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Kinetics of Iron Uptake by Wetland Plants

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Abstract: The aim of this study was to assess the kinetics of Fe removal by broad-leaved cattail, soft stem bulrush, soft rush and wool grass plants from contaminated wastewater under laboratory conditions. The approach used was based on a first order kinetic model which allowed for the evaluation of the specific metal uptake rate and the maximum accumulation of the metal in each plant species. The results showed that the model is capable of predicting the experimental data with relatively high confidence ($R^2 = 0.98$). The specific Fe uptake rate and the maximum amount of Fe that can accumulate in each plant species were affected by the initial Fe concentration in the wastewater and the plant species. As the initial concentration of Fe in the water increased, the specific Fe uptake rate of each species decreased with the exception of broad-leaved cattail. Soft stem bulrush displayed the highest specific Fe uptake rates followed by soft rush, cattail and wool grass. The maximum amount of Fe that accumulated in each species also increased as the initial Fe concentration in the wastewater increased. The results showed that soft stem bulrush plants would accumulate the highest amount of Fe in their tissues followed by broad-leaved cattail, wool grass and soft rush.

Key words: Wetland, aquatic plants, Fe, kinetics, uptake rate, maximum concentration

INTRODUCTION

Iron (Fe) is an essential element found in all plant and animal tissues. It is necessary for photosynthesis and enzyme production in plants and oxygen storage and transportation in animals. However, excess concentrations of Fe in both surface and groundwater threaten human health and the environment[1] . Excess Fe is introduced into natural ecosystems in the liquid waste streams from many industries including: spent pickle and etch baths from plating shops and steel manufacturing[2-4] , (b) acid mine drainage from metal mines and coal mines[5] and (c) leachates from municipal solid waste landfills[6]. Ferrous iron (Fe^{2+}) is a highly soluble species that exists in the aqueous phase and is easily absorbed into biological tissues. Therefore, it is considered to be the most acutely toxic form of Fe. Fe^{2+} creates oxidative stress by inducing the formation of oxygen based radicals that cause membrane and DNA damage. Ferric iron (Fe^{3+}) is a highly insoluble species that exists in the solid phase. It forms stable complexes with a variety of ligands including hydroxide ions to form $Fe(OH)_3$. $Fe(OH)_3$ blankets the sediment with a highly turbid orange floc that reduces light penetration and primary productivity, damages respiratory surfaces and blankets fish spawning sites and macroinvertebrate habitats[7].

Constructed wetlands are self-sustaining, inexpensive systems that have been used to treat many types of wastewaters contaminated with Fe. Processes that are responsible for remediation of Fe contaminated wastewaters in wetlands include: sedimentation and filtration of solids, precipitation as sulphides and oxyhydroxides, ion exchange with the sediments and plant uptake[8]. The ability of aquatic plants to absorb and accumulate metals from their aquatic environment has been demonstrated by a number of researchers[9-13]. The degree of metal uptake by plants is largely dependent on the type of metal and the plant species involved.

The aim of this study was to assess the performance of selective facultative and obligate wetland plants for the removal of Fe from contaminated wastewater by examining the Fe uptake kinetic parameters of each plant species. The specific objectives were to determine: (a) the changes in Fe concentration in the plants with time, (b) the specific metal uptake rate for each plant and (c) the maximum concentration of Fe that each plant could accumulate.

MATERIALS AND METHODS

Experimental apparatus: The experimental setup shown in Fig. 1 consists of holding tanks and lighting

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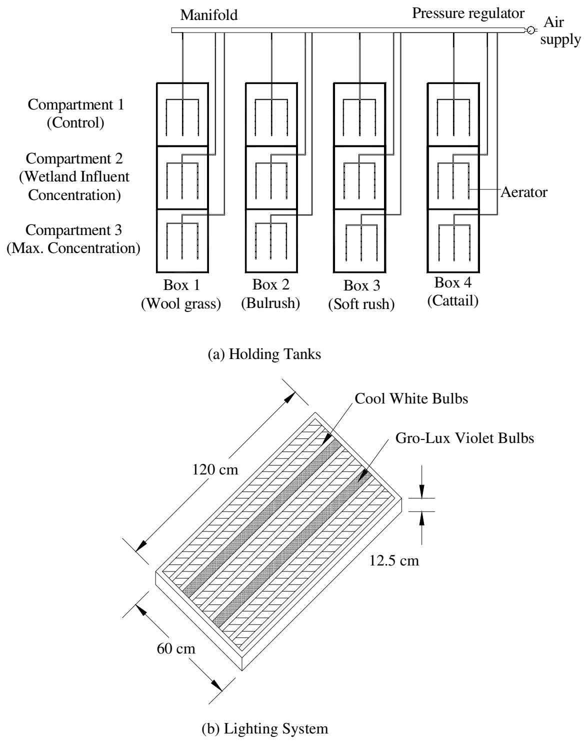

