Optimization of Piezoelectric Energy Harvesting System Using Split-Width Method

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Abstract—**In this paper, a novel method to optimize the harvesting of electrical energy from ambient vibration using piezoelectric, with high power density, is proposed. The piezoelectric in the form of a thin film is attached to a cantilever beam with similar dimensions. By folding equally and then splitting the piezo film with pre-defined dimensions, the width of each film reduces in which as a result reduces the damping of the system. Hence, the harvesting system becomes more efficient in converting ambient vibration into electricity. Experimental results show that the harvested electrical power increases with the increasing of folding number compared to the single piezo film with initial dimensions. The percentages of power increase for 1-fold and 2-folds are 145% and 176%, respectively. However, the splitting of the piezo material causes trade-off between the harvested power output with the effective bandwidth.**

Keywords-Piezoelectric harvesting system; ambient vibration; vibration-electricity converter

I. INTRODUCTION

Piezoelectric energy harvesting is one of the techniques to be used for renewing energy from surroundings. Similar to photovoltaic cells harvest electricity from sunlight and pyroelectric converts heat into electric energy, piezoelectric material is particularly good for renewing the wasteful ambient vibration into useful electricity. Due to its low output power density, many research efforts focused on optimization of the harvested energy. These included the studies of the physical properties of the piezoelectric material (such as length, thickness, piezo stress and strain constants) [1,2], the configurations of the piezoelectric transducer (unimorph, bimorph and multimorph) [3,4] and power conditioning circuits (such as DC-DC buck converter, synchronous charge extraction and SSHI techniques) [5,6,7,8]. However, the studies of the piezoelectric configurations and power conditioning circuits are the stage two and stage three optimization processes. The maximum energy can be harvested in these two stages is very much relied on the optimized output with the stage one optimization process, which is the study of the physical properties of the piezoelectric material. In order to increase the output energy in stage one process, the piezoelectric material needs to be longer in length, larger in thickness, higher in piezo stress and in strain constants. These give rise to the higher cost of material as well as the larger natural frequency of the setup. In this study, the effect on width-splitting for a fixed dimension piezoelectric material was modeled theoretically and investigated experimentally for increase of the output power. This researching work contributes to the present optimization studies of the piezoelectric energy harvesting with advantages of keeping the lowest costs, not much modifying the natural frequency and even direct use without conditioning circuit for some applications.

II. DESIGN AND THEORY OF OPERATION

A piezo bender consists of a layer of piezo film and a layer of host that they are bonded together. External stress to a piezo film in base vibration causes deflection and bending to the bender. The deflection distorts the internal dipole moments within the piezo film and generates electrical voltages. This results in the generation of charges on the film. From the theory of elasticity of a material, the relationship between the stress and strain of the piezo film [10] are

$$\sigma_{piezo} = Y_{piezo}\left(\varepsilon_{piezo} - g_{31}D_3\right), \tag{1}$$

$$E_3 = -g_{31}\sigma_{piezo} + \frac{D_3}{\varepsilon_r\varepsilon_0}, \tag{2}$$

where Y_{piezo} is the Young's Modulus of the piezo film, ε_{piezo} and σ_{piezo} are the strain and stress of the film respectively in x direction, g_{31} is the piezo stress constant, D_3 and E_3 are electric displacement and electric field strength in z direction, ε_0 and ε_r are the permittivity of the vacuum and the relative permittivity of the material, respectively, $\varepsilon_0 = 8.85\exp(-12)Fm^{-1}$.

The electric charge harvested on the piezo film due to an external force, F, can be obtained by integrating the electric displacement to its overlapping area. The harvesting of electric charge for the piezo film is expressed as [11]:

$$Q = \frac{-3AB(1-A+AB)g_{31}\varepsilon_r\varepsilon_0 L^2 F}{t_{bender}{}^2 k}, \tag{3}$$

This study was supported by the Ministry of Science, Technology and Innovation of Malaysia under ScienceFund No. 03-01-10-SF0144

where $h = 1 + A^4(1-B)^2 - 2A(2A^2 - 3A + 2)(1-B)$, (4)

$k = h(1 - A + AB)\left(1 + Y_{piezo} g_{31}{}^2 \varepsilon_r \varepsilon_0\right) - 39(1-A)A^2B^2 Y_{piezo} g_{31}{}^2 \varepsilon_0$, (5)

$A = \frac{t_{host}}{t_{bender}}$, (6)

is the ratio of the host thickness, t_{host}, to the respective bender thickness, t_{bender},

$B = \frac{Y_{host}}{Y_{piezo}}$, (7)

is the ratio of the Young's Modulus of the host, Y_{host}, to the Young's Modulus of the piezo film, Y_{piezo}, V is the external applied voltage to the piezo film, L and w_0 are the length and width of the piezo bender, respectively.

