Phosphate removal from water using low-cost dolomite filters

Faris M. Hamoodi¹, Mohammed Ibrahim Mohammed², Reham S. Alwash³*, Patryk Kot⁴

¹University of Technology, Iraq.
²Suleyman Demirel University, Turkey.
³University of Babylon, Babylon, Iraq.
⁴Department of civil engineering, Liverpool John Moores University, UK.

Email: k.s.hashim@2013.ljmu.ac.uk

Abstract. The extensive usage of phosphate in different industries, such as detergents and fertilizers, remarkably increased its concentration in water bodies. Moreover, the weathering of phosphate-containing geochemical deposits represents another source of water pollution with phosphate. This pollutant has significant impacts on water quality, aquatic life, and the cost of the water treatment process. Therefore, the current project investigates the applicability of calcium-rich dolomite as a filtration media to remove phosphate from water. Firstly, the chemical and physical properties of dolomite samples were examined to check the suitability of these samples for phosphate removal. Then, several batch flow experiments were carried out at a water/solid ratio of 1.77, taking into accounts the influence of some key operating parameters such as treatment time, and the initial concentration of phosphate. The obtained results showed that the longer the treatment time was, the higher the removal of phosphate was. It was found that the calcium-rich dolomite removes about 30 percent of initial phosphate concentration (10 mg/L) within 120 min. Additionally, the results obtained from the application of the Langmuir isothermal model, and the separation factor indicate a good affinity between dolomite and phosphate atoms.

1. Introduction

In spite of the acknowledged role of phosphate in the growth of living organisms, teeth, and bones [1], excessive presence of phosphate in water is responsible for several negative impacts on industries, water quality, and aquatic life [2, 3]. Additionally, the excessive growth of alga accelerates the depletion of dissolved oxygen in their aquatic environment, and consequently seriously limits the photosynthetic process of aquatic plants [4, 5]. While in industry, phosphate recognized as the main cause for the progressive fouling of the pipes [2, 6]. Recently, phosphate removal from water and wastewater has become a key issue for the water treatment sector due to its worldwide increasing concentration [7]. Where the extensive usage of phosphate in different industries, such as detergents and fertilizers, remarkably increased its concentration in water bodies. Weathering of phosphate-containing geochemical deposits represents another source for phosphate pollution. Moreover, effluents from agricultural fields and cattle-breeding fields are categorized as another main source for phosphate [1]. In addition, many studies claimed that the concentration of phosphate in waters, like other chemicals, has increased because of climate changes the caused lack of rainfalls [8-12] and increase water consumption [13-16]. Taking into consideration that a concentration of 0.1 mg/L of phosphorus is sufficient nutrient enrichment in an aquatic environment and the negative impacts of the eutrophication
phenomenon on water quality and aquatic life, all countries strictly limit phosphorous discharging. To meet these strict limitations, a large number of treatment methods have been suggested to remove phosphate from water and wastewater [17, 18]. Generally, removal methods are divided into three main groups depending on the removal mechanism; namely [19-22]; physical methods, chemical methods, and biological methods [23-27]. Although the biological method is considered as one of the most cost-effective phosphate removal methods, it has many vital drawbacks that highly limit its applications [28, 29]. For instance, it removal efficiency as low as 30 percent, which means that phosphate removal must be accomplished by another method, and it requires transferring phosphate from liquid to solid-state. Moreover, the performance of this method is high affected by several external factors, for instance, the variation of water temperature, the chemical composition of water, and concentration of nutrient are greatly influence the performance of the biological reactors [30-32]. In fact, application of the chemical methods for phosphate removal has remarkably decreased during the last few decades due to many undeniable disadvantages; firstly, chemical methods require high investment cost especially for dosing equipment and used polymers [33-35]. Secondly, it generates large quantities of sludge in comparison with other methods, which requires large spaces and equipment to handle and consequently maximize the operation cost [36-38]. In addition, the inaccurate dosing of chemicals and the possibility of exposing the operators to direct contact with chemicals are other vital drawbacks of this method. Where the required amount of chemicals is greatly affected by several parameters such as the pH of the water and the concentration of competitive ions, which in turn makes controlling of accurate dosing process too difficult. Finally, physical phosphate removal methods have brought increasing attention during the last few decades. Generally, physical phosphate treatment methods can be divided into three main groups: membrane methods, filtration methods, and magnetic separation. The previous studies indicated that physical phosphate removal methods are usually efficient and reliable [39-41]. For instance, it has been reported that the membrane methods are able to reduce phosphate concentration from 25 mg/L to about 1 mg/L, while the reverse osmosis technique is efficient enough to reduce it to about 0.008 mg/L. However, some physical methods still have unignorably disadvantages, for instance, membrane and filtration methods are considered as expensive, slow, and short life treatment methods. Additionally, it is noteworthy to highlight that the volume of the generated sludge plays a central role in the selection of the treatment method, as waste management requires expensive and complicated systems [42-45]. Therefore, the current work has been devoted to applying a low-cost sorption media, calcium-rich dolomite, to remove phosphate from water. The adsorption method has been selected here because of its cost-effectiveness [46, 47], availability of the adsorption material [2], and also the by-products of the adsorption material (the particles of the media) could be reused in many applications, such as concrete [48-51] and mortars [52-54].