Fig. 1: Experimental apparatus

and aeration systems. Four boxes were constructed from 2.5 cm thick plywood. Each box (60×120×80 cm) was divided into three compartments (30×60×80 cm each) and each compartment contained a holding tank.

The light was provided by an artificial lighting system (625 hectolux/7200 cm^2) and was similar to the natural light required for wetland plants. Each lighting unit consisted of eight light bulbs (six 34 watts cool white fluorescent bulbs and two Gro-lux 40 watts bulbs) of 122 cm in length. The lighting system was placed on the top of each box using wooden supports in such a way that it gave a space of 140 cm clearance between the light bulbs and the water surface in the box. This space was chosen to achieve good air circulation and provide the heat and light that were required for plant growth. The lights were controlled by a timer, which was set to provide 16 h of light per box per day and to maintain a temperature difference between the soil and the above ground part of 15°C[14].

An aeration unit was installed in the bottom of each compartment to provide oxygen for the plants. The air traveled from the main laboratory supply to a manifold with twelve outlets. Each outlet was connected to a pressure regulator (Model 129121/510, ARO, Bryan, Ohio), which was connected to an aerator located in each compartment. Each aerator consisted of a main

Table 1: Nutrients and heavy metal concentrations (mg L^{-1}) in the water

Element	Control	Wetland influent	Tolerance Concentration
Nutrient			
Potassium	163.40	163.40	163.40
Nitrogen	163.40	163.40	163.40
Phosphorus	163.40	163.40	163.40
EDTA	8.17	8.17	8.17
Boron	0.16	0.16	0.16
Sulfur	------	8.60	123.21
Heavy metals			
Iron	1.12	7.72	101.12
Manganese	0.41	0.41	0.41
Copper	0.41	0.41	0.41
Zinc	0.41	0.41	0.41

tube (26.5 cm long) with three perforated stainless steel laterals (30 cm in length and 0.6 cm in diameter) coming off it at right angles to the main. Tygon tubing of 0.75 cm outside diameter was used to connect the main air supply, manifold and aeration unit. The pressure regulator was adjusted at 0.068 atm during the whole experimental period to give an aeration rate of 7 cm^3 min^{-1}

Wetland plants: Two facultative (wool grass and soft rush) and two obligate (broad-leaved cattail and soft stem bulrush) wetland plant species were used in the study. The selection of these plants was based on their dominance in the constructed wetland[15]. Both soft rush and soft stem bulrush have been listed in many references as both obligate and facultative wetland plants. These wetland plants were obtained from Environmental Concern Inc., St. Michaels, Maryland, USA.

Contaminant preparation: The plants were supplied with nutrients using a fertilizer (20-20-20 Plant-Prod, Plant Products Co. Ltd., Brampton, Ontario) at a rate of 817 mg of fertilizer per 1 L of water. Ferrous ammonium sulfate ($Fe(NH_4)_2(SO_4)_2.6H_2O$) was used as a contaminant supply of Fe. This compound was purchased as a reagent grade chemical from Fisher Scientific, Ottawa, Ontario. Two Fe concentrations were selected: (a) one concentration to simulate Fe concentrations in the influent of a constructed wetland treating landfill leachate[16] and (b) the other concentration to represent the highest Fe tolerance concentration reported in the literature[17]. $Fe(NH_4)_2(SO_4)_2.6H_2O$ was dissolved in distilled water to achieve the appropriate contaminant level. A control with tap water was also used in the study. The final concentrations of Fe used in this experiment are presented in Table 1.

