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An efficient sorbent for phosphate removal from wastewater: a new application of phosphate mine wastes from Ruseifa City—Jordan

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ABSTRACT

Jordanian phosphate mine wastes (PMW) at Ruseifa City was fully characterized and tested for its PO_4 removal capacity by batch experiments using prepared phosphate solutions and domestic wastewater. PMW particles are positively charged with median particle size of 0.625 μm. Mineralogical and chemical analyses of PMW showed that it is mainly composed of calcite, fluorapatite, and quartz with high concentrations of calcium and phosphorous. The phosphate concentrations in PMW range from 11 to 24% expressed as P_2O_5. PMW as a sorbent has a very high PO_4 removal efficiency from wastewater and prepared solutions. PO_4 solutions with concentrations ranging from 5 to 5,000 mg L^{-1} were prepared and utilized in batch experiments in the presence of PMW as a sorbent. The concentration of PO_4 in the solution phase and pH were the main parameters influencing the PMW sorption capacity of PO_4. The PO_4 removal efficiency from prepared solutions was up to 99%. Moreover, Langmuir sorption model was able to describe the observed data for PO_4 sorption by PMW. The sorption data at PO_4 concentrations >50 mg L^{-1} were highly fitted to Langmuir model. The estimated sorption maximum capacity ($b_{\max}$) of PMW was 46,620 mg kg^{-1}. On the other hand, domestic wastewater samples obtained from six Jordanian wastewater treatment plants were subjected to PO_4 removal by PMW, and the results showed that the PO_4 removal efficiency exceeded 97%. The adverse environmental impacts and human health risks associated with PMW presence are briefly discussed.

Keywords: Phosphate mine waste; Phosphate removal; Wastewater; Natural minerals; Sorption

1. Introduction

The natural water systems are often threatened by the domestic wastewater released unpurified into the environment. Phosphorous is an important element for all living organisms since it is an essential component of cell membranes [1]. In spite of this fact, phosphorous is considered as a problematic nutrient because it is an essential macronutrient and a general growth-limiting factor in surface waters that provokes

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eutrophication phenomenon [2,3]. Eutrophication involves a disturbance and an alteration in the balance of nutrients present in the water spurring excessive algae growth. Then, algae will consume water's oxygen and produce undesired alterations in the water populations [4–6]. Therefore, the removal of phosphorous from effluents prior to discharge could contribute in controlling of eutrophication.

Phosphorous in wastewater is present mostly in the form of inorganic phosphate, organic phosphate, oligophosphates, and polyphosphates [7].

Various techniques for the removal of phosphorous from wastewater have been proposed and investigated, such as biological processes [8–12], chemical precipitation [13–17], and adsorption methods [18–22]. Biological and chemical methods have some drawbacks; for instance, biological methods require anaerobic and aerobic conditions and strict and highly skilled control of the operation conditions [23]. Chemical precipitation requires a large amount of chemicals and produces as a consequence a great quantity of waste sludge [24]. In addition, these methods are expensive. In the last 15 years, a considerable number of effective and low-cost adsorbents were investigated for the removal of phosphorous from wastewater such as date palm fibers [25], wood particles [26], limestone [27], apatite [28], phosphate mine slimes [7], zeolite [29], and dolomite [30].

Jordan is the 6th largest phosphate producer in the world (up to 7 million tonnes a year). Enormous phosphate deposits occur in Jordan along a belt extending from north to south. Phosphate bearing deposits were discovered in Ruseifa in 1934 and the phosphate rock production commenced in 1935. Ruseifa mine has been dormant since 1985 due to the depletion of economically exploitable reserves. The mine activities in Ruseifa produced millions of tonnes of phosphate mine wastes (PMW) which in turn form an important potential source of environmental pollution in that region. Although some studies on recycling and utilization of PMW and their impact on environment have been carried out, none of these studies employed the Jordanian PMW especially in Ruseifa City. Al-Hwaiti et al. [31] investigated the potentially toxic elements in the phosphorites from Shidiya mine (southeast Jordan), but they did not employ the PMW in their investigations. Silva et al. [32] studied the potential implications of heavy elements in the phosphorites from Kalaat Khasba mine (northwestern Tunisia). Gnandi et al. [33] investigated the impact of phosphate mine tailings on the bioaccumulation of heavy metals in marine fish and crustaceans from the coastal zone of Togo.

