Optimising water use in copper flotation with the design of experiments and machine learning

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DATES:
Received: 01 June 2023
Revised: 04 Sep. 2024
Accepted: 27 Jan. 2025
Published: 27 Mar. 2025

HOW TO CITE:
El-Bacha R, Salhi A, Abderrafia H, Rabi S. Optimising water use in copper flotation with the design of experiments and machine learning. S Afr J Sci. 2025;121(3/4), Art. #16239. https://doi.org/10.17159/sajs.2025/16239

ARTICLE INCLUDES:
☒ Peer review
☐ Supplementary material

DATA AVAILABILITY:
☐ Open data set
☐ All data included
☒ On request from author(s)
☐ Not available
☐ Not applicable

EDITORS:
Michael Inggs
Thywill Dzogbewu

KEYWORDS:
fresh water, recycled water, sustainable water management, machine learning, design of experiments, recovery, response surface

FUNDING:
None

As part of the management of water resources at the industrial level, especially with the drop in water levels caused by drought, we resort to the recycling of water in the copper flotation process at Bleida Mine in Morocco. This study aims to take into consideration both the environmental conditions in terms of the reduction in water reserves and economic conditions in terms of ensuring sufficient metal recovery. Experimental findings demonstrated that the use of recycled water has a significant impact on copper recovery and grade. For that, this impact was investigated in order to determine the optimal proportion of recycled and fresh water that can be used in the mining process to ensure sufficient metal recovery. Through the design of experiments with the integration of machine learning, especially for the choice of the model, the optimal proportion was determined, which made it possible to achieve a metal recovery of more than 80% using a 50/50 mix of fresh and recycled water. This result was confirmed with real tests by trying several proportions in the Denver flotation cell in the laboratory. This approach not only advances the field of water resource optimisation but also provides a practical experimental framework for similar applications in other industries' challenges by searching for a balance between environmental sustainability and economic efficiency.

Significance:

The use of 100% fresh water can lead to higher efficiency, but its high cost makes it economically unfeasible. However, using a mixture of 50% fresh water and 50% recycled water can be both cost-effective and efficient. Furthermore, the use of experimental designs to optimise reagents can help companies achieve the best possible efficiency despite using recycled water. Therefore, this approach can be a sustainable and cost-effective solution for companies looking to maximise their profits while reducing their environmental impact.

Introduction

In recent years, we have resorted to the use of recycled water in industry to compensate for the decline in fresh water. On the one hand, it helps conserve freshwater resources, but it also poses problems at the industrial level as this recycled water contains harmful elements that can negatively influence industrial processes, such as the copper flotation process, which is an important process used for the extraction of copper from its ores.[1-3] Among the factors that impact the efficiency of the flotation operation, we find the quality of the water used.[4-11] In recent years, there has been rising interest in using recycled water in copper flotation due to the decrease in the quantity of water in the resources.[12]

The effect of recycled water on copper flotation has been studied extensively in scientific research. Various studies have demonstrated that the use of recycled water can have a negative effect on copper flotation because it may contain contaminants that can disrupt the flotation process. Contaminants can be dissolved salts, organic compounds and minerals.[13]

To resolve this issue, researchers have focused on determining the ideal proportion of fresh water to use in copper flotation to ensure adequate efficiency.[14-16] To do this, tests on different proportions of fresh and recycled water were carried out to determine the optimal proportions that will ensure sufficient metal recovery.

Several studies[17-19] using recycled water in copper flotation have been conducted. Researchers have found that the use of recycled water can decrease copper recovery compared to fresh water and may increase the consumption of reagents as it contains elements such as calcium, magnesium and sulfate ions that react with reagents used in the flotation, and this also affects the pH and chemical composition of the flotation pulp.

However, Wang et al. found that the use of recycled water had no significant impact on recovery; even with recycled water, if the concentration of impurities was low, the effect on recovery was negligible.[20]

In addition, Feo et al.[21] studied the use of recycled water in copper flotation and found that it did not significantly affect the recovery of copper; on the contrary, it helped to reduce the consumption of fresh water and reagents because the recycled water already contained a quantity of the recycled reagents used before.

