Optimization of iron removal in water by nanobubbles using response surface methodology

Cuizhen Sun, Guoxiu Wang, Caijuan Sun, Rupeng Liu, Zhibin Zhang, Taha Marhaba and Wen Zhang

ABSTRACT
Iron contamination, causing staining, discoloration and bad taste, is a worldwide water problem. It is necessary to focus on iron oxidation from the water. This work aims to develop nanobubbles (NBs) technology to remove iron (Fe$^{2+}$) from aqueous solutions. In batch experiments, the effects of initial Fe$^{2+}$ concentration, pH, and aeration pressure on the Fe$^{2+}$ oxidation efficiency were carried out. The results showed that initial concentrations, pH and aeration pressure are significant parameters influencing Fe$^{2+}$ oxidation. On the basis of single factor experiments, the Box–Behnken design was used to optimize the Fe$^{2+}$ oxidation conditions with NBs using three parameters (Fe$^{2+}$ concentration, pH, and aeration pressure) under the response surface methodology. The optimal Fe$^{2+}$ oxidation was achieved when the initial concentration was 13.7 mg·L$^{-1}$, pH = 9, and the aeration pressure was 290 kPa. The regression model of Fe$^{2+}$ oxidation rate under optimized test conditions is accurate and effective. The results showed that the combination of single factor test and response surface optimization can be used to optimize the Fe$^{2+}$ oxidation process with NBs. It is concluded that NBs technology is promising for Fe$^{2+}$ oxidation from water.

Key words | Box–Behnken design, iron removal, nanobubbles, optimization, response surface optimization

HIGHLIGHTS

- Nanobubbles (NBs) were developed to remove iron (Fe$^{2+}$) from water.
- The initial Fe$^{2+}$ concentrations, pH, and aeration pressure significantly affected Fe$^{2+}$ oxidation.
- The Box–Behnken design was used to optimize the iron oxidation conditions in NBs system.
With the increase in industrial development, groundwater pollution is increasing worldwide. Iron is an indispensable basic element for human and animals. Its deficiency can cause changes in children’s physical activities and mental development (Demlie et al. 2014). However, high iron can cause water pollution and many risks to human health, such as heart and liver damage, diabetes, liver cirrhosis, cartilage calcium, and other diseases. For water supply, iron (Fe$^{2+}$) causes staining, discoloration, bad taste, corrosion of pipes, and increase fouling and clogging in the pipelines, thereby improving bacterial growth and affecting water quality (Xie et al. 2018). For industries, such as printing, dyeing, and papermaking, high iron in water can decrease the quality of the products. According to the current Sanitary Standard for Drinking Water of China (GB5749-2006), iron in drinking water should not be higher than 0.3 mg·L$^{-1}$ (Wang et al. 2018). Therefore, more attention must be paid to iron removal from water.

A common iron treatment for groundwater uses the processes of oxidation followed by sedimentation or filtration. The chemicals for iron oxidation include potassium permanganate (KMnO$_4$), chlorine, and ozone (Choo et al. 2005; Phatai et al. 2014). KMnO$_4$ is more expensive than other oxidants and it is important to control the dosage to ensure all the iron has been oxidized and prevent the formation of pink sediment. Chlorination may cause trihalomethanes (THMs) formation, which can cause serious problems to human health. The oxidation efficiency of ozone may be obviously reduced by the humic or fulvic substances in water (Chaturvedi & Dave 2012). Therefore, a suitable oxidizing agent for iron is oxygen without the addition of chemicals. The natural oxidation process takes a long time and requires large-scale equipment, resulting in increased costs. It is important to have a simple operation with high oxidation efficiency and sustainable development for iron pre-oxidation technology.