2. Materials and Methods

A wide body of literature demonstrated that the dolomite is a proper sorption media for phosphate because it usually contains enough quantity of calcium oxides and/or magnesium oxide. Therefore, samples of white dolomite have been used, in the current project, to remove phosphate from synthetic water samples. Specialist Aggregates Ltd. UK, supplied the required quantity of dolomite. The current experimental work consists of three main steps. Firstly, an examination of the physical properties and chemical composition of the dolomite sample. Secondly, carrying out a series of batch experiments to determine the ability of dolomite to remove phosphate from water. Finally, investigating the affinity between phosphate atoms and dolomite particles by applying both Langmuir isothermal model and separation factor.

2.1. Measurement of physical properties

Initially, four essential physical properties for the filtration process, which are the specific surface area (SSA), grain size distribution (GSD), uniformity coefficient (UC), and specific gravity (SG), were measured. GSD was measured by sieving 0.25 Kg of dolomite sample on four different sizes sieves
(3.55, 2.00, 1.18, and 0.60 mm from top to bottom), for 600 sec. These experiments were carried out using a sieve analyzer type Impact (Model: SV003). The retained amount of dolomite on each sieve was weighted to determine grain size distribution. The UC, which concerns the gradation of filtration media, was calculated using Eq. 1. Usually, good graded media has a UC > 4.0, while poorly graded media have a UC value < 4.0 [19].

\[
UC = \frac{d_{60}}{d_{10}}
\]  

(1)

Where \(d_{60}\) and \(d_{10}\) are the diameter corresponding to 60 and 10 percent finer in the grain size distribution, respectively. The SSA of the dolomite sample was calculated using the Nova 2000 device. While the specific gravity of the dolomite sample was provided by the supplier.

2.2. Analysis of chemical composition

The ability of a candidate filtration material for phosphate removal from water is determined by its chemical composition. Generally, the presence of soluble calcium, magnesium, iron (Fe), and/or aluminum (Al) oxides within the chemical composition of a material makes it a promising filtration material for phosphate removal from solution. In the current project, therefore, the chemical composition of the dolomite sample has been analyzed to check whether it contains such oxides or not. The chemical composition of the candidate sample has been carried out using the XRF Shimadzu EDX 720 analyzer, which utilizes the concept of rays reflections to measure the contents of the oxide and trace element.

2.3. Phosphate removal from water

The ability of dolomite to remediate phosphate from water has been investigated under batch flow conditions. In these experiments, the water/solids ratio was preserved at 1.770 [19]. Initially, 50 mg/L phosphate stock solutions were prepared by liquefying a proper amount of KH₂PO₄ in deionized water. Then, a 500 mL sample with a lowers concentration was diluted from the stock solutions. These samples were poured into 1.0 L plastic containers that already contain 282.5 g of dolomite and left to react for 240 min at room temperature (20 ± 1 °C). The removal of phosphates removal was checked by collection 5 mL water samples, from containers, at different intervals. Each collected sample was subjected to filtering at 0.45 µm filters to eliminate undesirable solid. The residuals (phosphates) concentrations, in the filtrates, were measured using Hach-Lange standard phosphate cuvette test (LCK350) and programmed Hach-Lange spectrophotometers (Model: DR-2800). All batch trials were commenced at initials pHs of 7.0. This pH value has been adopted in the current project because it represents the average pH value of domestic wastewater and surface water. Where the initials pHs of the domestic wastewaters and freshwater is ranging between 5.5 and 8. It is noteworthy to mention that the initial pH of the prepared samples increased to about 8.0 due to the alkaline influence of CaO. Therefore, before running the experiments, the initials pHs of these samples were adjusted to 7.0 using a proper volume of 1 M HCl solution. The removals efficiencies were calculated using this equation:

\[
R\% = \left(1 - \frac{C_t}{C_0}\right) \times 100\%
\]  

(2)

where R is removals efficiency (percent), \(C_0\) and \(C_t\) is the initial and final concentrations of phosphates (mg/L), respectively.