When the single piezo bender is split equally into two identical benders, it is referred as 1-fold (i.e. N = 1) to the bender. The further equal-splitting on each of the two identical benders is referred as 2-fold (N = 2). 0-fold (N = 0) refers to the single bender before any splitting. All these are illustrated in Figure 1.

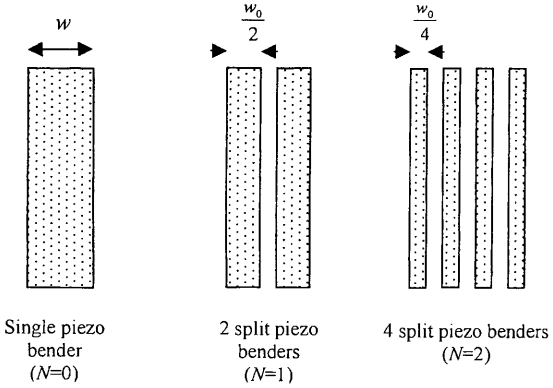

Figure 1. Piezo bender in 0-fold, 1-fold and 2-fold, respectively.

By connecting the split benders in parallel configuration, the electric charge harvested and the effective capacitance with N-fold to the single piezo bender can be summarized from (8) and derived, respectively, as

$Q_N = \frac{-3AB(2^N)(1-A+AB)g_{31}\varepsilon_r\varepsilon_0 L^2 F}{t_{bender}{}^2 k}$. (8)

$C_N = \frac{(1-A+AB)hw_0 L\varepsilon_r\varepsilon_0}{(1-A)t_{bender}\, k}$. (9)

The dynamic model of the piezo bender can be divided into mechanical and electrical models. For the mechanical model, the piezo bender can be modeled as a single degree of freedom system (SDOF), which consists of a equivalent spring constant, K, of the piezo bender, an equivalent mass, M, a dashpot with damping coefficient, C, and a vibrating base. The equivalent SDOF model is shown in Figure 2, where $d(t)$ is the vibrating base displacement and $x(t)$ is the equivalent mass displacement. $y(t)$ is the relative motion between the vibrating base and the equivalent mass, M.

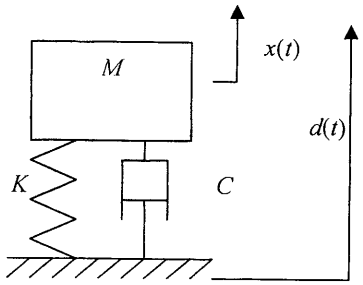

Figure 2 Equivalent SDOF model for the piezo bender with excitation at base.

When a sinusoidal input $d(t) = d_0 \sin(2\pi ft)$ is applied to the base excitation, the peak piezoelectric voltage generated with mechanical-electrical model can be obtained as

$V_N = \left(\frac{-3AB(2^N)(1-A+AB)g_{31}\varepsilon_r\varepsilon_0 d_0 L^2 K}{t_{bender}{}^2 k C_N}\right)\sqrt{\frac{(2\xi_N r)^2 + 1}{(2\xi_N r)^2 + (1-r^2)^2}}$, (10)

where $\xi = \sqrt{1 - \left(\frac{f_{damped}}{f_0}\right)^2}$ is the damping ratio, (11)

f_0 is the natural frequency, f_{damped} is damped natural frequency and $r = \frac{f}{f_0}$ is the ratio of the vibrating frequency to the natural frequency.

When an external resistive load is added to the output of the piezo benders in parallel with N-fold as shown in Figure 3, the load voltage can obtained from potential divider as

$V_{Load,N}(t) = \frac{R_{Load} V_N}{\sqrt{R_{Load}{}^2 + Z_p{}^2}} \sin(2\pi ft + \phi)$, (12)

where $\phi = \tan^{-1}\left(\frac{1}{2\pi f C_N R_{Load}}\right)$. (13)

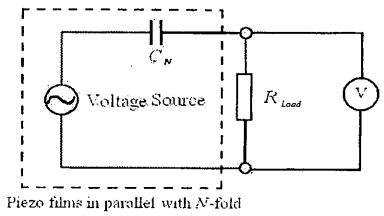

Figure 3. The piezoelectric circuit model connected with a load resistor.

