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Assessment of duckweed (*Lemna gibba* L.) growth on dam water surface as green cost-effective process to improving water quality

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ABSTRACT

Using living plants such as duckweed to remove pollutants from water is a cost-effective green technology. In this work, we investigated the ability of *Lemna gibba* L. to enhance water quality of Aydoghmush dam located in Miyaneh, Iran as target. Some water quality indicators that are investigated include the following: content of nitrate, nitrite, and phosphate, chemical oxygen demand (COD), and biochemical oxygen demand (BOD). For this purpose, the pilot system was designed that consisted of five ponds. Three ponds as duckweed culture medium filled with raw water of the dam without any addition of duckweed nutrients (culture pond), one pond filled with raw water of the dam without duckweed (unplanted pond), and another pond was used as plant growth control pond that filled with distilled water (control pond). Approximately 50 g of fresh *L. gibba* were grown for 1 week in the pilot system and some operational parameters such as aeration, temperature, and pH on the plant growth, and consequently on indicators of water quality were investigated. The results showed that the amount of duckweed became 1.32 times in the culture pond but did not grow tangibly in the control pond, which indicated raw water of the dam can be a suitable culture medium for the duckweeds growth. According to the quality indicators, water quality of the dam improved by plant growth, thus suggest that *L. gibba* can be a suitable candidate to improving the quality of the dam water. Under experimental conditions, the contents of nitrite, nitrate, phosphate, COD, and BOD decreased by 55.03%, 45.45%, 46.16%, 62.06%, and 74.23%, respectively. Also, the removal ability of the used duckweeds that are dead (nonliving duckweeds) in high concentration of nitrate from the aqueous solution was examined. The highest removal degree was obtained at initial concentration of 25 mg L^{-1}, which was 93.60%. The experimental data that obtained at different initial concentrations were fitted by the pseudo-first-order rate model with R^2 higher than 0.99. The rate constants of biosorption process for nonliving duckweeds at different initial concentrations of 25, 50, and 75 mg L^{-1} were 0.0312, 0.0164, and 0.0119 min^{-1}, respectively.

Keywords: *Lemna gibba* L.; Phytoremediation; Biosorption; Water treatment; Aeration; Dam water; Nonliving duckweed; Miyaneh

1. Introduction

At the end of the 20th century, about 45 thousand large dams with a total reservoir surface of about 500 thousand km^2 have been exploited in the world, usually for irrigation, hydroelectricity, and as drinking water reservoir [1]. The use of dam water can be the most promising immediate and economical option for securing more water for agriculture sectors in Iran. For this reason, in recent years, many dams have been built in Iran (more than 300 dams in the four decades), especially in Miyaneh County. Dams can even serve for supplying freshwater resources, which contributing to the development of socioeconomic through supplying

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drinking water. So, at the present time, monitoring of water quality has become a major concern to determine current condition and long-term pattern for future management of dam water [2].

The quality of any body of surface or groundwater is a function of either or both natural influences and human activities [3]. River waters and consequently dam waters are being polluted by indiscriminate disposal of sewerage, industrial waste, and plethora of human activities, which affects their physicochemical characteristics and microbiological quality [3]. Therefore, quality of dam water should be monitored to ensure not any risk for human health and ecosystem.

In the literature, there are several methods for removal of various aquatic pollutants and treating surface water such as dam water. These general treatment methods may include: chemical process such as ozonation [4], advanced oxygen processes such as photocatalytic degradation [5] and Fenton-like degradation [6], physical process such as adsorption [7], and the use of biological processes [8].

These technologies offer several advantages such as flexibility in design and operation, huge treatment capacity, high removal efficiency, and fast kinetics but also showcases limitations, such as generation of toxic sludge or other by products, high operation and maintenance cost, and high energy requirements [9] as well as their suitable efficiency in removal of different types of pollutants only at low concentrations [10]. Therefore, there is an urgent need to adopt technology with optimum efficacy and low-capital investment and can be acceptable for wide range of contaminations.