2.4. Application of Langmuir isothermal model and separation factor

Though many isotherm models have been practiced to analyze the equilibrium data, the most common two used isotherms models are Langmuir and Freundlich. In the current study, the Langmuir model has been applied to analyze the equilibrium data not only because it is an accurate and widely applied model, but also because it delivers the required information to determine the separation factor (SF). The values of the SF is governed by the values of the Langmuir constant (K). Langmuir model, based on an
assumption that the adsorptions occur through monolayer, is graphically described by the results of the following linearised equation:

$$\frac{1}{q_e} = \frac{1}{Q} + \frac{1}{Q.K} \times \frac{1}{C_e}$$  \hspace{1cm} (3)$$

Where $q_e$ characterizes the adsorbed masses of adsorbates/adsorbent’s mass (mg g$^{-1}$), while $Q$, $K$ and $C_e$ represents the highest adsorption rates (mg g$^{-1}$), Langmuir constant (mg$^{-1}$), and the equilibrium concentrations of adsorbates (mg L$^{-1}$), respectively. The SF that assesses the affinity among the adsorbates and the absorbents can be calculated using the following formula:

$$SF = \frac{1}{1+(K.C_i)}$$  \hspace{1cm} (4)$$

Where $C_i$ characterizes the initial concentrations of the adsorbates (mg L$^{-1}$). The adsorption is unfavourable if SF $>$ 1.0, linear if SF $=$ 1.0, favourable if 0.0 $<$ SF $<$ 1.0, and irreversible if SF $=$ 0. The linearised Langmuir models, like any other linearised models, must be validated before using it to deliver the required information (K value) to calculate the value of SF. The coefficient of determination ($R^2$), which is a measurement the agreement of readings with the line generated by the linear model, could be used to assess the validity of linear models. $R^2$ value is limited to a 0-1 range: the maximum the $R^2$, the maximum the reliability of the linear model; its value could be calculated as follows:

$$R^2 = \frac{S.S_{reg}}{S.S_Y}$$  \hspace{1cm} (5)$$

Where $S.S_{reg}$, and $S.S_Y$ indicate the sums of the square for regressions and the total sums of the square, respectively.

In the present research, the Langmuirs’ constant has been measured by saturated quantities of dolomite (182.5-482.5 g) in 500 mL phosphates solutions. The remaining phosphates concentrations were calculated at half hour-intervals till stable phosphates concentrations were observed. The gained concentration and the saturated quantity of dolomite were used to draw the relationships among the inverse of $q_e$ and $C_e$. These relationships deliver the needed data to compute the constant of the Langmuir model ($Q$, and $K$). $Q$ values can be found according to the grade of the produced line by the Langmuir model, $K$ values can be found according to the value of the interception points between the $1/q_e$ axis and the produced line, which is a necessary value to measure the SF values.

3. Results and Discussion

3.1. Physical properties

The physical properties of the dolomite were investigated to explore its appropriateness for the filtration process. In this context, four essential physical properties for the filtration process were investigated, which are GSD, UC, SSA, and SG. As it was mentioned before, the GSD and UC of the dolomite sample were measured by sieving 250 mg of each material, on 4 dissimilar sieves (3.55-0.60 mm), for 600 sec. The SSA was measured using Nova 2000, while the SP of dolomite was provided by the suppliers. The obtained results, Table 1, show that the UC value of dolomite was less than 4, which indicates a poor gradation. Low UC value means the studied sample has a relatively high voids ratio, which could negatively influence the performance of this media. In terms of SSA, the obtained results showed that the SSA of dolomite was 0.88 m$^2$/g, which is comparable to those used in the literature. Furthermore, it could be noticed from Table 1 SP of dolomites is bigger than that of water that indicates no floating of dolomite during the treatment.
Table 1. Key parameters of the dolomite.

| d10(cm) | d30(cm) | d60(cm) | Uc(d60/d10) | SP | SSA(m².g⁻¹) |
|---------|---------|---------|-------------|----|-------------|
| 0.12    | 0.201   | 0.266   | 0.221       | 0.27| 0.088       |

3.2. Chemical composition

The chemical composition of a candidate material, as it was mentioned before, determines its ability to remove the targeted pollutant. Therefore, the chemical composition of dolomite has been analyzed, using Shimadzu EDX 720 analyzer. The obtained results from this test, Table 2, show that the calcium and magnesium oxides together consist of about 52 percent of the chemical composition of the dolomite sample, which makes this material a promising phosphate adsorbent.