In the past decades, nanobubbles (NBs) have been used in many water or wastewater treatment processes. The lead (Pb(II)) adsorption process of activated carbon can be accelerated by 366% using air NBs (Kyzas et al. 2019). The combination of precipitation and flotation with micro-bubbles and NBs can remove 81% calcium ions (Ca$^{2+}$) and 91% magnesium ions (Mg$^{2+}$) from water (Silva et al. 2020). Using a...
micro-nano bubble aeration device to treat domestic sewage, the removal efficiency of chemical oxygen demand (COD), suspended solids (SS) and ammonia nitrogen (NH3-N) can be increased by 4.4%, 7.3%, and 15%, respectively (Ghadimi et al. 2019). Quiñones (Quiñones & Flores 2018) concluded that the chloroform in wastewater can be reduced from 0.8 mg·L⁻¹ to 0.2 mg·L⁻¹ by NBs. The supplementation of N₂ NBs, air NBs, and CO₂ NBs increased methane yields by 22%, 18%, and 10%, respectively, in the process of anaerobic digestion (AD) of refractory cellulose because cellulase activity was elevated (Ho et al. 2020; Wang et al. 2020). After 5 days of NBs aeration in an urban black-odor river, dissolved oxygen (DO) improved from 0.60 mg·L⁻¹ to over 5.00 mg·L⁻¹, and COD and NH₄-N removal were increased by 50% (Wu et al. 2019). O₂ NBs can enhance photodegradation of oxytetracycline to 98% at pH 11.0 (Wang et al. 2020b). O₂ NBs-modified mineral reduced the release of total phosphorus (TP), total nitrogen (TN), and NH₃-N from sediments in eutrophic lakes due to the improvement of DO levels near the sediment–water interface and also decreased TP, TN and NH₃-N fluxes loading by 96.4%, 24.9% and 51.1% (Wang et al. 2020a). The advantages of using NBs include the extraordinary longevity, good stability, large specific surface area, high gas transfer rate, and release a large amount of free radicals (Ahmed et al. 2018; Atkinson et al. 2019). NBs have great potential to improve or replace the current technologies without the addition of chemicals. However, as a high-efficiency green technology, NBs have not been used to remove Fe²⁺. Therefore, developing a NBs method for oxidizing Fe²⁺ in water is the purpose of this work.

The Fe²⁺ oxidation from water may depend on many parameters using NBs. In order to study the influence of different variables on the treatment, obtain the best operating conditions for Fe²⁺ oxidation, and reduce the number of experiments, the response surface method (RSM) was used to optimize the process and experimental design. RSM can fully consider the interactional influence of different operating parameters (Tasaki et al. 2009; Moorby et al. 2015; Temesgen et al. 2017). RSM can also be used to find the optimal combination of parameters and evaluate the influence of various factors in multivariable complex systems by establishing an empirical numerical model and analyzing regression. Box–Behnken design (BBD) is one of the most effective RSMs (Dhiman et al. 2017). Many researchers have applied BBD technology to optimize various types of processes, such as antibiotics adsorption by activated carbon, Acid Black 1 dye oxidation by microalgae, and Pb(II) oxidation by pistachio (Yetilmeszoy et al. 2009; Kousha et al. 2012; Teixeira et al. 2019). However, no publications has focused on investigating the response surface modeling of Fe²⁺ oxidation in water by NBs using BBD. Experimental analysis using BBD is a special research field for developing NBs technology for Fe²⁺ oxidation, as well as achieving optimum oxidation efficiency.

This work investigated Fe²⁺ oxidation from water and examined the influence of initial Fe²⁺ concentration, pH, and aeration pressure on the oxidation efficiency using NBs. The three-factor BBD was applied to optimize the operation conditions of Fe²⁺ oxidation using NBs with the comprehensive evaluation index of Fe²⁺ oxidation.

**METHODS**

**Preparation of NBs**

NBs are generated in the Fe²⁺ solution by aerating with O₂ (purity 99.999%). The NBs generation system is shown in Figure 1. The Fe²⁺ solution was prepared using ferric sulfate produced by Tianjin Damao Chemical Reagent Factory. The length, inner diameter, and outer diameter of the NBs ceramic tube (model WFA0.1-Refractron, USA) are 51 mm, 8 mm, and 13 mm, respectively, with many 100 nm pores.