Methods using living green plants such as duckweed for in situ, or in place, removal, degradation, or containment of contaminants in soils, sludge, sediments, surface water, and groundwater have been commonly called phytoremediation. Phytoremediation wetlands are claimed to be low-technology systems able to treat a variety of contaminated waters [11]. Duckweeds (*Lemnaceae*), as a group, are important early warning indicators for the assessment of contaminated ecosystems due to their propensity to accumulate pollutants [12].

Phytoremediation of contaminated water using duckweed species is promising due to its ability to grow at wide ranges of temperature, pH, and nutrient (N and P) level in areas where land is available for its application [13]. The efficiency of duckweed to treat drainage water [10], N- and P-rich water with NaCl concentrations [14], and water polluted with organic dye [15] was investigated. Nie et al. [16] reported the removal of uranium from aqueous solutions by *Spirodela punctata* (is a species of duckweed). The results presented *S. punctata* exhibited suitable potential for application in removal of uranium from aqueous solutions. In another research, the efficiency of duckweed (*Lemna gibba* L.) in wastewater treatment was also evaluated [17]. The results showed that total suspended solids, biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrate, ammonia, ortho-phosphate, Cu, Pb, Zn, and Cd decreased by 96.3%, 90.6%, 89.0%, 100%, 82.0%, 64.4%, 100%, 100%, 93.6%, and 66.7%, respectively. It is also reported that duckweed is able to remove La, Ce, and Y [18], Cr, Ni, and Co [19], uranium and thorium [20], Cu, Pb, Zn, and As [21], silver and gold [22], and arsenic, uranium, and boron [23] from water.

Therefore, the main objective of this research is presenting duckweed (*L. gibba*) growth on dam water surface as green cost-effective method in water treatment process.

2. Experimental

2.1. Materials

All used chemicals were obtained from Merck (Germany). Duckweed (*L. gibba*) was purchased from typical aquarium market in Miyaneh, then was cultured and used for batch experiments. The raw water of Aydoghmush dam was used for culture medium. Aydoghmush dam is an earthen dam that is located in the southwest Miyaneh, Iran. Results of the mean values of some physicochemical parameters determined in raw water of Aydoghmush dam are listed in Table 1. All experiments were repeated triple (the standard deviation (σ) values were calculated for all analyses). Physicochemical analyses were carried out according to standard methods for examination of water and wastewater [24].

2.2. Pilot system and phytoremediation/biosorption experiments

The pilot system was designed that consisted of five glassy ponds (the size of each pond was 40 × 60 × 40 (height) cm with 48 L of water) (Fig. 1(a)). Each five ponds were aerated with a multipore aeration system fitted at bottom of pond (100 mL min^{-1}). Three ponds (culture pond) as duckweed culture medium filled with raw water of Aydoghmush dam (Fig. 1(b)), in order to simultaneous three replications (water sampling period is: Jul 2017–Sep 2017) without any addition of duckweed nutrients, one pond (unplanted pond) filled with raw water of the dam without duckweed (to monitoring possible changes of the water quality due to other effective agents existing in the dam water), and another pond (control pond) was used as plant growth control pond that filled with distilled water. The walls of ponds were covered (Fig. 1(c)) to prevent light entering except at the top [25] and tow fluorescent lamps (36 W, Pars Co.) as artificial light at the top of each pond were also located (simulating natural climatic conditions). Temperature was maintained at 25°C, and 14 h of photoperiod was applied to duckweed. At first, approximately 50 g of wet (fresh) *L. gibba* (Fig. 2(a)) was grown for

Table 1
The mean values of some physicochemical parameters of raw water of Aydoghmush dam (water sampling period is: Jul 2017–Sep 2017)

Parameters	*T* (°C)		pH	DO(mg L^{-1})	Turbidity (NTU)	Organic (mg L^{-1})		Inorganic (mg L^{-1})		
	Air	Water				COD	BOD	Nitrate	Nitrite	Phosphate
Values	28	20	7.6	9.2	14.8	6.510	2.220	1.472	0.011	0.013