Table 2. Chemical composition of the candidate materials.

| Element | Units | Quantity | Element | Units | Quantity |
|---------|-------|----------|---------|-------|----------|
| Na₂O    | %     | 8.545    | BaO     | %     | 0.144    |
| MgO     | %     | 3.187    | F       | ppm   | 0.050    |
| Al₂O₃   | %     | 0.000    | P₂O₅   | Ppm   | 0.250    |
| SiO₂    | %     | 13.924   | Cl      | %     | 0.040    |
| K₂O     | %     | 0.050    | CO₂O₃  | %     | 0.000    |
| CaO     | %     | 48.807   | SrO     | %     | 0.015    |
| TiO₂    | %     | 0.094    | Y₂O₃   | %     | 0.002    |
| MnO     | %     | 0.000    | CHO     | %     | 0.000    |
| Fe₂O₃   | %     | 0.000    | SO₃     | %     | 0.000    |
| CuO     | %     | 0.012    | Rb₂O   | %     | 0.000    |
| ZnO     | %     | 0.002    | NiO     | %     | 0.000    |
| ZrO₂    | %     | 0.006    |         |       |          |

3.3. Phosphate removal

The ability of dolomite to remove phosphate from the water was investigated by connecting series of batch-flow experiments. Initially, 282.5 g of dolomite was placed in a 1.0 L plastic container, then, a measured volume, 500 mL, of phosphate solution was decanted into each container. The initial pH value of each sample was adjusted, before running any experiment, to 7.0 using the required volume of 1 M HCl solutions. To monitor the progress of phosphate removal, 5 mL samples were collected at 5 to 240 minutes intervals. Any collected sample was filtered at 0.45 μm filter paper to separate solids, then the remaining phosphates concentrations were calculated using a standard phosphates cuvettes test (LCK350) and Hach Lange spectro-photometer. The gained outcomes, Figure 1, showed ability of dolomite to remove about 30 percent of phosphate within the first 120 min of treatment. This could be attributed to the high content of Ca and/or Mg oxides. Liquifying of these oxides into phosphates solution followed by sets of reactions that leads to phosphates precipitations. However, Figure 1 shows that the phosphate removal slightly increased during the last 120 min of treatment, where it increased from 30 to about 34 percent as the treatment time increased from 120 to 240 min, respectively. This could be attributed to fact that the readily available amount of CaO and MgO (on the active surface of dolomite particles) was dissolved into the phosphate solution within the first 120 min of treatment. While the majority of these oxides are captured deep inside the dolomite particles that obstructed their
dissolution process, which in turn significantly slow down the phosphate removal during the last 120 min of treatment. Additionally, it can be seen from the figure that the pH of the solution being treated increased from 7.0 to the vicinity of 8.25 during the course of the experiment. This could be attributed to the alkaline influence of CaO.

Figure 1. Residual phosphate concentration and pH change in batch experiments.

3.4. Effect of initial phosphates concentrations on removals efficiencies
To investigate the influences of initial phosphates concentrations on the removals efficiencies, 0.5 L samples of phosphates solutions with two different phosphate concentrations (5 and 10 mg/L) were treated using 282.5 g of dolomite for 120 min. The gained results displayed that the lowers the initial phosphates concentrations are, the more rapid the phosphate removals are, as shown in Figure 2. This could be attributed to the fact that at low phosphate concentration, the available amount of phosphate adsorbents (calcium and magnesium oxides) is greater than the phosphate amount. While at high phosphate concentrations, the dissolved amount of CaO and MgO is not enough to accommodate phosphate atoms. Therefore, it could be reasonable to infer that the dolomite is suitable for the removal of low phosphate concentrations.

Figure 2. Influences of initial phosphates concentrations on the removals efficacy.
3.5. Langmuir isothermal model and separation factor

In order to gain an accurate insight into the adsorptions processes, it is significant to examine its equilibrium isotherms, as it explains the relationships among the adsorbed quantities of solutes, at constant temperatures, and its concentrations in the equilibrium solutions. In the current study, the Langmuir isotherm model has been applied to investigate the equilibrium isotherm of the current adsorption process depending on the obtained results from batch equilibrium experiments. While the affinity between the phosphate and the dolomite particles has been estimated using the separation factor. Experimentally, different amounts of dolomite (182.5 to 482.5 g) were soaked in phosphates solutions and the remaining phosphates concentrations regularly were calculated at half hour-intervals till stable phosphates concentrations were gained. The gained findings showed the ability of the Langmuir model to simulate the outcomes of the experiments. It was noticed that the correlations coefficient (R²) of the Langmuir model applications to the experimental data was 0.941, Figure 3. Statistically, it indicates that this model could explain 94.1 percent of the data, which is an acceptable value. Then, the Langmuir model was applied to measure the K value, the latter was used to measure the SP value. The gained outcomes, Table 3, showed K value was 35.22 L.mg⁻¹. The SP, according to Eq. 4, is 0.006, which confirms a good affinity among the phosphates and dolomites.