In summary, the impact of recycled water on copper flotation recovery depends on its quality, the flotation conditions and the nature of residual impurities. On the one hand, several studies have found a negative impact of recycled water on copper recovery, but on the other hand, others have found no significant impact or even a positive influence. Therefore, further research in this context is needed to fully understand the impact of recycled water on copper flotation recovery in order to achieve sufficient recovery while optimising the use of fresh water in the mining industry.

Traditional optimisation methods are mainly based on the design of experiments, which allows us to model the phenomena by mathematically linking the factors (fresh water and recycled water) with the response (metal recovery). However, a problem arises when choosing the model because all the phenomena are not linear. In the present study, to solve this challenge, machine learning was integrated into the step of choosing an adequate model during the design of experiments. By applying this approach, the optimal water proportion can be determined efficiently.

Materials and methods

To investigate the impact of different proportions of fresh and recycled water on copper flotation recovery, a series of laboratory experiments was conducted. A representative sample of the copper ore was collected and mechanically prepared by crushing, followed by grinding and then screening to achieve the liberation mesh of malachite ($Cu_2(OH)_2CO_3$), which is about 125 µm. The tests were then carried out in a Denver flotation cell in the laboratory, each time varying the proportions of fresh and recycled water.[22] Then, the experimental design was followed by selecting a range of different proportions of fresh and recycled water to be used in the experiments and systematically varying these proportions to identify the optimal ratio that provided the best recovery. During each experiment, recovery of copper and the grade of the concentrate were collected to analyse the impact of the different proportions. The data collected were then analysed using statistical graphics to identify the impact of the different proportions of fresh and recycled water on the copper flotation recovery. The results obtained from the experiments and the data analysis results were interpreted to conclude the optimal proportion of fresh and recycled water for copper flotation recovery.

To sum up, conducting a series of laboratory experiments with different proportions of fresh and recycled water is an effective way to investigate the impact of water quality on copper flotation recovery. By systematically varying the proportion of fresh and recycled water, researchers can identify the optimal ratio that provides the best results and optimise the use of water in copper flotation processes.[23,24]

The overflow from the hydrocyclone is conditioned and then fed into a flotation line where various reagents are added, such as collector, frother and activator.

Below is the flow sheet of the flotation process, which begins with a feed with a dimension of 120 µm. It undergoes two types of roughing, sulfide and then oxide, followed by cleaning, before directing the froths rich in copper towards the concentrate and the remaining material towards the gangue. The same circuit was applied at the laboratory level in a Denver flotation cell to assess the impact of water on copper recovery. All other parameters were fixed; we worked at ambient temperature and pressure and only the water proportions were changed. In this context, a data set containing the observations of metal recovery at different water proportions was collected during the tests (Figure 1).

Factor levels (proportions) and affectations are shown in Table 1.

The calculation of the number of tests is shown in Table 2.

Results and discussion

After conducting the four tests according to the complete factorial design at two levels, each test was triplicated, and the value indicated in Table 3 represents the mean.

Concerning the choice of the model, we carried out machine learning in which we trained the linear and polynomial models on a data set containing the observations of metal recovery at the different water proportions.

Table 4 presents the metrics of the two models, and we can conclude that the polynomial model is the most appropriate given the high values of R-squared, adjusted R-squared and cross-validated R-squared compared to the linear model as well as the lowest mean squared error, which means that the polynomial model had a lower error and better explains the relationship between factors and response.

Table 1: Low and high levels of the factors

Factor	Low level (–1)	High level (1)
Fresh water (FW)	0%	100%
Recycled water (RW)	0%	100%

The test (FW 100% and RW 100%) is an experimental constraint, brought back to an equilibrium of 50% FW and 50% RW.