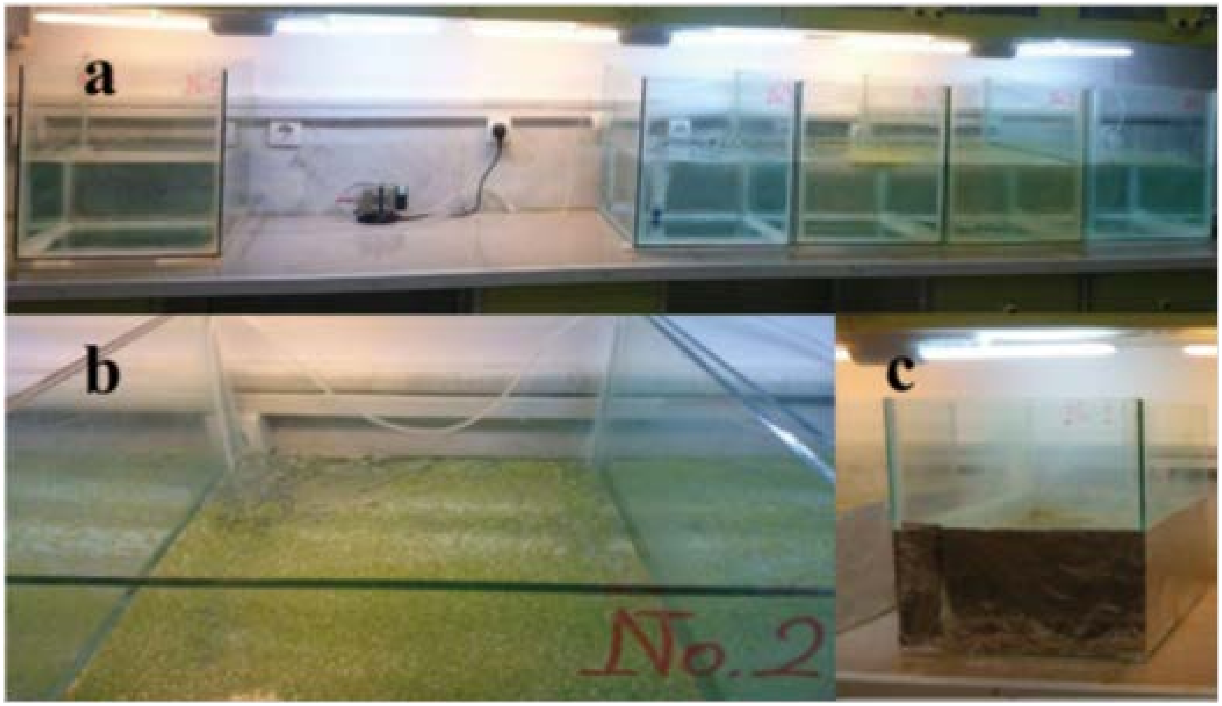

Fig. 1. The basic structure of the used pilot system (a), duckweed (*L. gibba*) inside the pond (b), and covered pond (c).

Fig. 2. The wet (fresh) (a) and senescent (died) duckweed (b).

1 week (the treatment duration was 7 d) in the culture and control ponds. Water samples were collected periodically, from the pilot system for the water quality analysis (water quality indicators include the following: content of nitrate, nitrite, and phosphate (as inorganic pollutants) and COD and BOD) (as organic pollutants). An important point that has not usually taken into account in other similar researches was the surface water evaporation that occurs over a period of treatment. In this work, the percentage of surface evaporation (EV%) was calculated using Eq. (1) and, by adding the

distilled water to the collected water samples, the error of the solution concentration was adjusted.

$$EV\% = \frac{V_0 - V_t}{V_0} \times 100 \quad (1)$$

where V_0 is the initial volume of water and Vt is the volume of water at time t.

Also, the removal degree (R%) was calculated at different time intervals using the Eq. (2) as follows:

$$R\% = \frac{C_0 - C_t}{C_0} \times 100 \quad (2)$$

where C_0 is the initial content of water quality indicator and C_t is the content of water quality indicator at time t.

According to the instruction given earlier, in testing the effect of one of the parameters, the others were kept constant under the basic conditions (aeration = 100 mL min^{-1}, temperature = 25°C and pH = 7.6).