Experimental protocol: A 10 cm layer of large gravel (1.25 cm average nominal size) was placed in each compartment to facilitate the collection of drainage water. A 35.5 cm long drainage tube, with holes in the lower 10 cm end, was placed vertically in each compartment. The drainage tube was connected to a wet vacuum pump (Bulldog 700, Shop-Vac Canada Ltd., Burlington, Ontario) to ensure complete drainage of water before introducing the next batch of contaminated water. Soil was used as a supporting media for the plants. It was placed into each compartment in layers (approximately 10 cm thick) and lightly compacted to remove excessive voids within the soil structure. One box (three compartments) was used for each plant species. About 8 plants (20-30 cm tall) were placed in each of the three compartments in each box. The start up procedure for growing wetland plants in a closed system followed that described by Mills[14]. The water level in each compartment was maintained below the root system of the plants while keeping the soil around the root system moist at all times. The plants were sprayed with the insecticide Malathion 500EC (The Solaris Group, Mississauga, Ontario) every week to control the spread of aphids in the system. The dilution rate recommended by the manufacture was followed (2.5 mL of Malathion was mixed in 1 L of water). After the startup period of 4 weeks, the experiment was run for 72 days.

The first compartment in each box was used as a control and received 30 L of tap water containing fertilizer, the second compartment received 30 L of contaminated water containing fertilizer and a Fe concentration similar to that of the influent of the constructed wetland and the third compartment received 30 L of contaminated water containing fertilizer and a Fe concentration similar to that reported in the literature as the highest tolerance level for the four plants. The wastewater was changed every 9 days to simulate the retention time of the water in the constructed wetland[15].

Sampling and analyses: Plant samples were collected from all compartments at 9 day intervals and analyzed for Fe. The plant samples (root, stem, leaf, and flower) were dried in a convection oven for 24 h at 45°C. After drying, the plant samples were ground and digested with hydrochloric-nitric-hydrofluric-perchloric acids (30+10+10+5 mL g^{-1} sample) in a closed vessel at a temperature of 100°C. The Fe concentration was determined using an atomic absorption spectometer (Varion SpectrAA, Model Number: 55B, Varion, Mulgrave, Victoria, Australia).

Table 2: Concentration of Fe in plant tissues

		Concentration (mg kg^{-1})			
Time	Compartment	Bulrush	Wool grass	Soft rush	Cattail
0	Initial Fe	5504	1690	2883	401
9	Tolerance	10570	2832	4364	7110
	Wetland influent	7439	2348	3160	4070
	Control	5997	1672	3601	920
18	Tolerance	12000	3792	4596	8620
	Wetland influent	9210	2932	3680	5250
	Control	6316	1892	3255	1020
27	Tolerance	14431	5552	5693	11060
	Wetland influent	10266	3499	4640	6800
	Control	6556	2116	3321	1290
36	Tolerance	16562	6358	5949	12007
	Wetland influent	11746	4098	4411	7630
	Control	6697	2331	3773	1560
45	Tolerance	18344	7238	6050	15310
	Wetland influent	11476	4661	5002	8080
	Control	6837	2922	4459	2330
54	Tolerance	19395	8058	6513	16059
	Wetland influent	13608	5700	5137	9100
	Control	6978	3443	4127	2600
63	Tolerance	20280	9218	7158	16810
	Wetland influent	13541	6538	6275	9240
	Control	7085	3893	4324	2500
72	Tolerance	22798	10547	7686	19959
	Wetland influent	14356	7030	6232	10125
	Control	7302	4594	4566	3500

Fe concentration in the control compartment = 1.12 mg L^{-1}; Fe concentration in the wetland influent compartment = 7.72 mg L^{-1}; Fe concentration in the tolerance compartment = 101.12 mg L^{-1}

RESULTS AND DISCUSSION

Fe concentration in plants: Table 2 displays the average initial Fe concentrations in each species at the beginning of the experiment (t = 0) and the total amount of Fe accumulated by each species throughout the experiment. The results showed that as the initial concentration of Fe in the wastewater increased, the concentration of Fe in each species also increased. At the end of the experiment, the highest amount of Fe in the total plant tissues was in soft stem bulrush with concentrations of 22798, 14356 and 7302 mg kg^{-1} followed by broad-leaved cattail with concentrations of 19959, 10125 and 3500 mg kg^{-1}, wool grass with concentrations of 10547, 7030 and 4594 mg kg^{-1} and soft rush with concentrations of 7686, 6232 and 4566 mg kg^{-1} in the tolerance, wetland influent and control compartments, respectively.