Jordan is located in an arid to semiarid region and is one of the most water scarce countries in the world. National consumption of water has increased by almost 50% over the 20-year period 1985–2005, and a rising population has nearly tripled municipal water consumption. The estimated water amount for agriculture until 2020 is approximately 70% of annual Jordanian water use, and domestic water demand increases with the growth of the Jordanian population and economy [34–36]. Converting wastewater to usable irrigation water can release the pressure on other traditional sources of water and provide a new source of water for agriculture. Treated wastewater in Jordan contains high concentration of phosphorous which contributes to eutrophication phenomena in dams. Therefore, it is essential to remove phosphorous from treated wastewater before it is released into rivers and dams for agricultural applications.

From the extensive literature survey and according to the best of our knowledge, no research work has been performed or reported to characterize and investigate the potential utility of Jordanian PMW for the treatment of urban or industrial wastewaters in general and for phosphate removal in particular. This encouraged us to enter into an experimental investigation of the utility of PMW from Ruseifa City–Jordan as a sorbent for the removal of phosphorous from wastewater, as well as the characterization of PMW which has never been reported before to the best of our knowledge.

2. Experimental methods

All chemicals and solvents were reagent grade. Potassium dihydrogen orthophosphate (99%, GCC) and calcium nitrate tetrahydrate (99%, fine-chem limited) were used as received without further purification.

2.1. Sampling, preparation, and characterization of sorbent

The sorbent utilized was obtained from the PMW of Ruseifa phosphate mine, located at about 16 km north of the capital Amman. The estimated amount of PMW is around 5–6 million tonnes. Representative samples were collected from 32 sites taking into considerations their GPS coordinates. All samples were air-dried, homogenized, and grounded utilizing vibrating cup mill with FRITSCH model PULVERISETTE 9. The produced powder was passed through sieve of 45 μm. Two hundred grams of each sample representing the 32 sites was taken and mixed thoroughly to produce a combined sample with weight of 6,400 g. This combined sample is a representative sample of the whole PMW in Ruseifa phosphate mine. All samples including the combined sample were characterized and analyzed by wavelength dispersive X-ray fluorescence (WD-XRF) with Shimadzu model XRF-1800, powder X-ray diffraction (PXRD) with Shimadzu model XRD-6000, inductively coupled plasma-optical emission spectroscopy (ICP-OES) with Shimadzu model ICP-7510, atomic absorption spectrometer (AAS) with Shimadzu model AA-6300, and by wet analytical methods of the Association of Fertilizer and Phosphate Chemists (AFPC) [37].

P_2O_5, SiO_2, and CaO were determined by WD-XRF, Fe_2O_3 and Al_2O_3 were determined by AAS, and MgO was determined by ICP-OES, whereas SO_4 and Cl were determined by wet analytical methods of AFPC.

2.2. Determination of heavy metal leaching

Two experiments were performed to determine direct bioavailable heavy metals and the total heavy metals of PMW.

2.2.1. Direct bioavailable heavy metals

Hundred milliliter of 0.01 M $Ca(NO_3)_2$ was added to 10 g of PMW sample. Suspension was shaken for 24 h on a horizontal shaker. After that, the samples were centrifuged for 5 min at 4,000 rpm. The supernatant was passed through filter paper and stored in plastic bottles. Concentrations of leached heavy metals were determined by AAS.

2.2.2. Total heavy metals

Five grams of PMW sample was digested in 70 mL of (3:1, HNO_3:HCl) for 45 min. Then, the sample was filtered and the volume of filtrate was made to 100 mL. Concentrations of heavy metals were determined by AAS.

2.3. Sorption experiment for prepared phosphate solutions

Thirteen phosphate solutions with concentrations ranging from 5 to 5,000 mg L^{-1} were prepared from potassium dihydrogen phosphate (KH_2PO_4) and used in sorption tests. Sorption experiments were carried out by adding 10 g of PMW to 100 mL of each PO_4 solutions whose concentrations were 5, 15, 30, 50, 100, 250, 500, 750, 1,000, 2,000, 3,000, 4,000, or 5,000 mg L^{-1}. Sorption experiments were performed in the absence and presence of background electrolyte 0.01 M $Ca(NO_3)_2$. The samples were shaken for 24 h on a horizontal shaker at 180 rpm at room temperature (20 ± 2°C). Afterward, the samples were centrifuged at 4,000 rpm for 5 min. A 50 mL aliquot of the supernatant was taken and 10 mL of vanadium molybdate reagent was added. The aliquot sample was left for 10 min. Consequently, PO_4 sorption phase concentrations were determined by using a UV–vis spectrophotometer (Thermo Spectronic Helios Gama) at wavelengths of 400 or 470 nm. Sorbed phase concentrations were calculated from the mass balance. After converting measured solution and sorbed phase concentrations to logarithms, the log-transformed Freundlich equation was fitted to the measured data [38,39]:

$$\log S = m \log C + \log k_F \tag{1}$$

where S (mg kg^{-1}) is the sorbed phase concentration, C (mg L^{-1}) is the concentration of dissolved chemical, k_F stands for the Freundlich coefficient (mg^{1-m} Lm kg^{-1}), and m denotes the Freundlich exponent (>1).

The Langmuir equation was fitted to the measured data [40,41]:

$$C/S = 1/(k_L \cdot b_{max}) + (1/b_{max})\ C \quad \text{(Linear equation)} \tag{2}$$

where S (mg kg^{-1}) is the sorbed phase concentration, C is equilibrium concentration (mg L^{-1}), b_{max} is Langmuir adsorption maxima (mg kg^{-1}), and k is the Langmuir bonding energy constant (L mg^{-1}). A plot of C/S vs. C gives a straight line. Constants k_L and b_{max} were obtained from the intercept and slope, respectively.

2.4. Sorption experiment for wastewater samples

Samples of wastewater with PO_4 concentrations ranging from 15 to 77 mg L^{-1} were obtained from six Jordanian wastewater treatment plants. Hundred milliliters of each wastewater samples (15.0, 16.7, 36.8, 50.7, 59.4, or 76.9 mg L^{-1}) was mixed with 0.5 g charcoal for 3 min and filtrated, and the pH of filtrate was adjusted to 7.0. Then, 2.0 g of PMW was added to filtrate and the mixture was shaken for 24 h on a horizontal shaker at 180 rpm at room temperature (20 ± 2°C). Afterward, the samples were centrifuged at 4,000 rpm for 5 min. A 50 mL aliquot of the supernatant was taken and 10 mL of vanadium molybdate reagent was added. The aliquot sample was left for 10 min. Consequently, PO_4 sorption phase concentrations were determined by UV–vis spectrophotometer.

2.5. Particle size analysis and zeta potential measurements

A laser diffractometer (Microtrac Zetatrac, Microtrac S 3000/S 3500 series Particle Size Analyzer, USA) was used to measure the size distribution of PMW particles. The zeta potential was determined by an electroacoustic method using an acoustic and electroacoustic spectrometer. The surface charge (Q) of PMW particles was characterized by a zeta potential (ζ) measurement. Zeta potential is a measure of the electrostatic potential generated by accumulation of ions that are organized into an electrical double-layer at the surface of a particle [42]. The zeta potential determines the colloidal stability [39,43], as given in the following equation:

$$Q = 4\pi\varepsilon\varepsilon 0\zeta r(1 + \kappa r) \qquad (3)$$

where ε is the relative dielectric constant of medium, $\varepsilon 0$ is the dielectric constant of vacuum, and κr is the electrokinetic radius.

3. Results and discussion

3.1. PMW characterization

PMW was grounded utilizing vibrating cup mill producing homogenized submicron powder. The particle size of PMW was determined by a particle size analyzer (laser diffractometer). The particle size distribution was found to be in the range of 0.28–1.15 μm, with median particle size of 0.625 μm (Fig. 1(A)). Our PMW particles are positively charged that could attract negatively charged ions such as PO_4 and trap them in their porous structure. According to the classification scheme of reference [44], the stability of the PMW particles is low at pH 7 since the zeta potential is 13 mV and the electrical conductivity is 1.297 μS cm^{-1}. Mineralogical analysis by PXRD (Fig. 1(B)) showed that our PMW is mainly composed of calcite, fluorapatite, and quartz. Chemical composition analysis of the PMW shown in Table 1 indicates that calcium, phosphorous, silicon, and oxygen are the main constituents of the PMW. The phosphate concentrations in our PMW range from 11 to 24% expressed as P_2O_5 (Fig. 2). Other components with concentration less than 2% are also present including aluminum, iron, magnesium, sulfur, and chloride. Our results indicate that the Jordanian PMW are chemically different from those from other countries [7] which in turn led to different results in the context of wastewater treatment.