**Batch experiments**

At 25 °C, the effects of initial Fe²⁺ concentration (1.5 mg·L⁻¹–15 mg·L⁻¹), pH (4.0–9.0), and aeration pressure (100 kPa–400 kPa) on the Fe²⁺ oxidation were investigated. The solution pH was adjusted using 0.1 M NaOH and 0.1 M HCl. Under the continuous aeration with a NBs system, a water sample was taken every 30 min to determine the Fe²⁺ concentration. The phenanthroline spectrophotometry method was used to determine Fe²⁺ concentration using an atomic absorption spectrophotometer.

**Box–Behnken response surface optimization**

In order to obtain the optimum conditions of Fe²⁺ oxidation using NBs, the BBD with three factors (pH, initial Fe²⁺ concentration,
concentration, and aeration pressure) and three levels (−1, 0, 1) were used to design and analyze the experiments. The corresponding design coded is shown in Table 1. The comprehensive evaluation index is Fe$^{2+}$ oxidation. The design and statistical analysis were carried out using the Design-Expert 8.0.6 software. Regression models were obtained.

### RESULTS AND DISCUSSION

**Batch experiments**

The results in Figure 2(a) show that Fe$^{2+}$ oxidation using NBs was highly dependent on pH. The Fe$^{2+}$ oxidation efficiency progressively increased when pH was enhanced from 4.0 to 9.0 at aeration pressure of 300 kPa and the initial Fe$^{2+}$ concentration of 15 mg·L$^{-1}$. The oxidation rate of Fe$^{2+}$ was higher with an increase in pH, which is consistent with other reports (Sharma et al. 2005a, 2005b). At pH 4, 6, 8, and 9, the maximum oxidation rates of Fe$^{2+}$ were 36.2%, 46.8%, 98%, and 98.8%, respectively.

Figure 2(b) shows the Fe$^{2+}$ oxidation at aeration pressure of 300 kPa and pH 9. There is no obvious

---

**Table 1** Experimental coded factors and levels in the BBD

| Factors and coded factors | Ranges and levels |
|---------------------------|-------------------|
|                         | Low level | Center level | High level |
| pH, A                    | 4.0       | 6.5          | 9.0        |
| Fe$^{2+}$ concentration (mg·L$^{-1}$), B | 9         | 12           | 15         |
| Aeration pressure (kPa), C | 100       | 250          | 400        |

---

**Figure 1** Design of NBs generation system and scanning electron microscopy image of the ceramic tubular filter.
The difference in oxidation efficiency (98.3–98.8%) when Fe^{2+} concentration was 9, 12, and 15 mg·L$^{-1}$ is slightly affected (92.3%, 95.2%, and 97.6%, respectively).

At lower pH, Fe^{2+} can combine with water to form hydrated ions Fe(H$_2$O)$_6^{++}$, thereby decreasing its oxidation. This has been confirmed scientifically. Electron transfer between the oxidant and the reducing agent is needed to complete the redox reaction. The central ion of Fe(H$_2$O)$_6^{++}$ is surrounded by six H$_2$O molecules, which shield the electron migration between O$_2$ molecules and Fe$^{2+}$. Therefore, the oxidation of Fe(H$_2$O)$_6^{++}$ is very slow. When the solution pH increases, OH$^-$ can capture H$^+$ in the water molecules around Fe$^{2+}$ and promote the hydrolysis of Fe(H$_2$O)$_6^{++}$ ions. The hydrolysis products of the ferrous ion are separated due to the neutralization of the electrical properties of the central ion, which weakens the polarization of the coordinated water molecules. Therefore, the shielding effect of the coordination water disappears and the oxidation rate of Fe$^{2+}$ increases.

The injection pressure can promote the dissolution of O$_2$ in water. When the pressure increased, the size of the generated nanobubbles declined and their specific surface area was enhanced. The mass transfer efficiency was improved. In the first 120 min, the amount of NBs increased with increasing pressure. The number of OH$^-$ radicals and DO in the solution increased, which enhanced the oxidation rate of Fe$^{2+}$. When the reaction lasted for 120 min, the OH$^-$ and DO reached saturation, and the reaction rate became stable.