2.3. Collection of senescent duckweeds

Under natural conditions (lack of sufficient nutrients), it is possible to see a mat of duckweeds, apparently wane and explode in growth patterns. Also, when a mature frond has produced its limit of daughter fronds, it ages (becomes senescent) and dies. Senescent duckweed fronds, like senescent leaves of other plants, appear yellow because they have lost chlorophyll. The senescent duckweeds were collected from the pond. They were cleaned with tap and distilled water, and dried at 90°C in a hot air oven for 1 h (Fig. 2(b)). The dried duckweeds were stored in a desiccator before use [15].

3. Results and discussion

3.1. Evaluation of water quality changes in ponds

The results showed that in the culture pond, the amount of duckweed became 1.32 times (by weight) but the plant has not grown tangibly in the control pond, which indicated that raw water of the dam can be a suitable culture medium for duckweeds growth (Fig. 3).

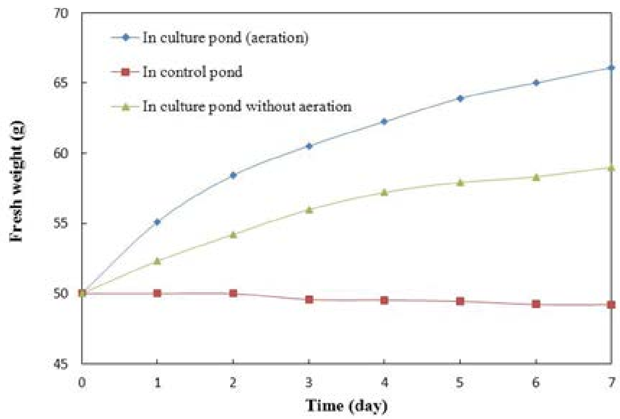

Fig. 3. The growth of duckweed in the culture (the raw water of dam) and control (distilled water) ponds.

The water quality of culture and unplanted ponds has changed, but the removal degree of nitrate, nitrite, phosphate, COD, and BOD was found higher in culture pond as compared with the unplanted pond (Table 2). In unplanted pond, these changes might be caused by the activity of the other factors, such as phytoplankton, existing in the water as following: (1) Aeration increases concentrations of dissolved oxygen (DO) and carbon in the algal culture media; two factors that are of primary importance for growth and physiology of phytoplankton, and prevents rising pH in the culture media [26]. (2) Aeration also facilitates mixing or turbulence of algal cultures, which prevents sedimentation of the cells and formation of nutritional and gaseous gradients, and therefore ensures that all cells are equally exposed to nutrients and light [27]. As the results given in Table 2, duckweed growth enhanced the removal degree of the investigated pollutants. It is found that duckweeds directly contribute to removal of pollutant through active uptake, which is strongly correlated with plant activity [28]. Also, in culture pond, the removal of organic pollutants indicators (COD and BOD) were found higher as compared with the inorganic indicators. The possible reason for higher reduction of BOD in the culture pond might be due to plant root system, which acts as suitable media for microbial growth providing oxygenic condition in the rhizosphere for microbial degradation of organic pollutants [29]. Also, higher decreases in nitrite content compared with nitrate might be due to oxidation of nitrite to nitrate by aeration.

3.2. The effect of some operational parameters on duckweed growth

3.2.1. Effect of aeration

Possible effects of aeration (and turbulence) on duckweed growth rate are not studied so far. For this purpose, the experiments were carried out with aeration (100 mL min^{-1}) and nonaeration and other parameters were kept under basic conditions (Fig. 3). The values of the water quality indicators for both are listed in Table 3. The results indicated that aeration enhanced growth rate of the plant and consequently, improves the water quality. This can be due to the following main reasons: (1) aeration provides oxygen for the duckweed fronds and prevents root fungal diseases (aeration had a significant impact on DO) [30], (2) aeration played a significant role in the removal of organic

Table 2
The values of the water quality indicators and removal degree (R%) of treated water in the culture and unplanted ponds