![Figure 3. Outcomes of Langmuir model.](image)

| Parameter | K  | R²  | SF  |
|-----------|----|-----|-----|
| Values    | 35.22 | 0.839 | 0.006 |

For a more accurate treatment process, embedded sensors could be used for this purpose because sensors were successfully used in civil [55, 56] and environmental engineering [57, 58].

3. Conclusions

The outcomes of the current study indicated that the calcium-rich dolomite has a reasonable efficiency in terms of phosphates removals from synthetic water samples. The ability of this natural adsorption media is attributed to its high CaO and MgO content. However, the obtained results from the experimental work indicated that the dissolved amount of CaO from the dolomite surface was not enough to achieve complete phosphate removal. This low dissolution process could be attributed to the fact that a large amount of these oxides is captured deep inside the
dolomite particles rather than the surface. Thus, using fine dolomite particles could enhance phosphate removal efficiency by increasing the SSA. Generally, the results of the current experimental work indicated that the calcium-rich dolomite, used in the current study, is suitable to remove low phosphate concentrations rather than high concentrations. For future work, grinding dolomite particles down to small sizes could enhance the performance of calcium-rich dolomite, because it increases the SSA, which in turn increases the contact between water and dolomite particles. Additionally, increasing the SSA maximizes the dissolved amount of CaO into the water being treated, which could shorten the treatment time.

References
[1] Hashim K S, Idowu I A, Jasim N, Al Khaddar R, Shaw A, Phipps D, Kot P, Pedrola M O, Alattabi A W and Abdulredha M 2018 Removal of phosphate from River water using a new baffle plates electrochemical reactor MethodsX 5 1413-8.
[2] Alenezi A K, Hasan H A, Hashim K S, Amoako-Attah J, Gkantou M, Muradov M, Kot P and Abdulhadi B 2020 Zeolite-assisted electrocoagulation for remediation of phosphate from calcium-phosphate solution IOP Conference Series: Materials Science and Engineering 888.
[3] Hashim K S, Shaw A, Al Khaddar R, Pedrola M O and Phipps D 2017 Iron removal, energy consumption and operating cost of electrocoagulation of drinking water using a new flow column reactor Journal of Environmental Management 189 98-108.
[4] Sibley B 2013 Phosphorus Control in Passive Wastewater Treatment and Retention Works Using Water Treatment Residual Solids. In: College of Graduate Studies and Research, (University of Saskatchewan: University of Saskatchewan)
[5] Hashim K S, Shaw A, Al Khaddar R, Ortoneda Pedrola M and Phipps D 2017 Defluoridation of drinking water using a new flow column-electrocoagulation reactor (FCER) - Experimental, statistical, and economic approach Journal of Environmental Management 197 80-8.
[6] Hashim K S, Ewadh H M, Muhsin A A, Zubaidi S L, Kot P, Muradov M, Aljefery M and Al-Khaddar R 2020 Phosphate removal from water using bottom ash: Adsorption performance, coexisting anions and modelling studies Water Science and Technology 83 1-17.
[7] Mohammed A-H, Hussein A H, Yeboah D, Al Khaddar R, Abdulhadi B, Shubbar A A and Hashim K S 2020 Electrochemical removal of nitrate from wastewater IOP Conference Series: Materials Science and Engineering 888.
[8] Zubaidi S L, Al-Bugharbee H, Muhsen Y R, Hashim K, Alkhaddar R M, Al-Jumeily D and Aljaaf A J 2019 The Prediction of Municipal Water Demand in Iraq: A Case Study of Baghdad Governorate 12th International Conference on Developments in eSystems Engineering (DeSE)
[9] Zubaidi S L, Kot P, Hashim K, Alkhaddar R, Abdellatif M and Muhsin Y R 2019 Using LARS–WG model for prediction of temperature in Columbia City, USA IOP Conference Series: Materials Science and Engineering 584.
[10] Zubaidi S L, Ortega-Martorell S, Al-Bugharbee H, Olier I, Hashim K S, Gharghan S K, Kot P and Al-Khaddar R 2020 Urban Water Demand Prediction for a City that Suffers from Climate Change and Population Growth: Gauteng Province case study Water 12 1-18.
[11] Zubaidi S L, Ortega-Martorell S, Kot P, Alkhaddar R M, Abdellatif M, Gharghan S K, Ahmed M S and Hashim K 2020 A Method for Predicting Long-Term Municipal Water Demands Under Climate Change Water Resources Management 34 1265-79.
[12] Grmasha R A, Al-sareji O J, Salman J M, Hashim K S and Jasim I A 2020 Polycyclic Aromatic Hydrocarbons (PAHs) in Urban Street Dust WithinThree Land-Uses of Babylon Governorate, Iraq: Distribution, Sources, and Health Risk Assessment Journal of King Saud University - Engineering Sciences 33 1-18.
[13] Zubaidi S, Al-Bugharbee H, Ortega Martorell S, Gharghan S, Olier I, Hashim K, Al-Bdairi N and Kot P 2020 A Novel Methodology for Prediction Urban Water Demand by Wavelet Denoising and Adaptive Neuro-Fuzzy Inference System Approach Water 12 1-17.
[14] Zubaidi S L, Abdulkareem I H, Hashim K S, Al-Bugharbee H, Ridha H M, Gharghan S K, Al-Qaim F F, Muradov M, Kot P and Alkhaddar R 2020 Hybridised Artificial Neural Network model with Slime Mould Algorithm: A novel methodology for prediction urban stochastic water demand Water 12 1-18.