The root-mean-square (rms) voltage across the resistive load can expressed as

$$V_{Load,N,rms} = \psi \sqrt{\frac{(2\xi_N r)^2 + 1}{\left(R_{Load}^{\ 2} + Z_p^{\ 2}\right)\left((2\xi_N r)^2 + (1-r^2)^2\right)}}, \qquad (14)$$

where $$\psi = \left(\frac{-3AB(2^N)(1-A+AB)g_{31}\varepsilon_r\varepsilon_0 L^2 K d_0 R_{Load}}{\sqrt{2}t_{bender}^{\ 2} k C_N} \right). \qquad (15)$$

The average power output in the resistive load is obtained as

$$P = \frac{V_{Load,N,rms}^{\ 2}}{R_{Load}}. \qquad (16)$$

III. SIMULATIONS AND EXPERIEMNTAL RESULTS

The theoretical model is verified as compared with experimental results. The prototype is built using the 52 μm piezo film from Measurement Specialties, Inc. (MSI) and the host material is polypropylene. The piezo stress constant, g_{31}, and the relative permittivity, ε_r, are given as 216 x 10^{-3} m^2C^{-1} and 13, respectively. The length and width of the single piezo bender are 45 *mm* X 20 *mm*, respectively. As a result, A (equation (6)) and B (equation (7)) are 0.704 and 0.3, respectively. The effective mass is 0.15 *g*. With this configuration, the single piezo bender will have its natural frequency of 27.2 *Hz*. A shaker powered by frequency generator is used in the experiment to provide base vibration to the piezo bender with vibration frequency, f, in the range of 21 *Hz* to 32 *Hz* and the base displacement, d_0, is set as 2.0 *mm*. Figure 4 shows the simulations (ξ = 0.38, 0.21 and 0.09 for N=0, 1 and 2, respectively) and experimental results for the piezo film(s) in 0-fold, 1-fold and 2-fold, respectively, when a 2 *MΩ* resistor is selected as a load. Table 1 summarizes the significant findings (such as resonant frequency, damping ratio, load power, percentage of power increase as well as the percentage of power increment from piezo film in 1-fold) from the experiment.

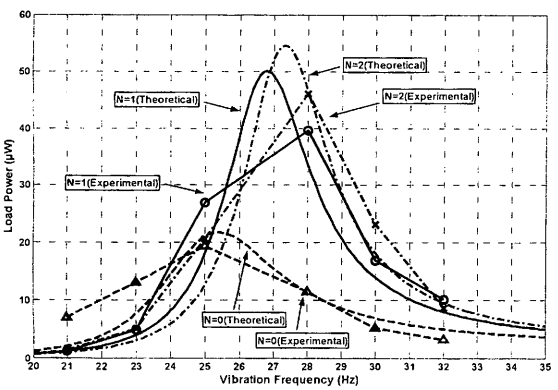

Figure 4. Comparison of simulation and experimental results.

Table 1. Summary of experimental results.

Number of Fold, N/ width of each split piezo film (total number of split piezo films)	Resonant frequency	Estimated damping ratio, ξ_N	$\frac{\xi_0}{\xi_N}$, where ξ_0 = 0.38	Output power to the external load of 2*MΩ*	Percentage of power increase from the piezo with N=0	Percentage of power increment from the piezo with N=1
N=0/ 20 *mm* (1)	25.1 *Hz*	0.38	$1 = 2^0$	19.2 μW		
N=1/ 10 *mm* (2)	26.6 *Hz*	0.21	$1.8 \approx 2^1$	47.0 μW	145%	
N=2/ 05 *mm* (4)	27.1 *Hz*	0.09	$4.2 \approx 2^2$	53.0 μW	176%	12.8%

From the ratio of $\frac{\xi_0}{\xi_N}$ as shown in Table I, it is found to be approximately equal to 2^N. Hence, the damping ratio with N-fold can be expressed as

$$\xi_N = \frac{\xi_0}{2^N}. \qquad (28)$$

When the width of the piezo film reduces, the natural frequency, f_0, of the overall vibrating system remains constant, however the variation of damped natural frequency, f_{damped}, from its natural frequency, f_0, decreases. This brings lower damping ratio, ξ, in the vibrating system and hence results in larger energy transfer to the piezo film for electric charge production. In parallel connection of the split piezo films, the combined capacitance remains the same but charge production increases. Therefore the open circuit voltage, V, and the load voltage, V_{Load}, increase accordingly.It is also noted that the piezo film in 0-fold has the widest 3dB bandwidth and that in 2-fold has the narrowest. However, the optimum power for the piezo film in 2-fold is the highest and that in 0-fold has the lowest

Table 2 summarizes the range of frequencies for half of the maximum power harvested (referred as 3dB bandwidth) from experiment with piezo films in 0-fold, 1-fold and 2-fold, respectively. The results show that the harvesting power increases but the 3dB bandwidth reduces as number of fold increases.

Table 2. Summary of experimental 3dB bandwidth.

