Removal of phenols and COD from petroleum refinery wastewater using electrocoagulation method

Hussam Abbas¹, Saba S. M. Al-Obaidy², Shatha Y. Al-Samarray³, Khaled Edwan⁴*, Anas Y. Al-Hayawi⁵, David Yeboah⁶

¹BS.c. Engineering, Karbala Refinery, Ministry of Oil, Iraq
²Department of Chemistry, College of Science, University of Babylon, Iraq
³Department of Chemistry, College of Science, Tikrit University, Iraq
⁴BS.c Engineering, Civil Engineering Department, Liverpool John Moores University, UK
⁵Biology Department, College of education for pure sciences, Tikrit University, Iraq
⁶Civil Engineering Department, Liverpool John Moores University, UK

Email: K.M.Aladwani@2017.ljmu.ac.uk

Abstract. This study investigates the possibility of removing phenols and chemical oxygen demand (COD) from petroleum wastewater (refinery wastewater) using an electrocoagulation (EC) reactor supplied with aluminium electrodes. The influence of current density (CD) (4 to 12 mA/cm²), distance between electrodes (DBE) (20 to 40 mm), and treatment time (T) (up to 120 min) was investigated by carrying out several sets of batch flow experiments. The concentrations of COD and phenols were measured using the Hach-Lang spectrophotometer and standard cuvette tests (LCK 514, LCK 314, or APC 400 for COD, and LCK 346 or LCK 345 for phenols (according to the residual concentration). The results of the present study confirmed the ability of the electrocoagulation method to reduce the concentrations of both phenols and COD in petroleum wastewater within a relatively short treatment time. It has been found that the best removal efficiency of COD and phenols were 80% and 58%, respectively. The best removal efficiency was attended, after 100 min of electrolysis, at CD of 8 mA/cm² and DBE of 20 mm.

1. Introduction

The petroleum industry has significant importance in the global economy not only because it represents the main pile in national income of many countries, but it also important to operate maintain the industrial civilization in its current configuration [1, 2]. However, serious environmental problems are related to the activities of this sector of the industry because it consumes huge quantities of water, especially for distillation, hydro-treating, desalination, and cooling processes [3-5]. The relevant literature confirms that about 293 L of water (average) are required to produce one barrel of crude, which means the global petroleum industry produces about 33,600,000 barrel/day of wastewater (base on the average global production of oil during the current decade) [6]. In addition, the rapid increase of the global oil demand indicates that production and discharge of polluted wastewater from the oil industry will continue to grow.
The chemical composition of petroleum refinery wastewater is varying depending on its origin. For example, petroleum wastewater could contain phenols, organic salts, selenium, aromatic hydrocarbons, sulphate, greases, cresols, cyanides, heavy metals, ammonia, and radioactive pollutants [1, 2]. However, COD and phenolic compounds can be found in all petroleum refinery wastewaters. The literature confirms that refinery wastewaters contain high concentrations of COD (up to 5300 mg/l) and phenolic compounds ranging between 20 to 200 ppm. It is noteworthy to mention that the permissible concentrations of phenol concentration and COD in treated wastewater are 1 ppm and 125 mg/l, respectively. These high concentrations of pollutants represent a serious threat to the environment, biodiversity, and human health, where these pollutants heavily pollute the surface water and groundwater making them unsuitable for human use [7-9], and also kill the aquatic life [10-12]. Besides, these pollutants pollute the bed soils of rivers/lakes, and soils around the petroleum stations and refineries, which requires costly remediation processes [5, 13].

In terms of human health, these pollutants lead to serious diseases or poisoning effects [14-16]. With the continuous increase in climate change that increases the consumption of freshwaters [17-19] and increases the amount of polluted runoff in other parts of the world [20-22], the need for efficient treatment technologies is becoming more urgent [23-25]. These effects were recently increased due to the changes in the climate of this planet that resulted from emitting harmful gases into the atmosphere of the Earth [26, 27]. Therefore, a significant body of studies was conducted to find a proper treatment method or a set of treatment methods to treat the petroleum wastewaters before discharging them into the environment, these methods are ranging from simple physical methods to very advanced combined methods [28, 29]. For example, photocatalytic-oxidation, coagulation-flocculation, adsorption, biodegradation, membrane, and chemical precipitation were applied to remove single or set of pollutants that could be found in the petroleum wastewaters, such as nitrate [30, 31], phosphate [32-34], organic matter [35-37], bacteria [38, 39], turbidity [40] and heavy metals [41-44]. However, most of these methods are either not economically-efficient or not efficient enough to meet the standard limits due to the variability of the chemical composition of petroleum wastewater.