**Box–Behnken experimental design and variance analysis**

The Box–Behnken experimental design, and the experimental and predicted Fe$^{2+}$ removal efficiency using NBs are presented in Table 2. To determine the impact of operating parameters on the response, the experimental values were fitted to the following second regression equation:

$$Y = a_0 + a_1 A + a_2 B + a_3 C + a_{12} AB + a_{23} BC + a_{13} AC + a_{11} A^2 + a_{22} B^2 + a_{33} C^2$$  (1)
where \( Y \) is the response; \( a_0 \) refers to a constant; \( a_1, a_2, a_3 \) are linear influences of factors; \( a_{12}, a_{25}, a_{13} \) are interactive effects of the factors; and \( a_{11}, a_{22}, a_{33} \) are quadratic influences of factors. \( A, B, C \) refer to \( \text{pH} \), initial \( \text{Fe}^{2+} \) concentration, and aeration pressure, respectively.

The quadratic model analyzed by the Design-Expert software is given in the following equation:

\[
Y = 47.52 + 2.01A + 5.19B - 0.034C - 4.86AB - 0.99AC + 3.33BC + 28.4A^2 - 11.27B^2 - 5.26C^2 \tag{2}
\]

This regression equation suggested that the \( \text{Fe}^{2+} \) removal efficiency was affected by the variables. The effective analysis of variance (ANOVA) is shown in Table 3 to evaluate the significance of the model. When \( P > F \)-value is less than 0.05, the model is significant under experimental conditions. When \( P > F \)-value is less than 0.01, the model is extremely important. For \( \text{Fe}^{2+} \) removal with NBs, the quadratic model is very significant. Only the aeration pressure has no linear effect on the response due to the higher \( P > F \)-value (0.6724) and the lower \( F \)-value (0.19). All interactive and quadratic effects of variables are highly significant to NBs system. The \( P > F \)-value (0.0645) for lack-of-fit is greater than 0.05, suggesting that the quadratic equation is valid for the prediction of all NBs systems. Additionally, the second-order model can explain all the variables in the response because of the high \( F \)-value. The linear term of \( \text{pH} \) is the most influential of all terms due to its \( F \)-value of 134,000.

### Table 2 | Experimental designs, and the actual and predicted responses for \( \text{Fe}^{2+} \) removal using NBs

| Run | Real (coded) value for variables | Response (\( \text{Fe}^{2+} \) removal efficiency, \%) | Exper. | Pred. |
|-----|---------------------------------|-------------------------------------------------|--------|------|
| 1   | 6.5 (0) 12 (0) 250 (0)          | 47.50                                           | 47.52  |
| 2   | 4.0 (−1) 15 (1) 250 (0)         | 46.72                                           | 46.69  |
| 3   | 6.5 (0) 15 (1) 100 (−1)         | 33.00                                           | 32.88  |
| 4   | 9.0 (1) 12 (0) 100 (−1)         | 99.50                                           | 99.70  |
| 5   | 6.5 (0) 12 (0) 250 (0)          | 47.50                                           | 47.52  |
| 6   | 9.0 (1) 12 (0) 400 (1)          | 97.79                                           | 97.64  |
| 7   | 6.5 (0) 12 (0) 250 (0)          | 47.58                                           | 47.52  |
| 8   | 6.5 (0) 9 (−1) 100 (−1)        | 29.40                                           | 29.17  |
| 9   | 6.5 (0) 12 (0) 250 (0)          | 47.33                                           | 47.52  |
| 10  | 9.0 (1) 9 (−1) 250 (0)         | 92.30                                           | 92.33  |
| 11  | 9.0 (1) 15 (1) 250 (0)         | 93.07                                           | 92.99  |
| 12  | 4.0 (−1) 9 (−1) 250 (0)        | 26.50                                           | 26.58  |
| 13  | 4.0 (−1) 12 (0) 400 (1)        | 43.80                                           | 43.60  |
| 14  | 4.0 (−1) 12 (0) 100 (−1)       | 41.54                                           | 41.69  |
| 15  | 6.5 (0) 12 (0) 250 (0)         | 47.67                                           | 47.52  |
| 16  | 6.5 (0) 15 (1) 400 (1)         | 39.26                                           | 39.49  |
| 17  | 6.5 (0) 9 (−1) 400 (1)         | 22.32                                           | 22.44  |