[15] Zubaidi S L, Al-Bugharbee H, Muhsin Y R, Hashim K and Alkhaddar R 2020 Forecasting of monthly stochastic signal of urban water demand: Baghdad as a case study IOP Conference Series: Materials Science and Engineering 888.

[16] Zubaidi S L, Hashim K, Ethaib S, Al-Bdaire N S S, Al-Bugharbee H and Gharghan S K 2020 A novel methodology to predict monthly municipal water demand based on weather variables scenario Journal of King Saud University-Engineering Sciences 32 1-18.

[17] Hashim K S, Hussein A H, Zubaidi S L, Kot P, Kraidi L, Alkhaddar R, Shaw A and Alwash R 2019 Effect of initial pH value on the removal of reactive black dye from water by electrocoagulation (EC) method 2nd International Scientific Conference

[18] Hashim K S, Khaddar R A, Jasim N, Shaw A, Phipps D, Kot P, Pedrola M O, Alattabi A W, Abdulredea M and Alawsh R 2019 Electrocoagulation as a green technology for phosphate removal from River water Separation and Purification Technology 210 135-44.

[19] Alhendal M, Nasir M J, Hashim K S, Amoako-Attah J, Al-Falufi D, Muradov M, Kot P and Abdulhadi B 2020 Cost-effective hybrid filter for remediation of water from fluoride IOP Conference Series: Materials Science and Engineering 888.

[20] Al-Marri S, AlQuzweeni S S, Hashim K S, AlKhaddar R, Kot P, AlKizwini R S, Zubaidi S L and Al-Khafaji Z S 2020 Ultrasonic-Electrocoagulation method for nitrate removal from water IOP Conference Series: Materials Science and Engineering 888.

[21] Alyafei A, AlKizwini R S, Hashim K S, Yeboah D, Gkantou M, Al Khaddar R, Al-Falufi D and Zubaidi S L 2020 Treatment of effluents of construction industry using a combined filtration-electrocoagulation method IOP Conference Series: Materials Science and Engineering 888.

[22] Aqeel K, Mubarak H A, Amoako-Attah J, Abdulraheem L A, Al Khaddar R, Abdellatif M, Al-Janabi A and Hashim K S 2020 Electrochemical removal of brilliant green dye from wastewater IOP Conference Series: Materials Science and Engineering 888.

[23] Alattabi A W, Harris C, Alkhaddar R, Alzyayadi A and Hashim K 2017 Treatment of Residential Complexes’ Wastewater using Environmentally Friendly Technology Procedia Engineering 196 792-9.

[24] Alattabi A W, Harris C B, Alkhaddar R M, Hashim K S, Ortoneda-Pedrola M and Phipps D 2017 Improving sludge settleability by introducing an innovative, two-stage settling sequencing batch reactor Journal of Water Process Engineering 20 207-16.

[25] Hashim K S 2017 The innovative use of electrocoagulation-microwave techniques for the removal of pollutants from water. In: Civil Engineering (Liverpool, United Kingdom: Liverpool John Moores University) p 229.

[26] Hashim K S, Shaw A, Al Khaddar R, Pedrola M O and Phipps D 2017 Energy efficient electrocoagulation using a new flow column reactor to remove nitrate from drinking water - Experimental, statistical, and economic approach Journal of Environmental Management 196 224-33.