Bernard[18] examined the heavy metal composition of *Typha glauca* growing in a constructed wetland for the treatment of landfill leachate in New York and found that the concentration of Fe in the plants ranged from 11037 to 19807 mg kg^{-1}. Surface *et al.*[19] investigated the heavy metal content of *Phragmites australis* from a constructed wetland for the treatment of landfill leachate and from an adjacent leachate seep and found that the average concentration of Fe in the total plant tissues were 4061.8 and 10193 mg kg^{-1}, respectively. Taylor and Crowder[20] studied the uptake of Fe by *Typha latifolia* from solution cultures and found that when supplied with 100 mg kg^{-1} of Fe, the plants accumulated an average of 7250 mg kg^{-1} of Fe in their tissues.

Kinetics of Fe uptake: The approach used in this study is based on a first order kinetic model and depends on the heavy metal concentration in the biomass of the plant. This method enables the evaluation of the specific metal uptake rate and the maximum specific content of the metal in the plant[21].

The uptake of dissolved Fe by an aquatic plant at given conditions (pH and temperature) can be expressed as a function of the maximum concentration of Fe that can be accumulated in the plant tissue and the specific uptake rate using the following first-order kinetic model[21]:

$$\frac{d(M_p)}{dt} = k \cdot (M_M - M_p) \qquad (1)$$

Where: M_p = Concentration of Fe in the wetland plant at a given time (mg kg^{-1})
M_I = Maximum concentration of Fe that can be accumulated in the wetland plant during a specific growth period (mg kg^{-1})
K = Specific Fe uptake rate (day)

Equation 1 shows that the higher the k-value the faster the Fe absorption by the plants. Equation 1 can be rearranged for integration using the limits $0 \rightarrow M_p$ and $0 \rightarrow t$ as follows:

$$\int_0^{M_p} \frac{d(M_p)}{M_I - M_p} = \int_0^t k.dt \qquad (2)$$

Where: t = time (d)

On integration, Eq. 2 can be written as follows:

$$\ln\left(\frac{M_I}{M_I - M_p}\right) = k \cdot t \qquad (3)$$

Equation 3 can also be written in a logarithmic form as follows:

$$2.3\ \log\left(\frac{M_I}{M_I - M_p}\right) = k \cdot t \qquad (4)$$

or

$$\log\left(\frac{M_I}{M_I - M_p}\right) = \frac{k\ t}{2.3} \qquad (5)$$

Equation 5 can then be transformed to the following equation:

$$\frac{M_I}{M_I - M_p} = 10^{\frac{k\,t}{2.3}} \qquad (6)$$

The concentration of Fe in the wetland influent was relatively constant over time. Therefore, the value of k was assumed to be constant. By substituting r for k/2.3, Eq. 6 can be rearranged as follows:

$$M_p = M_I\ (1\text{-}10^{-r\,t}) \qquad (7)$$

Equation 7 indicates that the concentration of Fe in the plant at any time is a function of the maximum concentration that can be accumulated in the plant and the specific uptake rate.

Determination of r and M_I: Two kinetic parameters (r and M_I) in Eq. 7 need to be determined for each plant. If the Fe concentration in the solution remains stable, which is the case of the constructed wetland, then r and M_I parameters for a wetland plant can be determined. Substituting M_1 for M_p/M_I in Eq. 7 yields the following equation:

$$M_1 = 1 - 10^{-r\,t} \qquad (8)$$

Equation 8 can also be rewritten in an exponential form as follows:

$$M_1 = 1 - e^{-2.3\,r\,t} \qquad (9)$$

Using Taylor series, a solution for Eq. 9 is as follows (Stroyan, 1999):

$$M_1 = (2.3\ r\ t)\ [1\text{-}½\,(2.3\ r\ t)\text{+}1/6\ (2.3\ r\ t)^2\text{-}1/24\ (2.3\ r\ t)^3\text{+}...] \qquad (10)$$