### Table 3 | Effective ANOVA of RSM equation model for \( \text{Fe}^{2+} \) removal

| Mode | Sum of squares | Degree of freedom | Mean square | \( F \)-value | \( P > F \) |
|------|----------------|------------------|-------------|--------------|------------|
| A    | 6,277.6        | 1                | 6,277.60    | 134,000      | <0.001     |
| B    | 215.59         | 1                | 215.59      | 4,603.24     | <0.001     |
| C    | 9.112E-003     | 1                | 9.112E-003  | 0.19         | 0.6724     |
| AB   | 94.58          | 1                | 94.58       | 2,019.34     | <0.001     |
| AC   | 3.94           | 1                | 3.94        | 84.13        | <0.001     |
| BC   | 44.49          | 1                | 44.49       | 949.91       | <0.001     |
| A\(^2\) | 3,395.32    | 1                | 3,395.32    | 72,495.46    | <0.001     |
| B\(^2\) | 534.36       | 1                | 534.36      | 11,409.51    | <0.001     |
| C\(^2\) | 116.30       | 1                | 116.30      | 2,483.10     | <0.001     |
| Residual | 0.33         | 7                | 0.047       | –            | –          |
| Lack-of-fit | 0.26     | 3                | 0.088       | 5.61         | 0.0645     |
| Pure error | 0.063       | 4                | 0.016       | –            | –          |
| Cor. total | 10,513.41    | 16               | –           | –            | –          |
The high correlation coefficient value ($R^2 = 0.986$) indicated that only 1.4% of the total variation cannot be explained by this model, and the predicted removal efficiency is close to the measured results (Sulaiman et al. 2018). The high adjusted determination coefficient ($R^2_{adj} = 0.999$) confirmed that the model is of great significance to the NB system. The coefficient of variation (CV) is an important index of model accuracy and reliability (Chi et al. 2012; Bedin et al. 2018). Low CV proves the high reliability of the model. The low CV (0.41%) of this experimental model indicated that the model is very reliable.

**Statistical analysis for experimental model**

Residual analysis can be used for the diagnosis of response surface optimization model. The residuals distribution and the normal probability are extremely significant to detect error variance homogeneity for checking the model’s adequacy (Mohammed et al. 2017). As seen in Figure 3(a), the homogeneity of residual variances is in line with the requirements because the residuals of the model predicted values are independently distributed. By displaying the linear residual fitting curve in Figure 3(b), the experimental model was able to represent the system under experimental conditions. This is confirmed by the plots of the predicted and experimental results in Figure 4(a). The predicted Fe$^{2+}$ removal efficiency is satisfactorily correlated with the experimental values because the data distribution along the diagnostic line of the model is approximately linear, and the deviation between the predicted and experimental results is small.

Figure 4(b) represented the perturbation diagrams of different variables to investigate their effects on response for NB technology. The Fe$^{2+}$ removal efficiency of the NBs system is controlled by pH (A), initial Fe$^{2+}$ concentration (B), and aeration pressure (C). Fe$^{2+}$ removal is...
highly sensitive to pH (A) on the sharp curve. Initial $\text{Fe}^{2+}$ concentration (B) and aeration pressure (C) have little influence on $\text{Fe}^{2+}$ removal efficiency on the flat curves.

**Three-dimensional surface response**

The three-dimensional (3D) surfaces graph obtained on the basis of the regression equation is shown in Figure 5 and was used to intuitively check the interactive influence of factors on the dependent variable. The non-linear nature of curves indicated that the interaction of initial $\text{Fe}^{2+}$ concentration, pH, and aeration pressure had an important effect on the $\text{Fe}^{2+}$ removal efficiency.