It should be pointed out that sample 33 was prepared by combining homogeneous and equal amount of each sample; hence, it represents the 32 sites. Therefore, it has been used in all of our sorption studies.

3.2. Results of sorption batch experiments

3.2.1. Sorption efficiency

To investigate the ability of PMW to remove PO_4 from wastewater, sorption batch experiments were carried out using various PO_4 concentrations in the absence and presence of 0.01 M $Ca(NO_3)_2$ as a background electrolyte. Thirteen PO_4 solutions with concentrations ranging from 5 to 5,000 mg L^{-1} were utilized in our experiments. Table 2 shows the concentrations utilized as well as the efficiency of PMW as a sorbent in the absence and presence of 0.01 M $Ca(NO_3)_2$. The sorption efficiency and sorption capacity of PMW were calculated using the following equations:

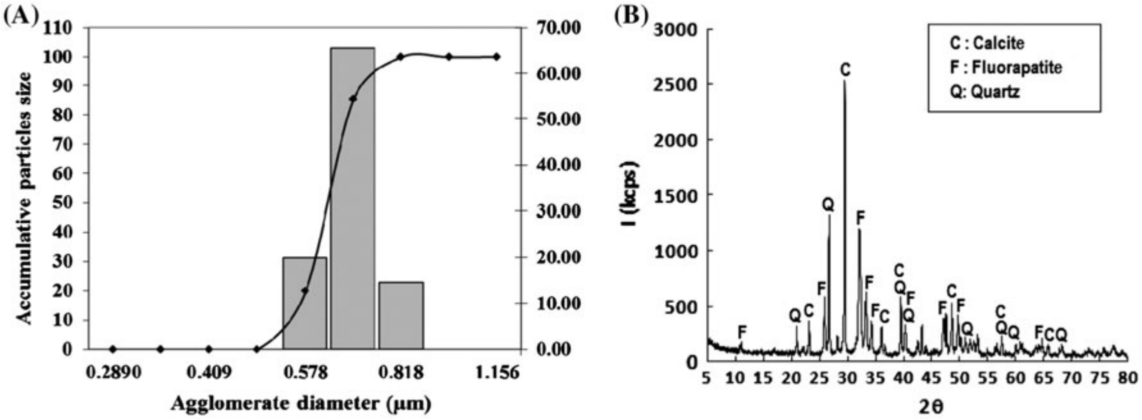

Fig. 1. Characterization of the used PMW. (A) Particle size distribution and (B) powder diffraction XRD.

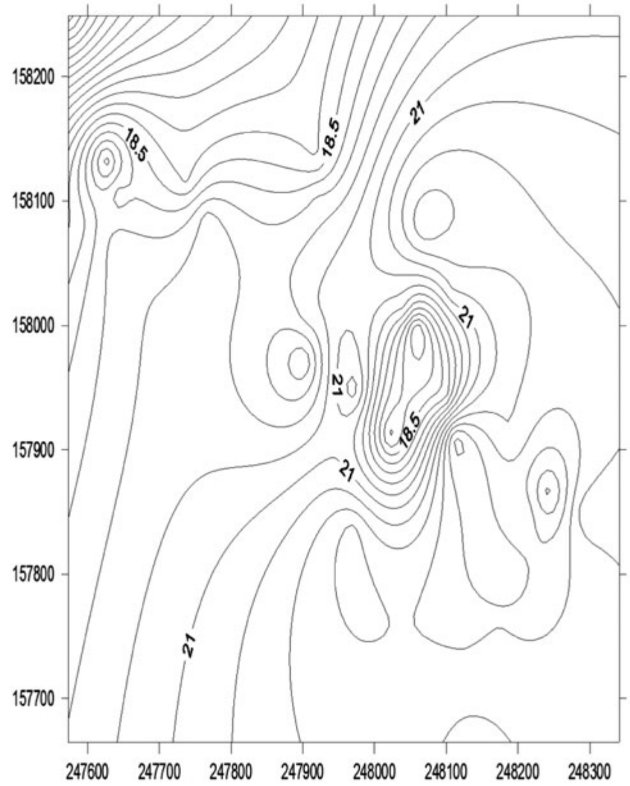

Fig. 2. P_2O_5 distribution vs. the GPS coordinates of the used PMW from Ruseifa mine site.

$$\text{Sorption efficiency} = [(C_\text{i} - C_\text{f})/C_\text{i}] \times 100\% \quad (4)$$

$$\text{Sorption capacity} = [(C_\text{i} - C_\text{f})V_\text{f}]/\text{W} \quad (5)$$

where C_i (mg L^{-1}) is the initial concentration of PO_4 before sorption, C_f (mg L^{-1}) is the final concentration of PO_4 after sorption, V_f (in L) is the final volume of the mixture consisting of phosphate solution and dry PMW, and W is the weight of dry PMW (in kg).