Number of fold	Output power to the external load of 2 *MΩ*	Range of 3dB bandwidth	3dB bandwidth
N=0	19.2 μW	21.6 – 28.5 *Hz*	6.9 *Hz*
N=1	39.6 μW	24.2 – 29.8 *Hz*	5.6 *Hz*
N=2	46.1 μW	25.0 – 30.0 *Hz*	5.0 *Hz*

IV. CONCLUSION

When the number of fold increases, the width of each split piezo film reduces and results in lower damping effect. Hence more mechanical power is harvested into piezoelectric power with trade off with reducing 3dB bandwidth. Split-width method can be concluded as the better optimization method as compared with length and thickness optimization method with the benefits of high power density, lower cost as well as lower variation in natural frequency of the system.

Removal of Heavy Metals by Indigenous Aquatic Plants from Simulated Wastewater

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ABSTRACT

Phytoremediation, the use of plants for remediation soil and waters contaminated with heavy metals has gained acceptance in the past ten years as a cost effectiveness and non-invasive technology. The use of plants such as *E. crassipes* and *P. stratiotes* have been investigated in removal of various heavy metals in simulated wastewater. *E. crassipes* and *P. stratiotes* were found to grow well in UMS Lake water where it can live well within 2 months period in the subculture tanks. Therefore, UMS Lake water was used to simulate metals contaminated wastewater by adding 0.5 ppm concentration of Pb, Zn, Ni, Cd and Cr simultaneously. The results showed that both indigenous aquatic plants were able to remove all heavy metals from the simulated wastewater within 12 days period. The average removal efficiency for both plant species was 86%, 85%, 79%, 68% and 67% of Cd, Ni, Cr, Zn and Pb respectively. Results revealed *E. crassipes* as the most efficient plant for the removal of selected heavy metals compare to *P. stratiotes*. The highest removal metal was Ni (0.35 mgg^{-1}) and Cr (0.22 mgg^{-1}) in *E. crassipes* and *P. stratiotes* respectively. The range of metals removal are as descending order as Ni> Cd> Pb> Cr> Zn for *E. crassipes* and Cr> Cd> Zn> Ni> Pb for *P. stratiotes*. It has been observed that both indigenous aquatic plants were able to accumulate heavy metals 3 times higher (0.090 mgg^{-1}) than the initial concentration before (0.030 mgg^{-1}). Both species tend to accumulate all elements in roots compared to leaves and stalks, except for Ni in *E. crassipes* and Cr in *P. stratiotes*.

Keywords: indigenous aquatic plants, *E. crassipes* heavy metals distribution, *P. stratiotes*,

1. INTRODUCTION

Heavy metals, industrial pollutants, in contrast to organic materials cannot be degraded and therefore they accumulate in water, soil, sediment and living organisms. Water contamination with heavy metals is a very important problem in the current world. Occurrence of toxic metals in lakes, ponds, ditch and river water affect the lives of local people that depend upon these water sources for their daily requirements (Rai *et al.*, 2002). Currently, anthropogenic input of metals exceed natural input. High level of Cd, Cu, Pb, and Fe can act as ecological toxins in aquatic and terrestrial ecosystem (Guilizzon, 1991; Balsberg-Pahlsson, 1989).

These excess metal levels in surface water may pose a health risk to human and to the environment. Therefore the approach of phytoremediation is an innovative tool with greater potential to remove heavy metal pollutants in water bodies.

It has been known that aquatic plants such as water hyacinth (*E. crassipes*), pennywort (*Hydrocotyle umbellate*), and duckweed (*Lemna* sp.) are effective in single pond wastewater treatment (USEPA, 1998). These aquatic plants are known for accumulating metals from their environment (Outridge & Noller, 1991; Ali & Soltan, 1999). These plants can accumulate heavy metal 100,000 times greater than in the associated water (Mishra *et al.*, in press). Moreover it is a well known fact that most aquatic plants such as *Myriophyllum spicatum* L., and *Lemna minor* L., can accumulate metals that they take from the environment and concentrate them on the tropic chains level with accumulative effect (Outridge, 1991; Tremp & Kohler, 1995). According to Kovacs (1981) *Lemna minor* L., may accumulate considerable amount of heavy metals in their tissues ($10\text{-}10^{-6}$) times higher than those in nearby environment.