As seen in Figure 5(a), incremental pH increased $\text{Fe}^{2+}$ oxidation efficiency under constant aeration pressure. The higher $\text{Fe}^{2+}$ concentration cause the oxidation efficiency of $\text{Fe}^{2+}$ to increase to the maximum. In addition, a further increase in $\text{Fe}^{2+}$ concentration led to a decrease in oxidation. At a fixed aeration pressure of 250 kPa, the maximum oxidation efficiency was obtained at pH of 9.0 and $\text{Fe}^{2+}$ of 12 mg·L$^{-1}$. It can be seen from Figure 5(b) that the $\text{Fe}^{2+}$ removal is enhanced with increasing pH, while aeration pressure has little effect on the response. When the fixed $\text{Fe}^{2+}$ concentration was 12 mg·L$^{-1}$, the maximum oxidation efficiency was obtained at pH 9.0 and aeration pressure of 250 kPa. It can be seen from Figure 5(c) that the maximum oxidation efficiency was obtained at $\text{Fe}^{2+}$ concentration of 12 mg·L$^{-1}$, aeration pressure of 250 kPa for a fixed pH of 6.5.

If the regression equation is taken as the partial derivative of each variable and is equal to 0, the quaternary system of first-order equation can be obtained. The virtual values of the corresponding optimization factor level are 1 (pH), 0.47 mg·L$^{-1}$ ($\text{Fe}^{2+}$), and 0.51 kPa (ventilation pressure). The corresponding actual values are 9.0 (pH), 11.97 mg·L$^{-1}$ ($\text{Fe}^{2+}$), and 251.5 kPa (aeration pressure). For the purpose of model validation, three other experiments were performed under the optimal conditions. The response of the proposed model was compared with the measured $\text{Fe}^{2+}$ oxidation efficiency, and the results are listed in Table 4. At pH 9.0, $\text{Fe}^{2+}$ concentration of 12 mg·L$^{-1}$ and aeration pressure of 250 kPa, the predicted value (99.33%) of the theoretical $\text{Fe}^{2+}$ oxidation efficiency regression model was clearly consistent with the measured value (99.21%). This demonstrated that the regression

![Figure 5](image_url) 3D response surface plot for the NBs system: (a) initial $\text{Fe}^{2+}$ concentration and pH at 300 kPa; (b) aeration pressure and pH with initial $\text{Fe}^{2+}$ concentration = 15 mg·L$^{-1}$; (c) aeration pressure and initial $\text{Fe}^{2+}$ concentration at pH 9.

Table 4 | Predicted values and measured values of $\text{Fe}^{2+}$ removal with NBs

| pH | $\text{Fe}^{2+}$ (mg·L$^{-1}$) | Aeration pressure (kPa) | $\text{Fe}^{2+}$ removal rate (%) |
|----|-----------------|-----------------|------------------|
| 9  | 12              | 250             | 99.39            |
| 9  | 12              | 250             | 99.33            |
| 9  | 12              | 250             | 99.27            |

C. Sun et al. | Iron removal in water by nanobubbles | Water Supply | 21.4 | 2021
model for describing the Fe\textsuperscript{2+} oxidation process using NBs was accurate and effective.

**CONCLUSIONS**

NBs have the characteristics of long hydraulic retention time, good stability, large specific surface area, self-pressurized dissolution, and can release a large number of free radicals. NBs can be used to degrade pollutants and heavy metals that are difficult to degrade, and to purify water. Therefore, the use of NBs to remove Fe\textsuperscript{2+} has important social and economic significance. In order to analyze the process of Fe\textsuperscript{2+} oxidation using NBs and study the influence of various factors on the response value, response surface optimization analysis techniques can be adopted. On the basis of the above experiments, the Box–Behnken response surface optimization method was used to optimize the parameters of NB oxidation, and a corresponding numerical model was established. The regression analysis on variance of the model was carried out. The response surface optimization conditions are pH 9, Fe\textsuperscript{2+} concentration 12 mg·L\textsuperscript{−1}, and aeration pressure of 250 kPa. The regression model for the Fe\textsuperscript{2+} oxidation rate under optimized test conditions is accurate and effective. The results show that the combination of single factor test and response surface optimization can be used to optimize the oxidation process of NBs on Fe\textsuperscript{2+}.

**ACKNOWLEDGEMENTS**

Funded by Science and Technology Plans of Ministry of Housing and Urban-Rural Development of the People’s Republic of China, and Opening Projects of Beijing Advanced Innovation Center for Future Urban Design Beijing University of Civil Engineering and Architecture (UDC201703151).