It can be seen from Table 2 that the sorption efficiency and capacity of PMW are up to 99% and 46,356 mg Kg^{-1}, respectively. In our experiments, $Ca(NO_3)_2$ was used as a background electrolyte to mimic the wastewater environmental conditions. In addition, Table 2 reveals that the presence of Ca^{2+} in the PO_4 solutions ranging from 5 to 1,000 mg L^{-1} has no observable effect on the sorption efficiency. But starting from 2,000 mg L^{-1} PO_4, it seems that the presence of Ca^{2+} enhances the removal of PO_4 from the solution. This can be seen clearly by the depression in the sorption efficiency down to 83% at concentrations ranging from 2,000 to 5,000 mg L^{-1} in the absence of Ca^{2+}. We propose that the enhancement of PO_4 removal in the presence of Ca^{2+} at high concentrations of PO_4 can be attributed to the fact that unsorbed PO_4 can precipitate in the form of $Ca_3(PO_4)_2$.

Next, we investigated the sorption efficiency of PMW utilizing wastewater samples obtained from six wastewater treatment plants located in Jordan. The concentrations of PO_4 in these wastewater samples ranged from 15 to 77 mg L^{-1}. Jellali et al. [7] reported that the phosphate removal efficiency from prepared solutions exceeded 94%, while the use of secondary treated wastewater in their studies decreased this removal efficiency due to anion competition phenomenon with probably chloride and sulfate anions. In our study, the use of secondary treated wastewater did not affect the phosphate removal efficiency of our PMW. This can be revealed from the results summarized in Table 3 which shows that the phosphate removal efficiency from secondary treated wastewater exceeds 97% reaching up to 99% and this is comparable and in agreement with the results shown in Table 2.

The sorption efficiency results summarized in Tables 2 and 3 reveal that PMW can be considered as promising and efficient material for the removal of phosphate from both wastewater and aqueous solutions.

3.2.2. Sorption isotherms

The sorption capacity results of PMW summarized in Table 2 reveal that the PO_4 uptake increases as the initial concentration increases. This finding could be attributed to the fact that as the initial concentration increases, the rate of diffusion gets higher since the contact probability between PO_4 species and the sorbent might be more privileged in high concentrations.

The PO_4 sorption isotherm depicting the relationship between PO_4 sorbed (S) and equilibrium solution concentration (C) for the PMW under investigation is given in Fig. 3(A).

The sorption isotherm reaches Plateau with increasing phosphate concentration. This could be attributed to that the adsorbent sites become covered.

The sorption isotherm of PO_4 of PMW can be classified as *L type*. Giles et al. [41] classify adsorption isotherms into four types *L*, *S*, *C*, and *H*. McBride [45] describes the *L type* (Langmuir) isotherm as one that is usually indicative of chemisorption, the *S type* suggests cooperative adsorption, the *C type* suggests constant portioning, and the *H type* also indicates chemisorption.

In addition, the log–log scale isotherm was fitted to the linear Freundlich and Langmuir isotherm