At the same time, a large number of scholars have claimed the efficiency of electrocoagulation (EC) in the removal of wide ranges of pollutants including the main pollutants in the petroleum wastewaters, such as heavy metals, phenols, phosphates, nitrates, colours, and organic matter [7, 10]. Additionally, the scholars indicated that the EC method is different from other treatment methods in terms of the low cost, needless for skilled operators, needless for chemicals (except for pH adjustment), the compact volume, and the selectivity [3, 32]. Furthermore, these scholars indicated that the sludge of the EC method contains a high amount of the electrodes’ materials (metals), which increases the chance to recycle this sludge in concretes [45-47], and other civil engineering applications [48-50], and at the same time decreases the need for landfilling processes the costs a lot [51-54].

In this context, the current study investigates the feasibility of the electrocoagulation method (EC) to remove two main pollutants in petroleum wastewater, which are the phenols and chemical oxygen demand (COD). The electrocoagulation method has been chosen in this study due to its attractive advantages. For instance, it does not require chemical additives, relatively low operating costs, easy to perform, and it enables the operators to control the reduction of the pollutants through both the material of the electrodes and the operating parameters.

2. Experimental work

2.1. Material and methods

Petroleum wastewater samples, containing 400 mg/l of COD and 100 mg/l of phenols, were treated using EC cell at different current densities density (CD), the distance between electrodes (DBE), and treatment time (T). The main characteristics of these samples are shown in table 1.
Table 1. Characteristics of the studied petroleum wastewater samples.

| Parameter | Value | Unit |
|-----------|-------|------|
| pH        | 6.8   |      |
| Conductivity | 9.76 | ms/cm |
| TSS       | 120   | Mg/l |
| Salinity  | 0.13  | %    |
| COD       | 400   | Mg/l |
| Phenols   | 100   | Mg/l |
| Colour    | Brownish | --- |

The desire current density value (4 to 12 mA/cm²) was provided using a DC rectifier (HQ Power; Model: PS 3010, 0-10 A, 0–30 V). While the distance between electrodes was manually adjusted to the required value (20 to 40 mm). The electrolysis process was carried out by pumping these petroleum wastewater samples continuously, at different flow rates, into the EC reactor. The flow rates were changed according to the required detention time (treatment time), which ranged from 0 to 120 min.

To monitor the removal process, 10 mL water samples were periodically collected from the outlet of the EC reactor. The collected samples were filtered at 0.45 μm filters; the residual COD in the filtrate was measured using a spectrophotometer (Hach Lange DR 2800) and the suitable standard cuvette test, LCK 514, LCK 314, or APC 400 (according to the residual concentration). While, the residual phenols were measured using LCK 346 or LCK 345, according to the residual concentration of phenols. The standard cuvettes were provided by Hach Lang, United Kingdom. All experiments were carried out at room temperature (20 ±1°C). Removal efficiency (RE %) was measured using the following formula:

\[ RE\% = \frac{C_0 - C}{C_0} \times 100\% \]  

(1)

where \(C_0\) and \(C\) are the influent and effluent concentrations of COD or phenols, in mg/L, respectively.

Figure 1: The EC unit.

A) The EC reactor  
B) Aluminium electrode.
2.2. Electrocoagulation cell

The decolourisation process was conducted using a rectangular EC reactor, figure 1-A. This EC reactor consists of a rectangular Perspex container (20 cm in length, 7.5 cm in width, and 12 cm in depth) and four aluminium electrodes. The aluminium electrodes are perforated plates, figure 1-B, with dimensions of 7 cm in width and 12 cm in height. Each electrode contains 35 holes (5 mm in diameter). The perforated electrodes help mix wastewater during the treatment process, which enhances the removal efficiency by increasing the collision rate between coagulants and pollutants.

3. Results and discussion

3.1. Influence of distance between electrodes (DBE)

To investigate the influence of the DBE on both COD and phenols removal efficiency, wastewater samples containing 400 mg/l of COD and 100 mg/l of phenols were electrolysed at different DBEs (20, 30, and 40 mm). The electrocoagulation experiments were carried out at a constant CD of 4 mA/cm², and a detention time of 60 min. The obtained results indicated that the wider the DBE was, the lower the removal efficiency was. For example, after 60 min of electrolysis, the removal efficiency of COD decreased from about 47% to 26% as the DBE increased from 20 to 40 mm, respectively, figure 2. The same trend was noticed in the removal of phenols, figure 3.

This behaviour could be attributed to two reasons, firstly; increasing electrodes spacing promotes the formation of the metallic anodic film that reduces the melting rate of the anode, which in turn slows down the removal rate [3]. Secondly, widening the gap between the electrodes results in decreasing the electrostatic attraction force that decreases flocs formation, and consequently reduces removal efficiency. Thus, it could be reasonable to keep the DBE at 20 mm for the rest of the experimental work [7].