The Taylor series in Eq. 10 is similar to the following binomial series provided by Vlyssides *et al*.[22]:

$$M_2 = (2.3\ r\ t)\ [1 - ½\ (2.3\ r\ t) + 1/6\ (2.3\ r\ t)^2 - 1/21.6\ (2.3\ r\ t)^3 + ...] \quad (11)$$

The first three terms in the functions M_1 (Eq. 10) and M_2 (Eq. 11) are similar and the small residue of the rest of the terms will minimally affect M_1 and M_2. Equation 11 follows the following binomial series formula[23]:

$$(a+x)^n = a^n + n\,a^{n-1}\,x + \frac{n\,(n-1)}{2!}a^{n-2}x^2 + \frac{n\,(n-1)\,(n-2)}{3!}a^{n-3}x^3 + ... \quad (12)$$

In order to transform the right hand side of Equation 12 to M_2 series (Eq. 11), the following conditions were maintained:

$$x = \frac{2.3\ r\ t}{6}$$
$$a = 1$$
$$n = -3$$

Substituting for x, a, and n values in Eq. 12 and multiplying by (2.3 r t) yields the following equation:

$$(2.3\ r\ t)\left[1+\frac{2.3\ r\ t}{6}\right]^{-3} = (2.3\ r\ t)\left[1^{-3} + \left((-3)\left(1^{-3-1}\right)\left(\frac{2.3\ r\ t}{6}\right)\right) + \left(\left(\frac{-3(-3-1)}{2!}\right)\left(1^{-3-2}\right)\left(\frac{2.3\ r\ t}{6}\right)^2\right) + ...\right] \quad (13)$$

or

$$(2.3\ r\ t)\left[1+\frac{2.3\ r\ t}{6}\right]^{-3} = (2.3\ r\ t)\ [1 - ½\ (2.3\ r\ t) + 1/6\ (2.3\ r\ t)^2 - 1/21.6\ (2.3\ r\ t)^3 + ...] \quad (14)$$

Combining Eq. 11 and 14 can, therefore, yield the following equation:

$$M_2 = (2.3\ r\ t)\left[1+\frac{2.3\ r\ t}{6}\right]^{-3} \quad (15)$$

Since $M_1 = M_p/M_I$ (Eq. 7 and 8) and $M_1 = M_2$ (Eq. 10 and 11), then Eq. 15 can be rewritten as follows:

$$M_p = (2.3\ r\ t)\left[1+\frac{2.3\ r\ t}{6}\right]^{-3} M_I \quad (16)$$

The linear form for Equation 16 is as follows:

$$\left(\frac{t}{M_p}\right)^{1/3} = \frac{1}{(2.3\ r\ M_I)^{1/3}} + \frac{(2.3\ r)^{2/3}t}{6\ M_I^{1/3}} \quad (17)$$

Equation 17 has the following linear form:

$$Y = A + B \bullet X \quad (18)$$

Where:

$$Y = (t/M_p)^{1/3} \quad (19)$$

$$X = t \quad (20)$$

$$A = (2.3\ r\ M_I)^{-1/3} \quad (21)$$

$$B = \frac{(2.3\ r)^{2/3}}{6\ M_I^{1/3}} \quad (22)$$

The A and B values can be obtained graphically for various plant-metal combinations according to the procedure described by Vlyssides *et al.*[22] by plotting $(t/M_p)^{1/3}$ vs. t as shown in Fig. 2. The results are shown in Tables 3 and 4.

In order to determine r and M_I in Eq. 7, Equations 21 and 22 must be solved simultaneously. Equation 21 can be rearranged as follows:

$$r = \frac{1}{2.3\ A^3\ M_I} \quad (23)$$

Substituting Eq. 23 in Eq. 22 yields the following equation:

$$B = \frac{\left(\frac{2.3}{2.3\ A^3\ M_I}\right)^{2/3}}{6\ M_I^{1/3}} \quad (24)$$