The use of plants or referred as aquatic macrophytes are plants that can grow in water or wet areas and quite diverse in ponds, ditch and lakes. Among these indigenous aquatic plants, *E. crassipes* and *P. stratiotes* are the most productive plants on earth; thus it is considered the world's worst aquatic weeds. (Charudattan, 1986). According to previous studies, *P. stratiotes* have been used for the removal of Cd, Cr and Pb from watercolumn (Nasu & Kugimoto, 1981). Scheinder (1995) reported that *E. crassipes* roots can accumulate several diavalent metal ions in the living plants. Furthermore, these indigenous aquatic plants are

easy to obtain in our environment and have high potential to absorb various heavy metals in different ways. The objective of this study is to compare the potential of *E. crassipes* and *P. stratiotes* in removing Pb, Zn, Ni, Cd and Cr at 0.5mgl^{-1} concentration added in simulated wastewater.

2. MATERIALS AND METHODS

2.1 Experimental set-up.

Continuous vertical-inlet flow (CVIF) reactor consisted of 4 glass tanks was set up vertically with the lowest glass tank (45 x 45 x 30 cm) containing a water pump to circulate the simulated wastewater continuously. The second (35 x 35 x 15 cm) and third (25 x 25 x 10 cm) tank was filled with *P. stratiotes* and *E. crassipes*. The fourth tank (11 x 11 x 13 cm) is the central outlet of the wastewater. The second, third and fourth tanks had protruding outlets on all sides which enable the water to circulate vertically. The experimental set up is shown on Figure 2.1

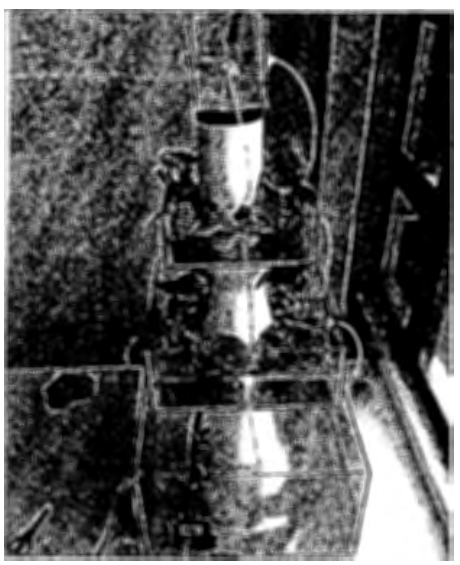


Figure 2.1 Experimental set up for removal of heavy metals by *P. stratiotes* and *E. crassipes* using CVIF Reactors

P. stratiotes and *E. crassipes* were obtained from a non-contaminated site and grown into aquaria filled with 40 L of water. The macrophytes were washed under running tap water to eliminate remaining debris. Five heavy metals Pb, Zn, Ni, Cd and Cr were added simultaneously as described by Miretzky (2004) in amounts which made their concentration in the CVIF as 0.5 mgl^{-1} respectively. Experimental plants were grown in duplicate as following;

Experiment I — *P. stratiotes* 50 g (fresh weight) plus *E. crassipes* 50 g (fresh weight) was grown in the second and third tank CVIF of 40L Lake UMS water. Heavy metal Pb, Zn, Ni, Cd and Cr was added simultaneously in the concentration 0.5 mgl^{-1}.

Experiment II — Plant control - *P. stratiotes* 50 g (fresh weight) plus *E. crassipes* 50 g (fresh weight) was grown in the second and third tank CVIF of 40L Lake UMS water. Plants was grown in 40L of water containing no metals.

2.2 Determination of Heavy Metals

2.2.1 Sampling and preparation of samples

(a) Simulated wastewater

Duplicates water samples (40ml) each from the reactor were take every day until 15 days experimental sets. The samples were filtered using 0.45um membrane filter (Whatman) and preserved at 4^{0}C.

(b) Aquatic Plants

Plant samples were collected and cleaned under running tap water and distilled water to remove debris from the roots and leaves. Then the plants were separated into roots, leaves and stalks before being dried at 60-75^{0}C to a constant weight and pulverized to facilitate wet digestion.

2.2.2 Digestion

2 g of dried aquatic plant samples was digested using the acid digestion process with 25 ml HNO_3 in *Kjeldahl* block digester at 120^{0}C for 2 hours. The liquid samples were filtered with 0.45um membrane filter (Whatman) and stored at 4^{0}C.

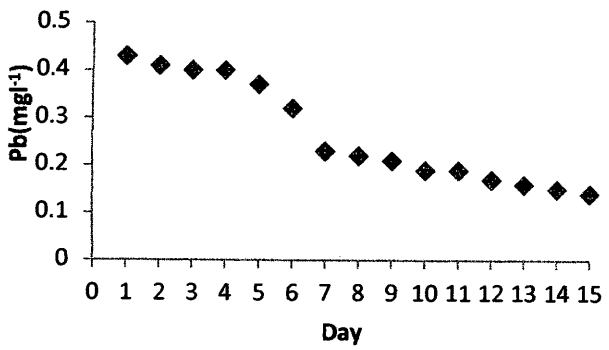
2.3 Determination of Heavy Metals Concentration

The concentrations of Pb, Zn, Ni, Cd and Cr in the simulated wastewater were determined before, during and after the experiments within 15 days periods. The plant samples (roots, leaves and stalks) were analyzed for heavy metals on two occasions, first on initiation date of removal experiment and second after 15 days removal experiment. All heavy metals were analyzed with Inductively Coupled Plasma Spectroscopy (ICP). Standard calibration curve for each metal was established to determine their concentrations.