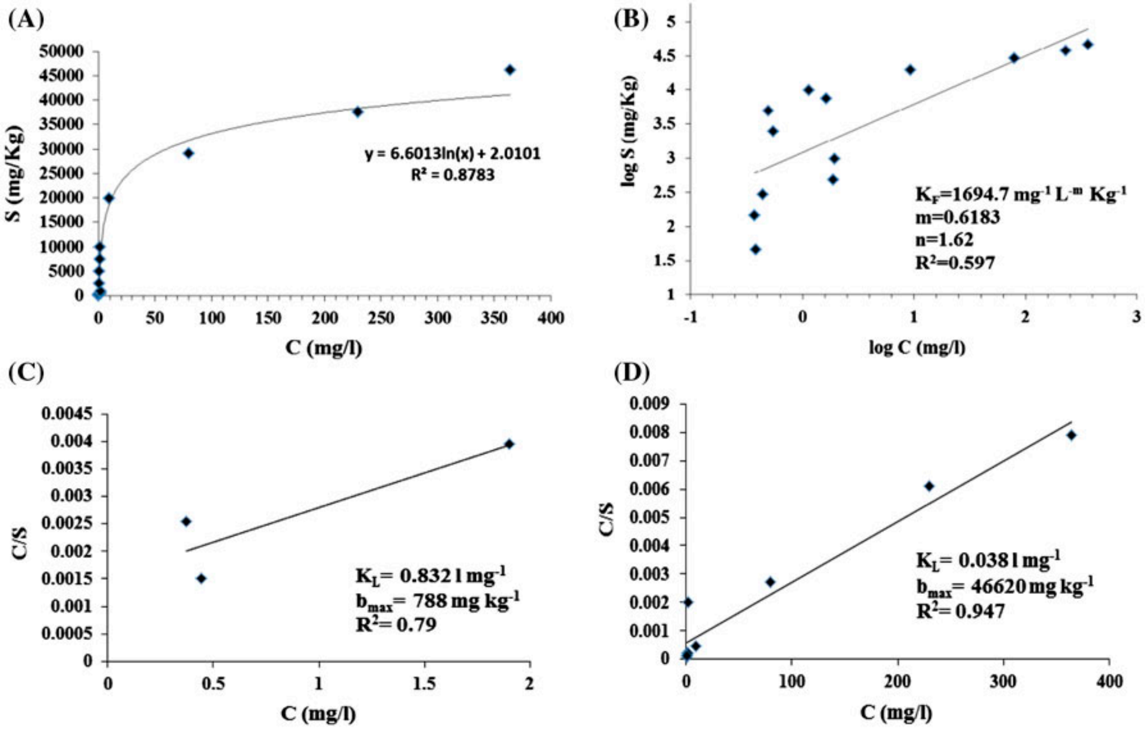

Fig. 3. Sorption isotherms of PO_4 of PMW at PO_4 initial concentrations 5, 30, 50, 100, 250, 500, 750, 1,000, 2,000, 3,000, and 5,000 mg L^{-1} at pH 7. Each data point was measured in triplicate. (A) General sorption isotherm. Error bars of the standard deviation are smaller than the symbols; (B) log–log scale Freundlich adsorption isotherms. The symbols k and m are the parameters of the Freundlich isotherm $\log S = m \log C + k$; (C) linearized Langmuir adsorption isotherm of PMW at PO_4 initial concentrations 5, 30, and 50 mg L^{-1} at pH 7; and (D) linearized Langmuir adsorption isotherm of PMW at PO_4 initial concentrations from 100 to 5,000 mg L^{-1} at pH 7. The symbols k_L and b_{max} are the parameters of the Langmuir isotherm $C/S = 1/(k_L \cdot b_{max}) + (1/b_{max})\ C$.

equations for a wide range of initial concentrations of PO_4. A positive relation between sorption and initial concentration was found. This is in line with the results of many previous studies [7,39,46–48]. Fig. 3(B) shows the log–log scale Freundlich adsorption isotherms with R^2 value of 0.60.

It has been found that the Langmuir model has two slopes and two b_{max} values (Fig. 3(C) and (D)). On the first hand, the sorption data at PO_4 initial concentrations ≤50 mg L^{-1} were good fitted to Langmuir model with R^2 value of 0.79. The Langmuir PO_4 sorption maximum capacity (b_{max}) was 788 mg $kg^{-}1$ and bonding energy constant (k_L) was 0.832 l mg^{-1}. On the other hand, the sorption data at PO_4 initial concentrations >50 mgL^{-1} were highly fitted to Langmuir model with R^2 value of 0.95. The Langmuir PO_4 sorption maximum capacity (b_{max}) was 46,620 mg kg^{-1} and bonding energy constant (k_L) was 0.038 l mg^{-1}. Based on these results and to the best of our knowledge, our PMW utilized in this study has the highest sorption efficiency and capacity among the other previously reported materials.

3.2.3. Heavy metal leaching experiments

Since Jordanian PMW could contain some heavy metals such as Cd, Cr, Cu, Mn, As, Ni, Hg, Sb, Sn, Pb, and Zn, two leaching experiments were performed: indeed, direct bioavailable heavy metals and total heavy metals. The direct bioavailable heavy metal experiment was carried out by agitating background electrolyte aqueous solution (0.01 M $Ca(NO_3)_2$) dosed with PMW for 24 h at pH 7. Then, the liquid phase was separated and the concentrations of heavy metals were determined. All concentrations were under the limit of detection (Table 4). From these results, we can conclude that the leachability of heavy metals to aqueous phase is not likely to be a major concern when PMW is used for PO_4 removal at a pH range typical for secondary treated municipal wastewaters (6 < pH < 8). This finding could be explained by the fact that these heavy metals are mainly present in the residual carbonates fractions [49]. The PMW acts as a buffer and it keeps pH at a nearly constant value (pH 7.5) in a wide variety of initial solution pH.