![Figure 2. Influence of the DBE on the removal of COD.](image)

![Figure 3. Influence of the DBE on the removal of phenols.](image)

3.2. Influence of currents densities on the removal efficiency

Currents densities plays a central role in the electrolysis process as it determines the production of coagulants, flocs growth, and sizes and generation rates of gases-bubbles [39]. Thus, the influence of CD on both COD and phenols removal was investigated by the electrolysis of wastewater samples containing...
400 mg/l of COD and 100 mg/l of phenols at different CDs (4, 8, and 12 mA/cm²), when the DBE and detention time was kept constant at 20 mm and 60 min, respectively. The gained outcomes, Figure-4, showed that the higher CDs were, the more quickly the COD removals were. Where, it could be understood from these gained outcomes that, afterward 60 minutes of electrolyzing, the removal of COD increased from 47% to 76% as the CD increased from 4 to 12 mA/cm², respectively. The same trend was noticed in phenols removal. This could attribute to the fact that the melted coagulant improved as the CD improved. As the coagulant number improved, the number of active places improved consistently and improved both COD and phenols removal as a consequence. However, increasing the applied CD will increase power consumption. So, in this search, it is sensible to retain the CDs at 8 mA/cm² to commence the rest of the experiments.

3.3. Influence of detention time on the removal efficiency

The literature indicated straight proportions between the treatment times and the production of coagulant, which improves the pollutant removals [16]. Therefore, the influence of detention time on both COD and phenols removal was explored by electrolyzing a petroleum wastewater sample containing 100 mg/L of phenols and 400 mg/l of COD for 120 min at CD of 8 mA/cm² and DBE of 20 mm. The obtained results, figure 6, prove that increasing the detention time enhances the removal efficiency of COD and phenols. Where, it has been noticed that the removal efficiency of phenols increased from 12% to the vicinities of 60% as the electrolyzing time growing from 10 to 120 minutes, correspondingly. Additionally, the removal of COD increased from 16% to about 85% as the detention times increased from 10 to 120 minutes, respectively.

This might be clarified by the libration of constant amounts of coagulants from the anodes for the constant CDs value and electrolyzing times [16]. Accordingly, growing the electrolyzing times rises the number of melted aluminum oxides (coagulant) in the solutions. Therefore, COD and phenol removals also rise. Furthermore, extended EC times give better contact times among contaminants and aluminum oxides that improves the removals of the targeted [39].
However, it can be seen from figure 6 that during the last 20 min of the experiment increase in removal efficiency was not very significant, where the removal of COD and phenols increased by about 3%. This could be attributed to the development of a passive layer on the surface of electrodes, which decreases the production of coagulants, consequently the removal efficiency. Therefore, it could be reasonable to keep the detention time, in the current study, at 100 min, which decreases the operational cost of this process. In summary, the obtained results indicated that the EC method could remove a significant amount of both phenols and COD from petroleum wastewater, but it is not enough to achieve the complete removal of these pollutants. Therefore, the authors believe that this method could be used as a pre-treatment unit for the petroleum wastewater, to enhance the performance of other treatment units (such as chemical precipitation units and filtration units).

![Figure 6. Influence of detention time on the removal of phenols and COD.](image)

The accumulation of solid particles on the surfaces of the electrodes results in the development of an inert layer of these electrodes, which consequently increases the consumption energy and decreases the removal efficiency [10, 11]. Therefore, continuous cleaning of electrodes is essential to maintain the efficiency of the EC unit, however, this process is not convenient as it is difficult to keep cleaning the electrodes during the treatment process. Some scholars have used sensors to monitor many processes, such as pollutants concentration [55], communication [56], and concrete quality [57, 58]. Thus, sensors could be used here to monitor the development of the inert layer on the electrodes.

4. **Technical and economic impacts**

The outcomes of the current study have important potential technical and economic benefits. In terms of economic benefits, the electrocoagulation method is a cost-effective alternative for traditional treatment methods because it minimises the volume of the produced sludge, it produces very dense sludge that means it does not require a dewatering process, and it could be operated using green energy sources (such as solar panels). Technically, the electrocoagulation method could be an eco-friendly and time-saving alternative for the traditional treatment methods because this method does not produce secondary pollutants and does not require chemical additives to achieve the removal process. Additionally, this method is easy to be installed, operated, and maintained, which means it does not require skilled labours to operate it.