3. RESULTS AND DISCUSSION

3.1 Heavy Metal Removal from Simulated Wastewater

Figure 3.1 (I-V) showed the removal profile of Pb, Zn, Ni, Cd and Cr in CVIF reactor within 15 days experimental set up. All metals are shown to have gradually decreased between 1st days of cultivation until 15 days experimental end except for Cr. Removal of Pb, Zn, Ni and Cd after 10 days cultivations were in the range of 56% - 68% as compared to Cr of 65% after 5 days cultivation.



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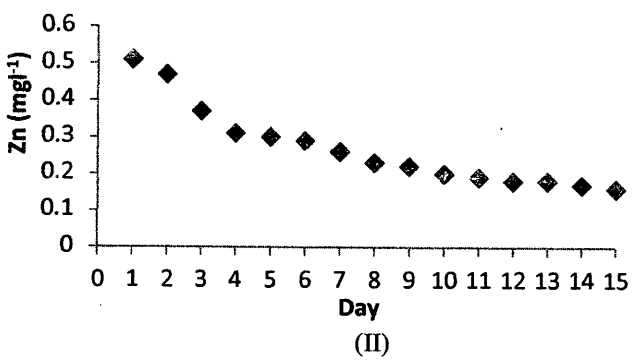

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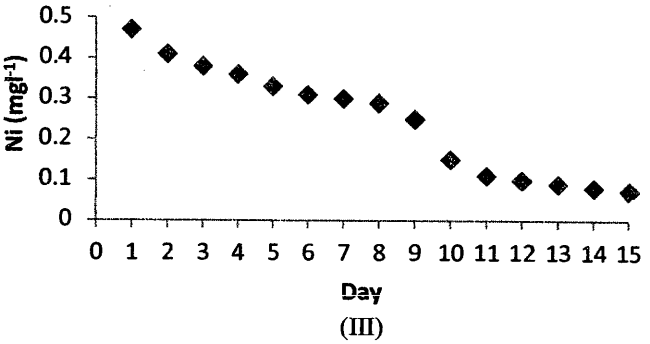

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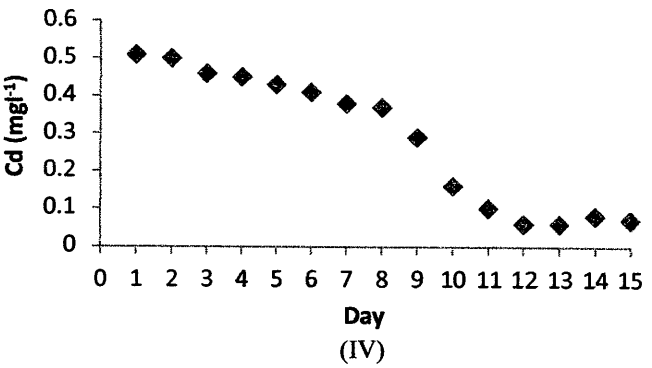

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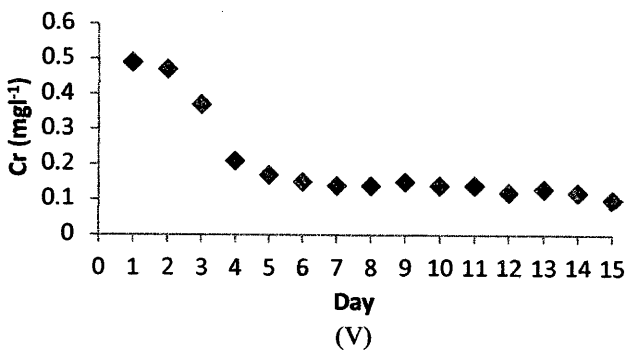

(V)

Figure 3.1 Removal profiles of heavy metals (mgl^{-1}) in simulated wastewater (I) Pb, (II) Zn, (III) Ni, (IV) Cd, (V) Cr at concentration of $0.5mgl^{-1}$ during 15 days cultivation of *P. stratiotes* and *E. crassipes*

Table 3.1 Removal efficiency of heavy metals from simulated wastewater after 15 days cultivation of *P. stratiotes* and *E. crassipes*