Total heavy metals leached from PMW in acidic conditions are summarized in Table 4 as well. From Table 4, it should be noted that the total heavy metal concentrations do not necessarily correspond with metal bioavailability. In this context, bioavailability can be described as the proportion of total metals that are available for incorporation into biota.

However, the potential adverse environmental impacts are mainly resulted from air contamination due to the presence of PMW, whereas the potential adverse human health risks associated with PMW are mainly stemmed from the inhalation of PMW dust and the intake of metals, non-metals, and their oxides. In windy weather, significant quantities of dust are generated and much of which settle onto the adjacent urban regions causing in turn health problems. As shown in Tables 1 and 4, PMW in Ruseifa contains considerable amount of silica and trace amount of chromium (Cr), cadmium (Cd), copper (Cu), and arsenic (As). When powder containing silica such as PMW is inhaled and get into human bodies, silica due to its high bio-persistivity could remain deposited within the body tissue [50,51] which consequently could cause cytotoxicity, lung cancer inflammation, and histopathological lesions, proved at least in rats [52,53]. On the other hand, Cr, Cd, Cu, and As have toxic effects to the living cells when accumulated in the body [54].

Table 1
Chemical characterization of the used PMW in this study

Sample No.	P_2O_5 (%)	SiO_2 (%)	CaO (%)	SO_4 (%)	Cl (%)	Fe_2O_3 (%)	Al_2O_3 (%)	MgO (%)
1	21.23	9.02	48.54	0.73	0.050	0.26	0.59	0.30
2	21.80	13.06	51.84	0.69	0.034	0.23	0.43	0.23
3	17.29	17.40	43.79	0.92	0.061	0.38	0.64	0.32
4	23.78	10.68	49.78	0.78	0.009	0.23	0.47	0.23
5	22.48	10.46	45.99	0.71	0.008	0.23	0.51	0.25
6	22.22	8.44	46.68	0.64	0.014	0.20	0.62	0.32
7	22.00	11.7	47.64	0.57	0.007	0.1	0.36	0.21
8	18.76	16.50	49.25	1.08	0.010	0.26	0.47	0.27
9	16.92	20.17	43.90	0.54	0.016	0.10	0.26	0.20
10	19.93	14.81	44.44	0.61	0.021	0.19	0.38	0.27
11	21.43	18.38	44.28	0.54	0.078	0.19	0.15	0.25
12	24.23	9.59	48.15	1.27	0.064	0.40	0.28	0.17
13	21.64	13.71	46.91	0.63	0.01	0.199	0.465	0.32
14	20.37	13.01	50.47	0.6	0.012	0.28	0.51	0.16
15	19.50	17.68	49.50	0.67	0.054	0.17	0.40	0.33
16	17.94	14.28	45.79	0.50	0.010	0.13	0.25	0.20
17	22.97	14.38	47.75	0.66	0.043	0.25	0.50	0.25
18	21.01	7.46	52.08	0.64	0.034	0.06	0.1	0.38
19	22.08	12.13	45.75	0.60	0.035	0.20	0.42	0.29
20	23.55	10.04	49.97	0.64	0.030	0.18	0.47	0.28
21	22.36	10.97	54.04	0.57	0.004	0.19	0.43	0.10
22	22.48	11.30	46.31	0.72	0.020	0.19	0.51	0.25
23	21.83	10.75	47.50	0.81	0.020	0.17	0.38	0.25
24	22.7	10.35	40.55	0.65	0.03	0.3	0.43	0.87
25	18.47	14.46	46.82	0.63	0.013	0.20	0.49	0.12
26	20.25	16.55	44.95	0.71	0.005	0.19	0.19	0.12
27	17.91	18.02	48.74	0.49	0.006	0.14	0.26	0.08
28	20.84	14.91	45.29	0.60	0.024	0.27	0.57	0.12
29	18.17	19.39	46.01	0.66	0.029	0.11	0.21	0.27
30	19.92	15.51	47.62	0.62	0.010	0.19	0.38	0.23
31	18.73	17.67	44.38	0.48	0.012	0.14	0.21	0.08
32	11.16	15.23	51.53	0.26	0.005	0.07	0.15	0.08
33*	21.19	13.79	47.29	0.60	0.032	0.19	0.34	0.23

*Sample 33 is a combined sample of all 32 sites and represents the whole PMW in Ruseifa phosphate mine.