Table 2: Calculation of the number of tests

Number of factors	Number of levels	Number of tests
2	2	$2^2 = 4$

Table 3: Results of tests

N° Test	Fresh water (%)	Recycled water (%)	Metal recovery (%)
1	–1	1	72.82
2	1	–1	87.55
3	1	1	81.73
4	–1	–1	0

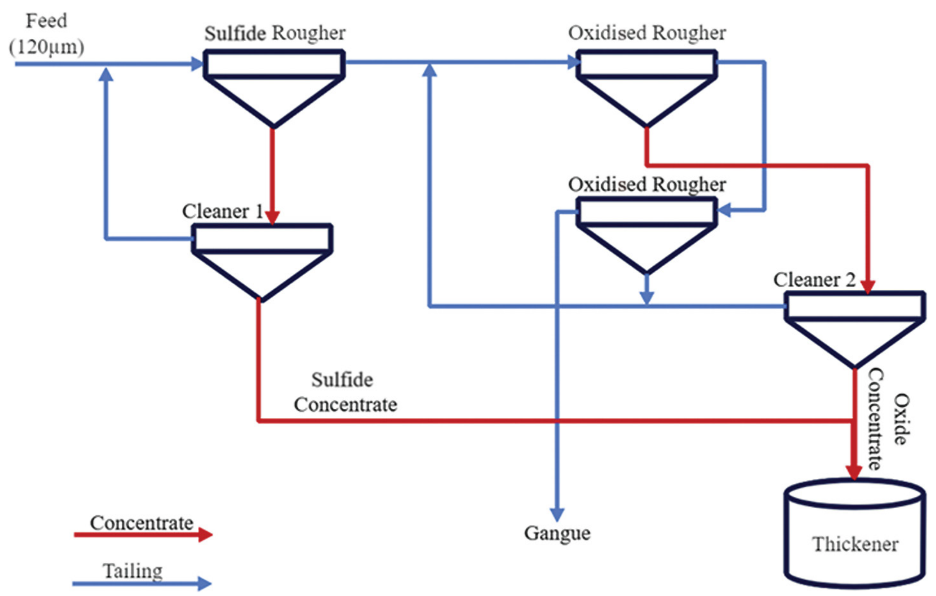

Figure 1: Flotation process flow sheet.

The postulated mathematical model is a polynomial model with respect to each factor. After calculating the main effects of fresh water (FW) and recycled water (RW) as well as the effect of their interaction, we obtained this mathematical modelling equation in uncoded units.

$$MR = 60.5250 + (24.1150) \times FW + (16.7500) \times RW + (0.0000) \times FW^2 + (-19.6600) \times FWRW + (0.0000) \times RW^2$$

This modelling equation mathematically links the response, which is metal recovery (MR), to the two factors: fresh and recycled water. Therefore, metal recovery can be predicted at any value of the factors without conducting the test. Other information that can be derived from this equation concerns the significant effect of fresh water compared to the effect of recycled water and their interaction. This is evident as its coefficient in the previous equation, in its absolute value, is higher. This observation can be confirmed by the Pareto diagram (Figure 2a) as well as the diagram of the main effects below.

These diagrams allow us to identify the most influential factor in a response: we notice that fresh water has a greater influence on turbidity because a small change significantly affects it, whereas recycled water requires larger variations to observe its effect (Figure 2b), and this confirms the result obtained with the Pareto diagram (Figure 2a).

Table 4: Results of tests

Metric	Linear regression	Polynomial regression
R-squared	0.28	0.84
Adjusted *R*-squared	0.27	0.83
Mean squared error	39.32	8.48
Cross-validated *R*-squared	−14.91	0.16

The response surface gives two points where the metal recovery is maximum (80%): the first point using the maximum fresh water and the second using a mixture of 50% fresh water and 50% recycled water (Figure 3).

It is clear that by using fresh water, the metal recovery will be at its maximum thanks to the absence of penalising elements which disrupt the flotation process, such as calcium, magnesium, sulfates and carbonates; in this case, the flotation is done under the best conditions.

By recycling the water at almost 50%, we see that the recovery is close to that obtained by using fresh water, which means that this recycled quantity is optimal for flotation, and we can explain this by saying that the dose of recycled reagents is not yet disruptive and contributes to the activation and collection of copper elements, yet the influence of other elements is not noticed.

In order to confirm this result, we first compared the kinetics of the copper grade during the flotation process for the two types of water – fresh and recycled; several tests were conducted in the laboratory. Table 5 shows the results of these tests.