Metals	Initial concentration in simulated wastewater (mg/l)	Final concentration in simulated wastewater (mg/l)	Removal efficiency (%)
Pb	0.43	0.14	67
Zn	0.51	0.16	68
Ni	0.47	0.072	85
Cd	0.51	0.07	86
Cr	0.49	0.10	79

The percentages of metals removed by *P. stratiotes* and *E. crassipes* when the added metals concentration was 0.5mgl^{-1} were detailed in Table 3.1. Cd showed the highest percentage of removed heavy metal (86%) followed by Ni (85%), Cr (79%), Zn (68%) and Pb (67%). The final concentration of Cd in simulated wastewater was the lowest (0.07mgl^{-1}) compared to the other metals. Thus, these metals are believed to have been absorbed highly by both aquatic plants in CVIF reactor. On the contrary, Zn states the high value (0.16mgl^{-1}) by the end of 15 days cultivation. However, all metals have been removed by *P. stratiotes* and *E. crassipes* in different removal efficiency percentages. The total removal of all heavy metal in CVIF reactor was in the descending order with Cd> Ni> Cr> Zn> Pb.

3.2 Accumulation of heavy metals in both indigenous aquatic plants

Table 3.2 showed the initial and final concentration of heavy metals in three plants part (roots, leaves and stalks). A comparison between initial and final metal concentration within both plants had shown that the final concentration (0.09 mgg^{-1}) were more than 3 times the initial (0.03 mgg^{-1}) for *P. stratiotes* and *E. crassipes*. Total metals accumulated by *P. stratiotes* was in descending order Cr> Cd> Zn> Ni> Pb. However the metals accumulated in *E. crassipes* showed a different pattern where the highest metal accumulates was Ni followed by Cd, Pb, Cr and Zn.

High concentration of Ni in *E. crassipes* was probably because it is considered as essential micronutrients for plants growth (Gabbrielli, 1990) and it has been found to be distributed preferentially in the epidermal cells, most likely in the vacuoles rather in the cell wall (Kupper *et al.*, 2001). However this metal is regarded as poisonous at high level concentration > 10mg/kg dry weight (DW) in sensitive species (Kozlow, 2005) and >50 mg/kg DW in moderately tolerant species (Asher, 1991). Axtell (2003) reported that *E. crassipes* can accumulate Ni up to 80% higher than those of non-accumulators (Axtell, 2003). Our results agreed with their findings indicating that *E. crassipes* has a high tolerance of Ni and can be applied to remove heavy metals in our environment.

Table 3.2 Distribution of metals in *P. stratiotes* and *E. crassipes* after 15 days cultivation

Metals	*P. stratiotes*			
	Initial conc. (mgg^{-1})		Final conc. (mgg^{-1})	
	Roots	Leaves	Roots	Leaves
Pb	0.030	0.011	0.09	0.04
Zn	0.016	0.017	0.11	0.08
Ni	0.008	0.003	0.05	0.09
Cd	0.001	0.011	0.12	0.08
Cr	0.006	0.013	0.09	0.13

Metals	*E. crassipes*					
	Initial conc. (mgg^{-1})			Final conc. (mgg^{-1})		
	Roots	Leaves	Stalks	Roots	Leaves	Stalks
Pb	0.008	0.028	0.019	0.12	0.07	0.032
Zn	0.009	0.017	0.015	0.10	0.03	0.029
Ni	0.021	0.025	0.033	0.08	0.24	0.034
Cd	0.012	0.021	0.011	0.14	0.09	0.021
Cr	0.011	0.014	0.017	0.11	0.07	0.024

Analysis in Table 3.2 showed that *P. stratiotes* has a slightly different result where Cr was the most accumulated metals (0.22 mgg^{-1}) followed by Cd (0.20 mgg^{-1}), Zn (0.19 mgg^{-1}), Ni (0.14 mgg^{-1}) and Pb (0.13 mgg^{-1}) in both plant parts (roots and leaves). Cr is considered as non-essential micronutrient and has been reported to be one of the most toxic heavy metals present in wastewater (Rai *et al.*, 1995). It is reported to be toxic to most of the higher plants at 100 gkg^{-1} dry weight. Under present investigation, *P. stratiotes* showed highest accumulation of Cr in leaves as 0.13 mgg^{-1} followed by *E. crassipes* in roots as 0.11mgg^{-1}.

