This partial model produced a model efficiency of 13% only. After optimization the optimum parameters were k_{pH} = 0.001, k_{DO} = 0.0037, K = 6 m^{-1}, k_s/KH = 1.889 x 10^{-3} cm^2/cal. Based on the depth of the pond of H= 0.9 m, solar intensity mortality rate constant k_s was equal to 0.0102 cm^2/cal, which was within the range of 0~0.011 cm^2/cal reported in the literature (Lantrip, 1983).

Fig. 4 shows the effect of environmental factors such as solar intensity, pH and dissolved oxygen on the mortality rate of faecal coliforms. The predicted trend showed a decrease with time because the relative surface area of the water hyacinths pond exposed to sunlight λ_t decreased with time. The increased coverage of the pond by water hyacinths with time, which covered the pond at the rate of 0.23 m^2/day, hindered the penetration of solar radiation, which is known to influence bacterial mortality rate (Calkins *et al*., 1976; Mayo, 1995).

The growth of plants also caused reduction of algae in the system, which in turn resulted in the decrease of pH and dissolved oxygen concentration. The reduction in pH meant successive reduction in mortality rate, since the pH data were successively drifting away from the threshold pH of 9.3, which was reported by Parhad and Rao (1974) as critical pH for mortality of bacteria. As a result the number of fecal coliforms predicted from the effects of environmental factors increased with time because of the increased surface area of attachment as water hyacinths continued to grow (Fig. 5).

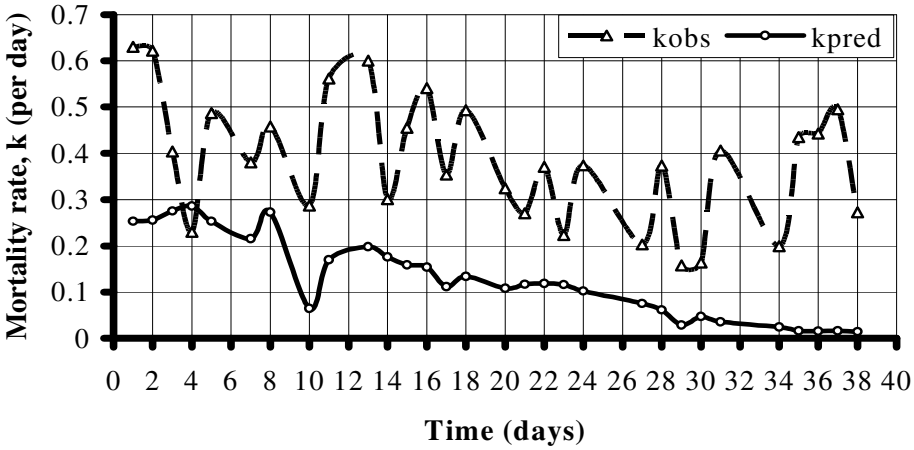


Fig. 4: Effect of environmental factors on mortality rate of fecal coliforms

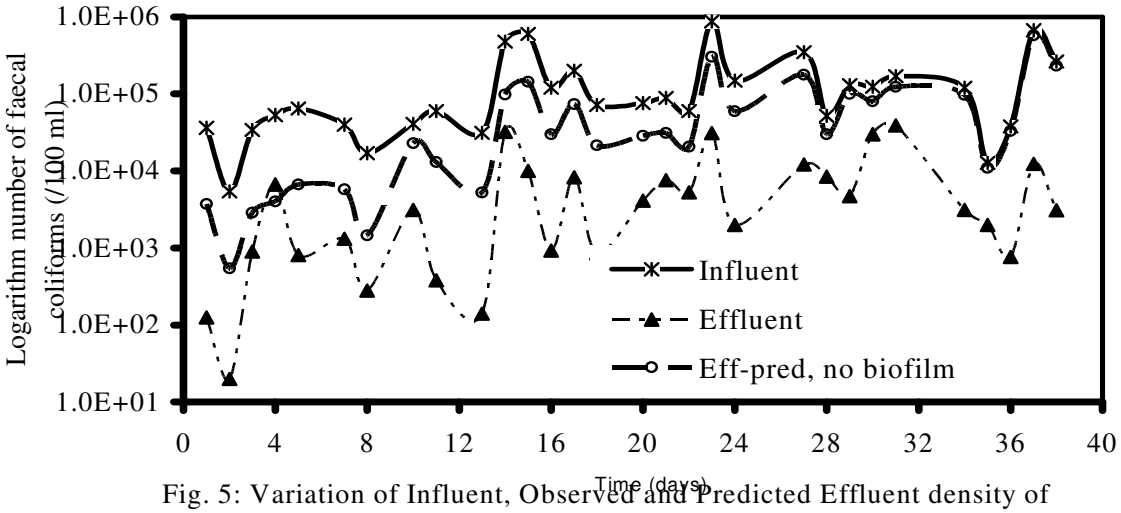


Fig. 5: Variation of Influent, Observed and Predicted Effluent density of faecal coliforms with time.