**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

**REFERENCES**

Ahmed, A. K. A., Sun, C. Z., Hua, L. K., Zhang, Z. B., Zhang, Y. H., Zhang, W. & Marhaba, T. 2018 Generation of nanobubbles by ceramic membrane filters: the dependence of bubble size and zeta potential on surface coating, pore size and injected gas pressure. *Chemosphere* **203**, 327–335.

Atkinson, A. J., Apul, O. G., Schneider, O., García-Segura, S. & Westerhoff, P. 2019 Nanobubble technologies offer opportunities to improve water treatment. *Accounts of Chemical Research* **52** (5), 1196–1205.

Bedin, K. C., Cazetta, A. L., Souza, I. P. A. F., Pezoti, O., Souza, L. S., Souza, P. S. C., Yokoyama, J. T. C. & Almeida, V. C. 2018 Porosity enhancement of spherical activated carbon: influence and optimization of hydrothermal synthesis conditions using response surface methodology. *Journal of Environmental Chemical Engineering* **6** (1), 991–999.

Chaturvedi, S. & Dave, P. N. 2012 Removal of iron for safe drinking water. *Desalination* **303**, 1–11.

Chi, G., Hu, S., Yang, Y. & Chen, T. 2012 Response surface methodology with prediction uncertainty: a multi-objective optimisation approach. *Chemical Engineering Research and Design* **90** (9), 1235–1244.

Choo, K.-H., Lee, H. & Choi, S.-J. 2005 Iron and manganese removal and membrane fouling during UF in conjunction with prechlorination for drinking water treatment. *Journal of Membrane Science* **267** (1), 18–26.

Demlie, M., Hingston, E. & Minis, Z. 2014 A study of the sources, human health implications and low cost treatment options of iron rich groundwater in the northeastern coastal areas of KwaZulu-Natal, South Africa. *Journal of Geochemical Exploration* **144**, 504–510.

Dhiman, N., Shukla, S. & Kisku, G. 2017 Statistical optimization of process parameters for removal of dyes from wastewater on chitosan cenospheres nanocomposite using response surface methodology. *Journal of Cleaner Production* **149**, 597–606.

Ghadimkhani, A., Zhang, W. & Marhaba, T. 2016 Ceramic membrane defouling (cleaning) by air Nano Bubbles. *Chemosphere* **146**, 379–384.

Ho, T. H., Yang, X. J., Nie, J. M., Zhao, Z. W., Wei, Y., Shimizu, K., Zhang, Z. Y. & Lei, Z. F. 2020 Effect of nanobubble water on anaerobic methane production from lignin. *Research on Chemical Intermediates* **46** (11), 4767–4780.

Kousha, M., Daneshvar, E., Dopeikar, H., Taghavi, D. & Bhatnagar, A. 2012 Box–Behnken design optimization of Acid Black 1 dye biosorption by different brown macroalgae. *Chemical Engineering Journal* **179**, 158–168.

Kyzas, G. Z., Bomis, G., Kosheleva, R. I., Efthimiadou, E. K., Favvasa, E. P., Kostoglou, M. & Mitropoulos, A. C. 2019 Nanobubbles effect on heavy metal ions adsorption by activated carbon. *Chemical Engineering Journal* **356**, 91–97.

Mohammed, I. Y., Abakr, Y. A., Yusup, S. & Kazi, F. K. 2017 Valorization of Napier grass via intermediate pyrolysis: optimization using response surface methodology and
pyrolysis products characterization. *Journal of Cleaner Production* **142**, 1848–1866.

Moorthy, I. G., Maran, J. P., Surya, S. M., Naganyashree, S. & Shivamathi, C. S. 2015 Response surface optimization of ultrasound assisted extraction of pectin from pomegranate peel. *International Journal of Biological Macromolecules* **72**, 1323–1328.

Phatai, P., Wittayakun, J., Chen, W. H., Futalan, C. M., Grisdanurak, N. & Kan, C. C. 2014 Removal of manganese(II) and iron(II) from synthetic groundwater using potassium permanganate. *Desalination and Water Treatment* **52** (51–53), 5942–5951.