5. **Conclusion**

Several sets of continuous flow experiments were carried out to investigate the feasibility of the EC method as a treatment method for petroleum wastewater. The obtained results indicated that this method could be used effectively to decrease the concentration of both phenols and COD in petroleum wastewater. Additionally, it has been found that the performance of this method, in terms of COD and phenols removals,
might be improved by raising the applied CD or the treatment times, or by decreasing the distance between electrodes. The authors recommend integrating the EC unit (as a pre-treatment unit) with other traditional methods to achieve a complete removal efficiency within a relatively short treatment time and at a reasonable cost. Additionally, as it is mentioned above that the accumulation of solid particles on the surfaces of the electrodes results in the development of an inert layer of these electrodes, which consequently increases the consumption energy and decreases the removal efficiency. Therefore, studies could be commenced to explore the effectiveness of sensors in monitoring the development of the inert layer on the electrodes.

References

[1] Aljuboury D, Palaniandy P, Abdul Aziz H and Feroz S 2017 Treatment of petroleum wastewater by conventional and new technologies-A review Glob. Nest J 19 439-52.
[2] Emamjomeh M M, Mousazadeh M, Mokhtari N, Jamali H A, Makkabiadi M, Nghdali 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.
[3] 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.
[4] Al-Saati N H, Hussein T K, Abbas M H, Hashim K, Al-Saati Z N, Kot P, Sadique M, Aljefery 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.
[5] 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 dreged sediment First International Conference on Materials Engineering & Science 38-41.
[6] Diya’uddeen B H, Daud W M A W and Aziz A A 2011 Treatment technologies for petroleum refinery effluents: A review Process safety and environmental protection 89 95-105.
[7] Hashim K S, AlKhaddar R, Shaw A, Kot P, Al-Jumeily D, Alwash R and Aljefery M H 2020 Electrocoagulation as an eco-friendly River water treatment method. In Advances in Water Resources Engineering and Management (Berline: Springer).
[8] Hassan Alnaimi I J I, Abduljaleel 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.
[9] 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.
[10] Hashim K S, Al-Saati N H, Alqzuweeni S S, Zubaidi S L, Kot P, Kraidi L, Hussein A H, Alkhaddar R, Shaw A and Alwash R 2019 Decolourization of dye solutions by electrocoagulation: an investigation of the effect of operational parameters First International Conference on Civil and Environmental Engineering Technologies (ICCEET) 584.
[11] 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
[12] Hashim K S, Khaddar R A, Jasim N, Shaw A, Phipps D, Kot P, Pedrola M O, Alattabi A W, Abdulredha M and Alawsh R 2019 Electrocoagulation as a green technology for phosphate removal from River water Separation and Purification Technology 210 135-44.

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

[14] 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.

[15] Alyafei A, AlKizwini R S, Hashim K S, Yeboah D, Gkantou M, Al Khaddar R, Al-Faluji 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.

[16] 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.

[17] 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)

[18] 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.

[19] 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.

[20] 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.

[21] 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.

[22] Zubaidi S L, Hashim K, Ethaib S, Al-Bdairi 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.

[23] 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.

[24] 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.

[25] 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.

[26] Zubaidi S L, Kot P, Alkhaddar R M, Abdellatif M and Al-Bugharbee H 2018 Short-Term Water Demand Prediction in Residential Complexes: Case Study in Columbia City, USA. In: 11th
International Conference on Developments in eSystems Engineering (DeSE), (University of Cambridge, UK: IEEE)

[27] 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 Within Three Land-Uses of Babylon Governorate, Iraq: Distribution, Sources, and Health Risk Assessment Journal of King Saud University - Engineering Sciences 33, 1-15

[28] Mohammed A-H, Hussein A H, Yeboah D, Al Khaddar R, Abdullhadi B, Shubbar A A and Hashim K S 2020 Electrochemical removal of nitrate from wastewater IOP Conference Series: Materials Science and Engineering 888.

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

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

[31] Al-Marri S, AIQuzweeni 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.

[32] Alenezi A K, Hasan H A, Hashim K S, Amoako-Attah J, Gkantou M, Muradov M, Kot P and Abdullhadi B 2020 Zeolite-assisted electrocoagulation for remediation of phosphate from calcium-phosphate solution IOP Conference Series: Materials Science and Engineering 888.

[33] 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.

[34] 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.

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

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

[37] 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.

[38] 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.

[39] 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

[40] Alenezi M, Hashim K S, Hassan A A, Muradov M, Kot P and Abdullhadi B 2020 Turbidity removal using natural coagulants derived from the seeds of strychnos potatorium: statistical and experimental approach IOP Conference Series: Materials Science and Engineering 888.
[41] Aqeel K, Mubarak H A, Amoako-Attah J, Abdul-Rahaim 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.

[42] 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.

[43] 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.

[44] 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.

[45] 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.

[46] 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.

[47] 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.

[48] 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.

[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] Idowu I A, Atherton W, Hashim K, Kot P, Alkhaddar 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.

[52] 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 in eSystems Engineering (DeSE)

[53] 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.

[54] 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.
[55] 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)*

[56] 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.

[57] 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.

[58] 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.