Equation 24 can be rearranged as follows:

$$B = \frac{(A^{-3}\ M_I^{-1})^{2/3}}{6\ M_I^{1/3}} \quad (25)$$

or

$$B = \frac{1}{6\ A^2\ M_I} \quad (26)$$

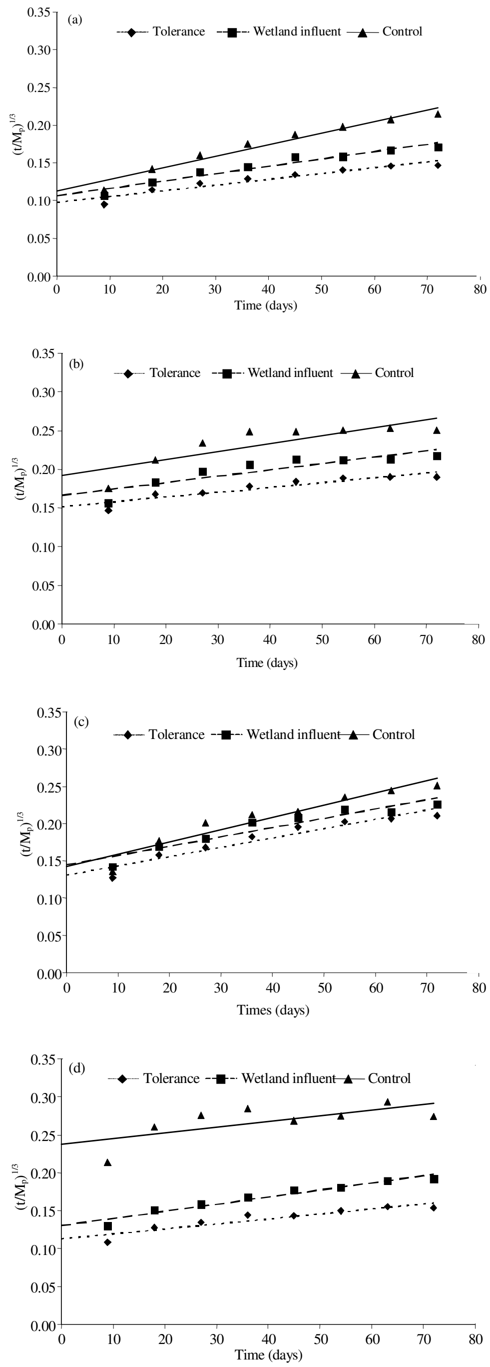

Fig. 2: Graphical determination of A and B for Fe in wetland plants, (a): Soft stem bulrush, (b): Wool grass, (c): Soft rush and (d): Cattail

or

$$M_I = \frac{1}{6\,A^2\,B} \tag{27}$$

Table 3: Values of A and B in Eq. 18

Plant	Concentration	A	B
Broad leaved cattail	Tolerance	0.1129	0.0007
	Wetland influent	0.1306	0.0009
	Control	0.2378	0.0007
Wool grass	Tolerance	0.1516	0.0006
	Wetland influent	0.1665	0.0008
	Control	0.1922	0.0010
Soft stem bulrush	Tolerance	0.0978	0.0008
	Wetland influent	0.1067	0.0010
	Control	0.1131	0.0015
Soft rush	Tolerance	0.1306	0.0012
	Wetland influent	0.1446	0.0012
	Control	0.1421	0.0017

Table 4.: Linear form of Eq. 18 for Fe uptake

Plant	Concentration	Equation	R^2
Broad leaved cattail	Tolerance	$(t/M_p)^{1/3} = 0.0007t+0.1129$	0.86
	Wetland influent	$(t/M_p)^{1/3} = 0.0009t+0.1306$	0.95
	Control	$(t/M_p)^{1/3} = 0.0007t+0.2378$	0.47
Wool grass	Tolerance	$(t/M_p)^{1/3} = 0.0006t+0.1516$	0.85
	Wetland influent	$(t/M_p)^{1/3} = 0.0008t+0.1665$	0.77
	Control	$(t/M_p)^{1/3} = 0.0010t+0.1922$	0.69
Soft stem bulrush	Tolerance	$(t/M_p)^{1/3} = 0.0008t+0.0978$	0.91
	Wetland influent	$(t/M_p)^{1/3} = 0.0010t+0.1067$	0.94
	Control	$(t/M_p)^{1/3} = 0.0015t+0.1131$	0.96
Soft rush	Tolerance	$(t/M_p)^{1/3} = 0.0012t+0.1306$	0.92
	Wetland influent	$(t/M_p)^{1/3} = 0.0012T+0.1446$	0.90
	Control	$(t/M_p)^{1/3} = 0.0017T+0.1421$	0.91