Quiñones, I. M. B. & Flores, J. V. 2018 Treatment of wastewater with chloroform from an environmental laboratory using air micro-nanobubbles. *Journal of Nanotechnology* **2** (2), 23–28.

Sharma, S. K., Petrusevski, B. & Schippers, J. C. 2005a Biological iron removal from groundwater: a review. *Journal of Water Supply: Research and Technology – AQUA* **54** (4), 239–247.

Sharma, S. K., Petrusevski, B. & Schippers, J. C. 2005b Biological iron removal from groundwater: a review. *Journal of Water Supply: Research and Technology-AQUA* **54** (4), 239–247.

Silva, R. D. R., Rodrigues, R. T., Azevedo, A. C. & Rubio, J. 2020 Calcium and magnesium ion removal from water feeding a steam generator by chemical precipitation and flotation with micro and nanobubbles. *Environmental Technology* **41** (17), 2210–2218.

Sulaiman, N. S., Hashim, R., Amini, M. H. M., Danish, M. & Sulaiman, O. 2018 Optimization of activated carbon preparation from cassava stem using response surface methodology on surface area and yield. *Journal of Cleaner Production* **198**, 1422–1430.

Tasaki, T., Wada, T., Baba, Y. & Kukizaki, M. 2009 Degradation of surfactants by an integrated nanobubbles/VUV irradiation technique. *Industrial & Engineering Chemistry Research* **48** (9), 4237–4244.

Teixeira, S., Delerue-Matos, C. & Santos, L. 2009 Application of experimental design methodology to optimize antibiotics removal by walnut shell based activated carbon. *Science of the Total Environment* **646**, 168–176.

Temesgen, T., Bui, T. T., Han, M., Kim, T. I. & Park, H. 2017 Micro and nanobubble technologies as a new horizon for water-treatment techniques: a review. *Advances in Colloid and Interface Science* **246**, 40–51.

Wang, L. L., Li, Q., Li, Y., Sun, X. Y., Li, J. S., Shen, J. Y., Han, W. Q. & Wang, L. J. 2018 A novel approach for recovery of metals from waste printed circuit boards and simultaneous removal of iron from steel pickling waste liquor by two-step hydrometallurgical method. *Waste Management* **71**, 411–419.

Wang, J. F., Chen, J. G., Yu, P. P., Yang, X. H., Zhang, L. J., Geng, Z. L. & He, K. K. 2020 Oxygenation and synchronous control of nitrogen and phosphorus release at the sediment-water interface using oxygen nano-bubble modified material. *Science of The Total Environment* **725**, 138258–138266.

Wang, L., Ali, J., Wang, Z. B., Oladoja, N. A., Cheng, R., Zhang, C. B., Mailhot, G. & Pan, G. 2020b Oxygen nanobubbles enhanced photodegradation of oxytetracycline under visible light: synergistic effect and mechanism. *Chemical Engineering Journal* **388**, 124227–124236.

Wang, X. Z., Yuan, T., Guo, Z. T., Han, H. L., Lei, Z. F., Shimizu, K., Zhang, Z. Y. & Lee, D. J. 2020c Enhanced hydrolysis and acidification of cellulose at high loading for methane production via anaerobic digestion supplemented with high mobility nanobubble water. *Bioresource Technology* **297**, 122499–122506.

Wu, Y. F., Lin, H., Yin, W. Z., Shao, S. C., Lv, S. H. & Hu, Y. Y. 2019 Water quality and microbial community changes in an urban river after micro-nanobubble technology in situ treatment. *Water* **11** (1), 66–76.

Xie, S. W., Xie, Y. F., Ying, H., Gui, W. H. & Yang, C. H. 2018 A hybrid control strategy for real-time control of the iron removal process of the zinc hydrometallurgy plants. *IEEE Transactions on Industrial Informatics* **14** (12), 5278–5288.

Yetilmezsoy, K., Demirel, S. & Vanderbei, R. J. 2009 Response surface modeling of Pb(II) removal from aqueous solution by Pistacia vera L.: Box–Behnken experimental design. *Journal of Hazardous Materials* **171** (1–3), 551–562.

First received 27 September 2020; accepted in revised form 26 January 2021. Available online 11 February 2021