[27] Hashim K S, Al-Saati N H, Hussein A H and Al-Saati Z N 2018 An investigation into the level of heavy metals leaching from canal-dreged sediment: a case study metals leaching from dredged sediment First International Conference on Materials Engineering & Science

[28] Abdulhadi B A, Kot P, Hashim K S, Shaw A and Khaddar R A 2019 Influence of current density and electrodes spacing on reactive red 120 dye removal from dyed water using electrocoagulation/electroflotation (EC/EF) process First International Conference on Civil and Environmental Engineering Technologies (ICCEET) 584.

[29] Hashim K S, Al-Saati N H, Alquzweeni S S, Zubaidi S L, Kot P, Kraidi L, Hussein A H, Alkhaddar R, Shaw A and Alwash R 2019 Decolourisation of dye solutions by electrocoagulation:
an investigation of the effect of operational parameters First International Conference on Civil and Environmental Engineering Technologies (ICCEET) 584.

[30] Al-Jumeily D, Hashim K, Alkaddar R, Al-Tufaily M and Lunn J 2019 Sustainable and Environmental Friendly Ancient Reed Houses (Inspired by the Past to Motivate the Future) 11th International Conference on Developments eSystems Engineering (DeSE)

[31] Al-Saati N H, Hussein T K, Abbas M H, Hashim K, Al-Saati Z N, Kot P, Sadique M, Aljeferiey M H and Carnacina I 2019 Statistical modelling of turbidity removal applied to non-toxic natural coagulants in water treatment: a case study Desalination and Water Treatment 150 406-12.

[32] Omran I I, Al-Saati N H, Al-Saati Z N, Patryk K, Khaddar R A, Al-Jumeily D, Shaw A, Ruddock F and Aljeferiey M 2019 Assessment of heavy metal pollution in the Great Al-Mussaib irrigation channel Desalination and Water Treatment 168 165-74.

[33] Hashim K S, Ali S S M, AlRifaie J K, Kot P, Shaw A, Al Khaddar R, Idowu I and Gkantou M 2020 Escherichia coli inactivation using a hybrid ultrasonic–electrocoagulation reactor Chemosphere 247 125868-75.

[34] Hashim K S, AlKhaddar R, Shaw A, Kot P, Al-Jumeily D, Alwash R and Aljeferiey M H 2020 Electrocoagulation as an eco-friendly River water treatment method. In Advances in Water Resources Engineering and Management (Berline: Springer).

[35] Hassan Alnaimi I J I, Abuduljaleel Al-Janabi, Khalid Hashim, Michaela Gkantou, Salah L. Zubaidi, Patryk Kot, Magomed Muradov 2020 Ultrasonic-electrochemical treatment for effluents of concrete plants Ultrasonic-electrochemical treatment for effluents of concrete plants IOP Conference Series Materials Science and Engineering 888.

[36] Zanki A K, Mohammad F H, Hashim K S, Muradov M, Kot P, Kareem M M and Abdulhadi B 2020 Removal of organic matter from water using ultrasonic-assisted electrocoagulation method IOP Conference Series: Materials Science and Engineering 888.

[37] Abdulhadi B, Kot P, Hashim K, Shaw A, Muradov M and Al-Khaddar R 2021 Continuous-flow electrocoagulation (EC) process for iron removal from water: Experimental, statistical and economic study Science of The Total Environment 756 1-16.

[38] Hashim K S, Shaw A, AlKhaddar R, Kot P and Al-Shamma’a A 2021 Water purification from metal ions in the presence of organic matter using electromagnetic radiation-assisted treatment Journal of Cleaner Production 280

[39] Abdulla G, Kareem M M, Hashim K S, Muradov M, Kot P, Mubarak H A, Abdellatif M and Abdulhadi B 2020 Removal of iron from wastewater using a hybrid filter IOP Conference Series: Materials Science and Engineering 888.

[40] Emamjomeh M M, Mousazadeh M, Mokhtari N, Jamali H A, Makkabadi M, Naghdali Z, Hashim K S and Ghanbari R 2020 Simultaneous removal of phenol and linear alkylbenzene sulfonate from automotive service station wastewater: Optimization of coupled electrochemical and physical processes Separation Science and Technology 55 3184-94.

[41] Hashim K, Kot P, Zubaid S, Alwash R, Al Khaddar R, Shaw A, Al-Jumeily D and Aljeferiey M 2020 Energy efficient electrocoagulation using baffle-plates electrodes for efficient Escherichia Coli removal from Wastewater Journal of Water Process Engineering 33 101079-86.