Pond	Inorganic (mg L^{-1})			Organic (mg L^{-1})	
	Nitrate	Nitrite	Phosphate	COD	BOD
Culture	0.662	0.006	0.007	2.47	0.572
σ	0.010	0.001	0.001	0.101	0.020
Unplanted	1.421	0.009	0.012	6.001	2.009
σ	0.010	0.001	0.002	0.021	0.011
Removal degree (R%)					
Culture	55.03	45.45	46.15	62.06	74.23
Unplanted	3.46	18.18	7.69	7.82	9.50

Table 3
The values of the water quality indicators and removal degree (R%) for the culture pond with aeration (100 mL min^{-1}) and nonaeration

Culture pond	The used water quality indicators (mg L^{-1})				
	Nitrate	Nitrite	Phosphate	COD	BOD
With aeration	0.662	0.006	0.007	2.47	0.572
σ	0.011	0.001	0.001	0.101	0.020
Without aeration	1.021	0.007	0.009	3.004	1.001
σ	0.011	0.001	0.002	0.113	0.013
Removal degree (R%)					
With aeration	55.03	45.45	46.15	62.06	74.23
Without aeration	31.32	26.36	29.23	53.86	58.42

(BOD_5, COD) and inorganic (nitrate and phosphate) pollutants by enhancing DO availability (DO provides favorable condition for nitrification, while denitrification occurs under anoxic conditions) [29], and (3) mixing (turbulence) would increase the mass transfer rates between the cells and culture medium for both nutrient uptake and exudation of metabolites [31]. Similar findings were also presented by Kumari and Tripathi [29] who reported higher removal of pollutants in units planted with aeration as compared to the nonaeration system.

3.2.2. Effect of temperature

Phytoremediation of contaminated water using duckweed species is promising due to its ability to grow at wide ranges of temperature [13]. Duckweed can grow at temperatures ranging from 5°C to 35°C with optimum growth between 20°C and 31°C depending on the specie [32].

To study the effect of temperature on the plant growth, the experiments were carried out with different temperatures varying from 15°C to 30°C and other parameters were kept under basic conditions (Fig. 4). The values of the water quality indicators for different temperatures are summarized in Table 4. As shown in Fig. 4, the growth rate increased with increasing temperature up to 25°C. The results also showed that the maximum and the minimum phytoremediation were obtained at 25°C and 15°C, respectively.

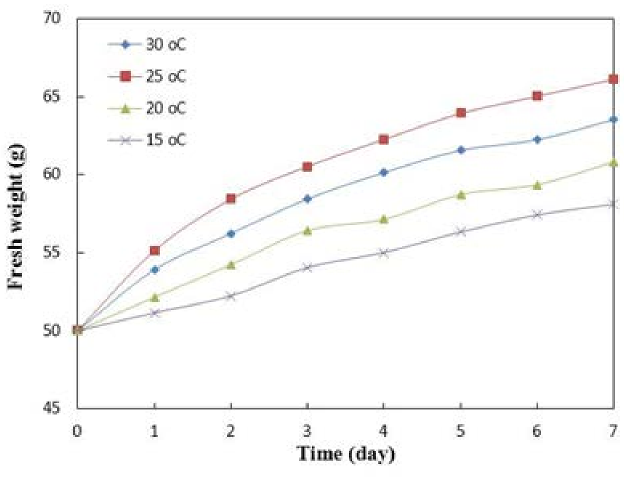

Fig. 4. The growth of duckweed at different temperatures in the culture pond.

Temperature might be effective on the plant growth for two main reasons: (1) Indirect effect (effect on content of DO). The DO values increase as temperature values decreases, revealing that the more cooler the water the more DO it can hold [17]. (2) Direct effect (temperature tolerance limit of duckweed). Temperature tolerance limit for duckweed growth is around 34°C [32]. Also, the plants show a slight decrease in growth below 10°C [17]. Lasfar et al. [33] reported that for temperatures lower than 10°C or higher than 35°C, duckweed growth is strongly inhibited. They concluded as the temperature increases to 26°C, the growth rate is increasing. Finally, according to the findings, it can be concluded that the temperature increasing has a positive effect on the duckweed growth rate and consequently on the water quality of the dam.