By substituting Eq. 27 in Eq. 23, the following equation is obtained:

$$r = \frac{1}{2.3\,A^3\left(\frac{1}{6\,A^2\,B}\right)} \tag{28}$$

Equation 28 can be rewritten as follows:

$$r = 2.61\frac{B}{A} \tag{29}$$

By substituting the value of k/2.3 for r in Eq. 29, the value of k can be determined as follows:

$$k = 4.3839\frac{B}{A} \tag{30}$$

Model results: Equations 27 and 30 were used to determine the maximum concentrations (M_I) of Fe that can be accumulated by the wetland plants and the specific uptake rates (k), respectively. The results are shown in Table 5. The results showed that the specific Fe uptake rate is affected by the initial Fe concentration in the wastewater as shown in Fig. 3. As the initial Fe concentration in the wastewater increased, the specific uptake rate for each species first increased and then

Table 5: Fe kinetic uptake parameters (k, M_I)

Plant	Concentration	k (d^{-1})	M_I (mg kg^{-1})
Broad-leaved cattail	Tolerance	0.0272	18679
	Wetland influent	0.0302	10857
	Control	0.0129	4210
Wool grass	Tolerance	0.0174	12086
	Wetland influent	0.0211	7515
	Control	0.0228	4512
Soft stem bulrush	Tolerance	0.0359	21781
	Wetland influent	0.0411	14639
	Control	0.0581	8686
Soft rush	Tolerance	0.0403	8143
	Wetland influent	0.0364	6642
	Control	0.0524	4855

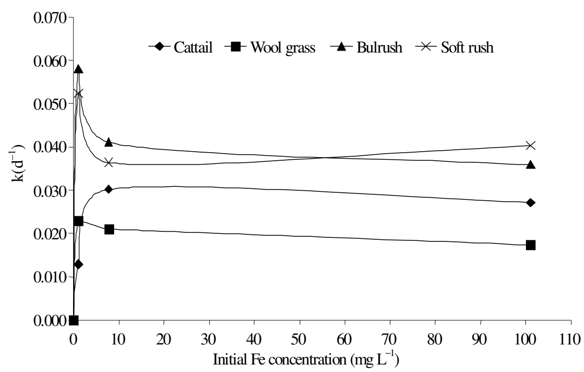

Fig. 3: Effect of initial Fe concentration in the wastewater on the specific uptake rate

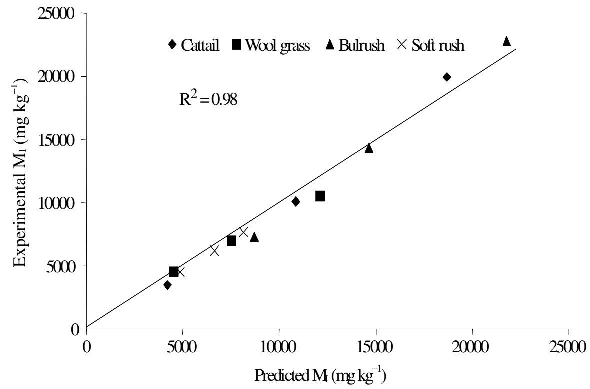

Fig. 4: Maximum predicted and experimental Fe concentrations

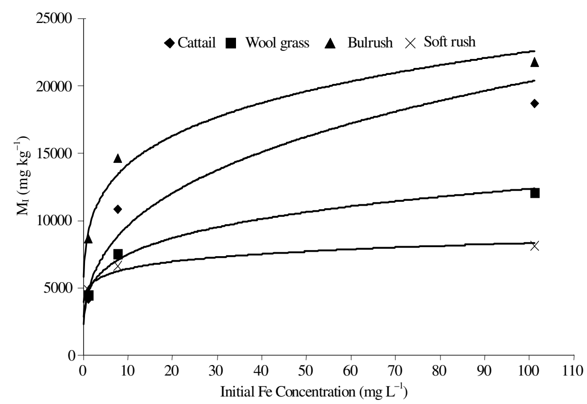

Fig. 5: Effect of initial Fe concentrations in the wastewater on the maximum Fe uptake

decreased with exception of broad-leaved cattail. Bulrush, wool grass and soft rush showed signs of toxicity as the k value of each plant decreased with Fe concentrations above 1.12 mg L^{-1}. Reported Fe concentrations for the occurrence of Fe toxicity vary widely between 1 to 1,000 mg Fe/L[24]. The specific Fe uptake rate for bulrush was the highest followed by soft rush, cattail and wool grass.