Table 2
Sorption efficiency and capacity of PMW for the removal of PO_4 from prepared solutions. Concentrations are given in ppm (mg L^{-1}) and sorption capacity is expressed as the weight (mg) of phosphate ion (PO_4) per weight (kg) of dry PMW

Initial conc. (mg L^{-1})	*Final conc. (mg L^{-1})	*(%) Sorption efficiency	*Sorption capacity (mg kg^{-1})	**Final conc. (mg L^{-1})	**(%) Sorption efficiency	**Sorption capacity (mg kg^{-1})
5	0.38	92.36	46	0.42	91.60	46
15	0.37	97.53	146	0.84	94.40	142
30	0.45	98.51	296	0.76	97.48	292
50	1.90	96.20	481	1.03	97.95	489
100	1.95	98.05	981	1.58	98.42	984
250	0.55	99.78	2,495	2.00	99.20	2,480
500	0.50	99.90	4,995	3.51	99.29	4,965
750	1.65	99.78	7,484	7.08	99.06	7,429
1,000	1.15	99.88	9,989	12.92	98.71	9,871
2000	9.40	99.53	19,906	221.35	88.93	17,786
3,000	79.75	97.34	29,203	490.63	83.65	25,094
4,000	229.85	94.25	37,702	522.92	86.93	34,770
5,000	364.40	92.71	46,356	647.92	87.04	43,521

*In the presence of $Ca(NO_3)_2$.

**In the absence of $Ca(NO_3)_2$.

Table 3
Sorption efficiency of PMW for the removal of PO_4 from wastewater samples obtained from Jordanian wastewater treatment plants. Concentrations are given in ppm (mg L^{-1})

Sample No.	Treatment plant (start of operation)	Initial conc. (mg L^{-1})	Final conc. (mg L^{-1})	(%) Sorption efficiency
1	Abu Nuseir (1988)	15.00	0.30	98.00
2	Fuhais (1996)	16.70	0.20	98.80
3	Tafilah (1989)	36.80	0.10	99.73
4	Karak (1988)	50.70	0.80	98.42
5	Laggoon (2005)	59.40	1.55	97.39
6	Mafraq (1988)	77.00	1.60	97.92

Table 4
Direct bioavailable and total heavy metals concentration of PMW

Element	Direct bioavailable $Ca(NO_3)_2$ (mg L^{-1})	Total acidic digestion (mg L^{-1})
Cd	<1	22.3
Cr	<1	66
Cu	<1	16.4
Mn	<1	10.8
As	<0.01	7.6
Ni	<1	<1
Hg	<1	<1
Sb	<1	<1
Sn	<1	<1
Pb	<1	<1
Zn	<1	300

4. Conclusion

(a) The results obtained in this study show that Jordanian PMW can be considered as promising materials in wastewater purification, indeed for PO_4 removal and recovery from wastewater.

(b) PMW has high potential sorption capacity for PO_4 compared to other materials used in the previous literature review. Consequently, it will contribute in the prevention or reduction of the water bodies' eutrophication phenomena.

(c) The main parameter influencing the PMW sorption capacity of PO_4 is the concentration of PO_4 in the solution phase and pH. The PO_4 removal efficiency from prepared solutions and domestic wastewater was up to 99%. Moreover, Langmuir sorption model was able to describe the observed data for PO_4 sorption by PMW.

(d) The PMW direct bioavailable heavy metals in aqueous phase are illegible and lower than the limits of detection which allows reuse of huge amounts of wastes as fertilizer for agricultural purposes or as low-cost construction materials. Large-scale pilot studies are recommended in order to confirm the promising results obtained at laboratory scale.

(e) In conclusion, this study provides a deeper insight into the potential of natural minerals and wastes which are available in local community in water reclaimed. Moreover, long-term studies should investigate the longevity of the PO_4 immobilizing effect of this new material and provide a deeper insight into the potential of PMW in waste water remediation. Such studies must also focus on reusing the exhausted-phosphate waste mine to produce low-cost construction materials and on examining their mechanical properties.

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