3.2.3. Effect of pH

In order to determine the effect of different initial pH values (5–8) on the plant growth and consequently on the water quality, the initial pH of pond water was adjusted by using HCl and NaOH solutions, and the change of pH was monitored daily. In the other hand, the effect of pH on phytoremediation process was studied in order to find out the optimum pH for the process, and to find out whether *L. gibba* was able to show a suitable efficiency in improving water quality of the dam at a wide range of pH values. According to the results, pH affected significantly on duckweed growth and consequently on the water quality. Similar to the previous results of this work, the removal degree of pollutants was also high wherever plant growth was high (Table 5). For example, Fig. 5 shows this trend for removal degree of nitrate at different pHs.

The reason for the significant decrease of the removal degree at acidic pH <6 might be because of strong acidic conditions lead to severe damages of the living duckweed [16]. The results of another research reported by Uysal [11] confirmed these results. This work showed that the maximum growth rate values of duckweed were obtained at pH values of 6.0.

Also, Khellaf and Zerdaoui [34] studied the effect of pH on phytoaccumulation of zinc using the duckweed (*L. gibba*). They reported low Zn accumulation in duckweed biomass

Table 4
The removal degree (R%) of some pollutants in the culture pond at different temperatures

T (°C)	Removal degree (R%)				
	Nitrate	Nitrite	Phosphate	COD	BOD
15	50.54	38.18	40.77	59.14	70.63
20	51.70	39.10	42.31	60.06	72.12
25	55.03	45.45	46.15	62.06	74.23
30	53.19	42.73	43.85	61.44	73.06

Table 5
The removal degree (R%) of some pollutants in the culture pond at different pHs

pH	Removal degree (R%)				
	Nitrate	Nitrite	Phosphate	COD	BOD
5	53.21	42.03	43.51	58.11	71.62
6	58.89	47.11	48.22	65.13	77.33
7	57.83	46.23	47.82	63.36	76.51
8	56.02	44.23	45.95	61.43	73.85

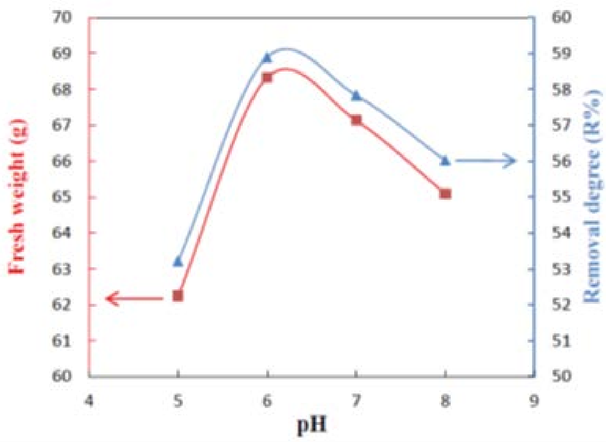

Fig. 5. The fresh weight of duckweed and the removal degree (R%) of nitrate in different pHs at the end of seventh day.

corresponding to a low plant growth was observed at pH 3 and 4 indicating that this species is not tolerant to water acidity.

3.3. *Nonliving (dried) duckweed application in removal of nitrate as target pollutant*

According to the results of the dam water analysis, the most probable water contamination of Miyaneh's Aydoghmush dam can be nitrate. Nitrate can stimulate eutrophication where pollution is caused in waterways by heavy algal growth, as they are both rate-limiting nutrients for the process [35]. Also, according to the results, the plant growth stopped after 2 weeks in the experimental condition. These nonliving duckweeds, besides other applications such as human food [36] and animal feeds [33], can be used again in water treatment. For this reason, the removal ability of nonliving (dead and dried) duckweed in high concentration of nitrate from the aqueous solution was tested. That way, 1 g of dried duckweed was added to 100 mL solutions of nitrate at concentrations of 25, 50, and 75 mg L^{-1} (T = 25°C, pH = 7, time 120 min, and shaking speed = 100 rpm). The removal degree of nitrate with dried duckweed at initial concentrations of 25, 50, and 75 mg L^{-1} was 93.60%, 39.54%, and 22.24%, respectively. Then, *qt* and *qm* were calculated at different time intervals (t = 0–120 min) and at the equilibrium time (>>120 min), respectively. By using the obtained data, kinetics of nitrate biosorption on dried duckweed was modeled by the pseudo-first-order Lagergren equation [15] that can be expressed as in Eq. (3) as follows:

$$\ln\left(q_e - q_t\right) = \ln q_e - k_1 t \quad (3)$$

where q_e and q_t are the amount of nitrate adsorbed on duckweed (both in mg g^{-1}) at equilibrium and time t, respectively; and k_1 is the rate constant. The rate constants (k_1) were calculated from the slopes of the linear plots of ln (q_e – q_t) versus t (Fig. 6). The results showed that the process followed the pseudo-first-order rate kinetics at different initial concentrations of nitrate with R^2 higher than 0.99 and the rate constants were significantly decreased at increasing the initial concentration of nitrate. Lagergren rate constants (k_1) values at initial concentrations of 25, 50, and 75 mg L^{-1} were 0.0312, 0.0164, and 0.0119 min^{-1}, respectively. The previous researches had similar findings. Waranusantigul et al. [15] studied the kinetics of basic dye (methylene blue) biosorption by giant duckweed. They reported that the process followed the first-order rate kinetics. Also, Allam et al. [10] studied the treatment of drainage water containing pharmaceuticals by active and inactive (dried) duckweeds (*L. gibba*). They concluded that the removal rate decreases with the increase in the initial concentrations of pollutants.

4. Conclusion

Removal of pollutants from water using aquatic plants especially, duckweed species is a cost-effective "green" technology on which many studies have been carried out. When considering the previous researches, it can be seen that many studies have not been conducted to simulate an in-situ dam water treatment system. Thus, the important differences of this study are following: (1) Carrying out in a pilot system with raw water of the dam (Aydoghmush) without any addition of duckweed nutrients in order to simulate an in-situ dam water treatment system. (2) Evaluating the effect of

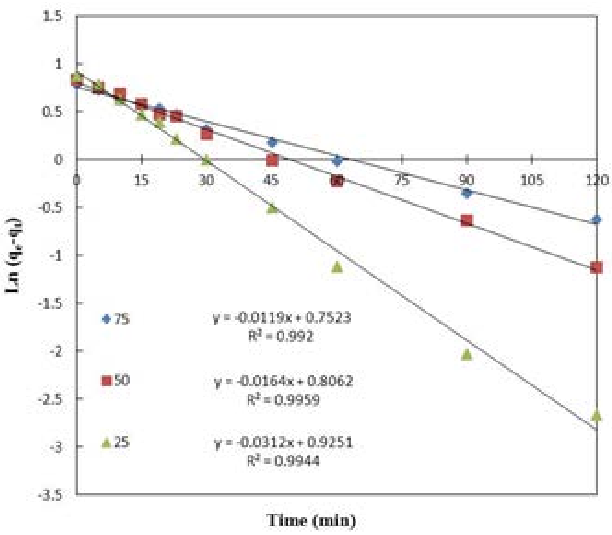

Fig. 6. Lagergren plots for biosorption of nitrate on dried duckweeds at different initial concentrations (25, 50, and 75 mg L^{-1}).

important parameters such as aeration on the duckweed growth and consequently water quality of raw samples. (3) Introducing the used duckweeds that are dead (senescent and nonliving duckweeds), besides other uses as effective biosorbent for removal of pollutants from aqueous solution such as nitrate. Finally, the results showed that duckweed (*L. gibba*) growth had a positive effect on the water quality of the dam and effectively eliminated organic and inorganic contaminants from the water. Duckweed growth on water surface of the dam decreased the amount of nitrate, nitrite, phosphate, COD, and BOD by 55.03%, 45.45%, 46.16%, 62.06%, and 74.23%, respectively. Aeration was an effective factor on the plant growth and the water quality indicators. Under experimental conditions, the optimal values of pH and temperature were 6 and 25°C, respectively. Nonliving duckweed was able to remove 93.60% nitrate from the aqueous solution in high concentrations (25 mg L^{-1}) and removal rate decreased with the increase in the initial concentrations of nitrate. The biosorption process followed pseudo-first-order kinetics model.

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