Heavy metals Cd was found to be higher in roots (0.12mgg^{-1} and 0.14mgg^{-1}) compared to the leaves and stalks of *E. crassipes* and *P. stratiotes*. These macrophytes have high biomass fibrous root and can absorb higher concentration of heavy metals. According to (William *et al.*, 2000) plants acquire essential metals

as micronutrients, but can also regulate their concentration and to prevent intoxication plants have a wide variety of metal influx as well as efflux transporters. Similar to the Pb and Zn were also more in roots for both indigenous aquatic plants. The accumulation of Pb in roots *E. crassipes* was higher with 0.12 mgg^{-1} compare to *P. stratiotes* 0.09mgg^{-1}. At the same time, Zn was found more in roots *P. stratiotes* with 0.11mgg^{-1}compared to *E. crassipes* 0.10mgg^{-1} (Figure 3.2).

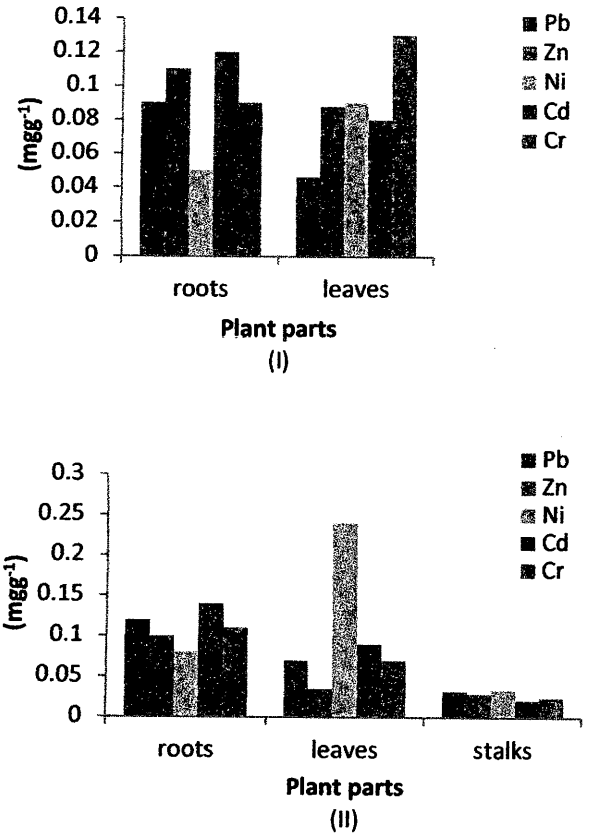

Figure 3.2 Distribution of Pb, Zn, Ni, Cd and Cr in *P. stratiotes* (I) and *E. crassipes* (II) after 15 days.

It is well reported that accumulation of metals in various parts of both indigenous aquatic plants is often accompanied by an induction of a variety of cellular changes, some of which directly contribute to metal tolerance capacity of the plants (Prasad *et al.*, 2001). The metal accumulation for *P. stratiotes* was in the descending order of Cr> Cd> Zn> Ni> Pb meanwhile for *E. crassipes* the metals were : Ni> Cd> Pb> Cr> Zn. Both species tend to accumulate all elements in roots compared to leaves and stalks, except for Ni in *E. crassipes* and Cr in *P. stratiotes* (Figure 3.2). Previous studies on the accumulation of various metal ions by aquatic plants have shown that the deposition of most metals was higher in roots than the other parts (Satyakala and Jamil, 1992; Zaranyikan and Ndapwadza, 1995; Chandra and Kulshreshtha, 2004). Our results are therefore in agreement with findings of these previous studies.

The difference in concentration and order of accumulated metals in each plant was probably influenced by the species of plants used. Gupta and Sinha (2007) reported that the process of metal uptakes and accumulation by different plants depend on the concentration of available metals in water, solubility sequences, and the plant species. However, the fact is both aquatic plants are known to have a great potential to accumulate heavy metals inside their plant body.

4.0 CONCLUSION

The results of this study showed that both indigenous aquatic plants investigated (*P. stratiotes* and *E. crassipes*) have the ability to remove heavy metals (Pb, Zn, Ni, Cd, and Cr) from simulated wastewater. The removal efficiency of heavy metals in simulated wastewater was 86%, 85%, 79%, 68% and 67% for Cd, Ni, Cr, Zn, and Pb respectively. The selectivity of heavy metals by *P. stratiotes* was in descending order Cr>Cd> Zn>Ni> Pb meanwhile for *E. crassipes* was found in descending order of Ni> Cd> Pb> Cr> Zn. It has been observed that the maximum quantity of element contaminant was contained in roots compared to leaves and stalks for both plants. The results revealed *E. crassipes* as the most efficient for the removal of selected metals compared to *P. stratiotes*. However it is believed that both of these plants can be employed to remediate either wastewater effluent streams or water bodies contaminated with heavy metals.

ACKNOWLEDGMENT

The study was supported by a grant (FRG0195-SG-1/2010) from the Ministry of Higher Education Malaysia.

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