[42] Abdulredha M, Rafid A, Jordan D and Hashim K 2017 The development of a waste management system in Kerbala during major pilgrimage events: determination of solid waste composition Procedia Engineering 196 779-84.

[43] Abdulredha M, Al Khaddar R, Jordan D, Kot P, Abdulridha A and Hashim K 2018 Estimating solid waste generation by hospitality industry during major festivals: A quantification model based on multiple regression Waste Manag 77 388-400.

[44] Idowu I A, Atherton W, Hashim K, Kot P, Alkaddar R, Alo B I and Shaw A 2019 An analyses of the status of landfill classification systems in developing countries: Sub Saharan Africa landfill experiences Waste Management 87 761-71.
[45] Abdulredha M, Al Khaddar R, Jordan D, Kot P, Abdulridha A and Hashim K 2018 Estimating solid waste generation by hospitality industry during major festivals: A quantification model based on multiple regression *Waste Management* **77** 388-400.

[46] Abdulraheem F S, Al-Khafaji Z S, Hashim K S, Muradov M, Kot P and Shubbar A A 2020 Natural filtration unit for removal of heavy metals from water *IOP Conference Series: Materials Science and Engineering* **888**.

[47] Alenazi M, Hashim K S, Hassan A A, Muradov M, Kot P and Abdulhadi B 2020 Turbidity removal using natural coagulants derived from the seeds of strychnos potatorum: statistical and experimental approach *IOP Conference Series: Materials Science and Engineering* **888**.

[48] Shubbar A A, Al-Shaer A, AlKizwini R S, Hashim K, Hawesah H A and Sadique M 2019 Investigating the influence of cement replacement by high volume of GGBS and PFA on the mechanical performance of cement mortar *First International Conference on Civil and Environmental Engineering Technologies (ICCEET)* **584**.

[49] Shubbar A A, Sadique M, Nasr M S, Al-Khafaji Z S and Hashim K S 2020 The impact of grinding time on properties of cement mortar incorporated high volume waste paper sludge ash *Karbala International Journal of Modern Science* **6** 1-23.

[50] Shubbar A A, Sadique M, Shanbara H K and Hashim K 2020 *The Development of a New Low Carbon Binder for Construction as an Alternative to Cement*. In *Advances in Sustainable Construction Materials and Geotechnical Engineering* (Berlin: Springer).

[51] Shubbar A A, Jafer H, Dulaimi A, Hashim K, Atherton W and Sadique M 2018 The development of a low carbon binder produced from the ternary blending of cement, ground granulated blast furnace slag and high calcium fly ash: An experimental and statistical approach *Construction and Building Materials* **187** 1051-60.

[52] Kadhim A, Sadique M, Al-Mufti R and Hashim K 2020 Long-term performance of novel high-calcium one-part alkali-activated cement developed from thermally activated lime kiln dust *Journal of Building Engineering* **32** 1-17.

[53] Kadhim A, Sadique M, Al-Mufti R and Hashim K 2020 Developing One-Part Alkali-Activated metakaolin/natural pozzolan Binders using Lime Waste as activation Agent *Advances in Cement Research* **32** 1-38.

[54] Majdi H S, Shubbar A, Nasr M S, Al-Khafaji Z S, Jafer H, Abdulredha M, Masoodi Z A, Sadique M and Hashim K 2020 Experimental data on compressive strength and ultrasonic pulse velocity properties of sustainable mortar made with high content of GGBFS and CKD combinations *Data in Brief* **31** 105961-72.

[55] Gkantou M, Muradov M, Kamaris G S, Hashim K, Atherton W and Kot P 2019 Novel Electromagnetic Sensors Embedded in Reinforced Concrete Beams for Crack Detection *Sensors* **19** 5175-89.

[56] Teng K H, Kot P, Muradov M, Shaw A, Hashim K, Gkantou M and Al-Shamma’a A 2019 Embedded Smart Antenna for Non-Destructive Testing and Evaluation (NDT&E) of Moisture Content and Deterioration in Concrete *Sensors* **19** 547-59.

[57] Ryecroft S, Shaw A, Fergus P, Kot P, Hashim K, Moody A and Conway L 2019 A First Implementation of Underwater Communications in Raw Water Using the 433 MHz Frequency Combined with a Bowtie Antenna *Sensors* **19** 1813-23.

[58] Ryecroft S P, shaw A, Fergus P, Kot P, Hashim K and Conway L 2019 A Novel Gesomin Detection Method Based on Microwave Spectroscopy *12th International Conference on Developments in eSystems Engineering (DeSE)*