Jain *et al.*[25] investigated the uptake of Fe by duckweed and water velvet from heavy metal polluted waters with Fe concentrations ranging from 1.0 to 8.0 mg L^{-1} and found that the uptake rate of Fe by both plants was highest when the initial Fe concentration in the water was 1.0 mg L^{-1}. Similar toxicity effects of other heavy metals were reported by several researchers. Martins and Boaventura[26] determined that as the concentration of zinc in a synthetic solution increased from 1.05 to 3.80 mg L^{-1}, the uptake rate of zinc decreased from 145 to 59 h^{-1} in the aquatic moss *F. antipyretica*. The authors attributed the reduced metal uptake rate to a toxic effect on the plant. Goncalves and Boaventura[27] studied the uptake of copper by *F. antipyretica* and found that the uptake rate decreased from 846 to 628 h^{-1} as the concentration of copper in solution increased from 0.14 to 0.60 mg L^{-1}.

The model indicated that the maximum concentration of Fe (21781 mg kg^{-1}) that can be accumulated by the end of the experimental period was in soft stem bulrush (21781 mg kg^{-1}) followed by cattail with a concentration of 18679 mg kg^{-1}, wool grass with a concentration of 12086 mg kg^{-1} and soft rush with a concentration of 8143 mg kg^{-1}. The predicted maximum concentrations were plotted against the experimental maximum concentrations obtained at the end of the experiment as shown in Fig. 4. The results showed that the model is capable of predicting the experimental data with relatively high confidence ($R^2 = 0.98$).

The maximum concentration of Fe that can be accumulated in plants is also affected by the initial Fe concentration as shown in Fig. 5. As the initial Fe concentration in the wastewater increased, the total Fe concentration in each species increased. Jain et al.[25] showed that as the initial Fe concentration in the wastewater increased from 1.0 to 8.0 mg L^{-1}, the total Fe concentration in each species increased from 1221 to 6826 mg kg^{-1} and from 1363 to 9676 mg kg^{-1} for duckweed and water velvet after 14 days, respectively. Similar results were reported for other elements such as chromium, nickel and zinc. Maine *et al*.[28] showed that as the initial concentration of chromium in solution increased from 1 to 6 mg L^{-1}, the concentration in the aerial parts of *S. herzogii* and *P. stratiotes* increased from 0.0162±0.006 and 0.0114±0.002 mg g^{-1} to 0.448±0.019 and 0.269±0.026 mg g^{-1}, respectively. Ingole and Bhole[29] studied the uptake of heavy metals by water hyacinth and determined that as the concentration of nickel and zinc in solution increased from 5 to 25 mg L^{-1}, the metal concentration in the plant tissue increased from 0.2230 to 0.7530 mg g^{-1} and from 0.1830 to 1.1090 mg g^{-1}, respectively.

CONCLUSIONS

A first order kinetic model was used to describe the uptake of Fe by two facultative (wool grass and soft rush) and two obligate (soft stem bulrush and broad-leaved cattail) wetland plants. The results showed that the model is capable of predicting the experimental data with relatively high confidence ($R^2 = 0.98$). The results also showed that the specific Fe uptake rate and the maximum amount of Fe that can accumulate in each species were affected by the initial Fe concentration in the wastewater and the plant species. As the initial concentration of Fe in the water increased from 1.12-101.12 mg L^{-1}, the specific Fe uptake rate of each species decreased with the exception of broad-leaved cattail. Soft stem bulrush displayed the highest specific Fe uptake rates followed by soft rush, cattail and wool grass. The maximum amount of Fe that accumulated in each species increased as the initial Fe concentration in the water increased. According to the model results, soft stem bulrush plants growing in the compartment receiving wastewater with a concentration of 101.12 mg L^{-1} of Fe would accumulate the highest concentration of Fe in their tissues (21781 mg kg^{-1}) and cattail plants growing in the compartment receiving wastewater with a concentration of 1.12 mg L^{-1} of Fe would accumulate the lowest concentration of Fe in their tissues (4210 mg kg^{-1}).

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