4.2. Effect of sedimentation

The optimum sedimentation parameters were d_P = 4 μm, α = 0.008 to 0.012, d_C = 0.06 cm and ρ_p=1100 kg/m^3. Unfortunately, the effect of sedimentation improved the model efficiency by only 3.2 %. These findings suggest that the contribution of sedimentation to the mortality rate of faecal coliforms in the system was insignificant. When sensitivity analysis was done on the model by increasing the range of d_P, the model efficiency improved slightly. This implied that sedimentation would play a significant role only when raw wastewater is treated in this system on the assumption that bacteria trapped in solid particles in wastewater are removed as sediments settle to the bottom of the ponds or on plants. The role of sedimentation was insignificant in this study because wastewater was abstracted from a primary facultative pond, where most of the sediments were removed. Moreover, a strainer at the intake structure to water hyacinths wetland screened the influent.

4.3. Attachment of bacteria to water hyacinths

After optimization of the model parameters the following biofilm parameters were obtained: L_f = 2.5x10^{-4} m, k'_{fb} = 40 d^{-1}, α= 0.233 *m/d*, R_S = 10.4 m^2/m^2, and biofilm parameter $\gamma\beta/(\gamma+\beta)H$ = 0.0408 d^{-1}. Equation (15) represents the bacterial disappearance rate due to attachment to water hyacinths or pond walls.

$$k_{biofilm} = \frac{R_S(1-\lambda_i)}{H} \bullet \frac{\gamma\beta}{(\gamma+\beta)} = 0.0408 R_s(1-\lambda_i) \quad \text{.....(15)}$$

Fig. 6 shows that the rate of disappearance of faecal coliform due to biofilm attachment $k_{biofilm}$ increased with time because of the increased surface area of attachment as water hyacinths continued to grow. The fast growth in turn provides a large R_S in the root zone for attachment of bacteria. As a result in the initial stages of growth of the plants (day 0 to 8) the predicted density of faecal coliforms predicted from biofilm term was closer to the observed influent values. As days went by (day 28 to 40), this curve deviated significantly from the observed influent curve, and gradually shifted towards the observed effluent curve. Towards the end, effluent faecal coliform mortality rate predicted from biofilm term and the observed effluent curve closely matched. This was because during this stage of data collection the pond surface was fully covered by water hyacinths. The plants provided a large surface area for attachment of bacteria. As a result other physical-chemical factors were suppressed.

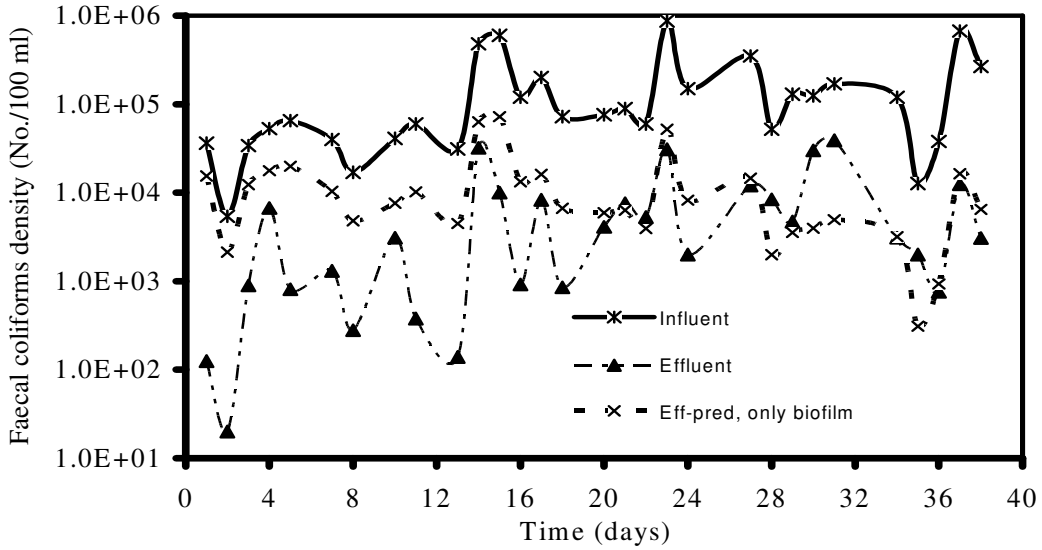


Fig. 6: Effect of attachment of bacteria on disappearance of faecal coliforms

4.4. Model application

This model is suitable for water hyacinths ponds, which receive pretreated wastewater either from primary sedimentation tank, anaerobic or facultative ponds. Application of the model requires the knowledge of the influent density of faecal coliforms, forcing functions such as pH, dissolved oxygen, temperature, solar intensity, and extent of pond coverage by water hyacinths, depth of the pond, and influent flow rate. Various coefficients and constants given in the development of the model are also required. Stella software may conveniently be applied because it has an in-built

program that provides the selection of estimation methods for integration of the differential equations. Fourth-order Runge-Kutta estimation is recommended because of its low truncation error and fast convergence on the given initial data. Development of a program in FORTRAN or any other language is also another alternative.

5. Conclusions

A mathematical model that used the plug flow philosophy and incorporated the effects of solar intensity, pH, dissolved oxygen, sedimentation, and attachment of fecal coliform on water hyacinths, *Eichhornia crassipes* was developed for prediction of fecal coliform mortality in a water hyacinths pond. From the results obtained in this work, the following conclusions are made:

1. The proposed multifactor model satisfactorily predicted fecal coliforms mortality rate in a pilot-scale water hyacinths pond.
2. The environmental factors such as solar intensity and pH were the key factors in an uncovered pond, but attachment of bacteria to water hyacinths played a major role in a pond fully covered by water hyacinths.

Acknowledgement

Water Net is thanked for providing research scholarship to the second author.

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