Sulfide copper was better recovered using fresh water than using recycled water, while oxidised copper was better recovered using recycled water than fresh water. This can be explained by the fact that recycled water already contains a quantity of sulfates resulting from the decomposition of the activator (NaHS), which forms a first layer on the sulfide copper. When the collector is added, a double layer is formed, which depresses the sulfide copper. On the other hand, using fresh water forms a single layer, and flotation takes place under favourable conditions. The good content of oxidised copper using recycled water can be explained by the fact that it contains a quantity of decomposed sulfates, which adds to the amount of NaHS added, surrounding the oxidised copper with a sulfur layer, which leads to its activation, as the oxidation rate is around 75% (Figure 4).

After conducting several copper flotation tests with different types of water, we obtained the results shown in Table 6.

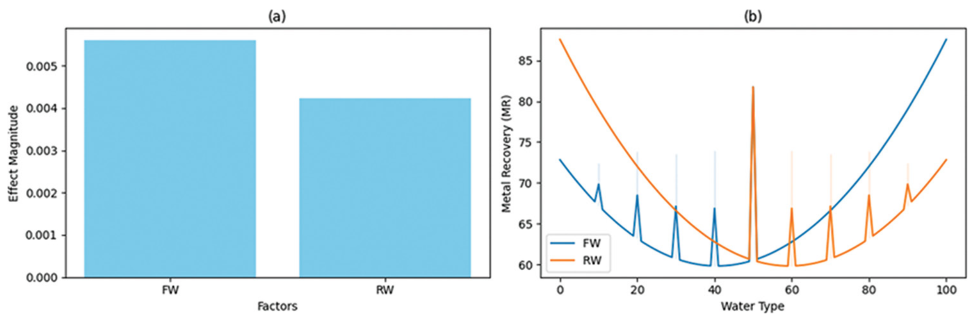

Figure 2: (a) Pareto chart; (b) main effects plot for metal recovery.

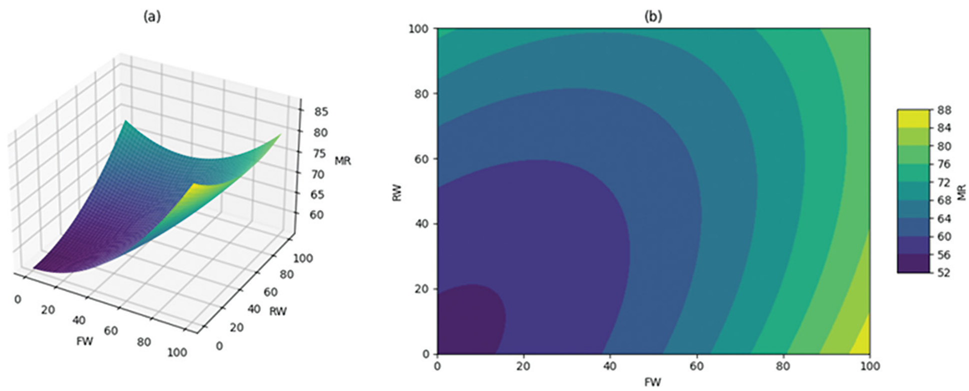

Figure 3: (a) Surface plot of metal recovery; (b) contour plot of metal recovery.

Metal recovery decreases with the increase in the proportion of recycled water. This can be explained by the fact that fresh water does not contain or contains low quantities of penalising elements such as Ca, Mg, sulfates and carbonates. However, introducing recycled water in quantities greater than 50% is detrimental to recovery due to the high number of penalising elements that are recycled and disrupt the flotation process (Figure 5).

Table 5: Results of the kinetics of the copper grade during flotation

	Concentration (%)	
Flotation stages	**Using fresh water**	**Using recycled water**
Sulfide rougher 1, 2	28.36	24.93
Oxidised rougher 1, 2	9.25	11.35
Oxidised rougher 3, 4, 5	7.29	7.85
Oxidised cleaner 1, 2	3.85	6.8
Final reject	0.12	0.33

Ca and Mg consume reagents, especially the frother, which causes the foam to explode during the collection of useful copper elements, leading to their release into the pulp instead of flotation. Recycling water, which already contains a quantity of reagents (collector and activator), adds to the quantity added during flotation, causing the phenomenon of the double layer, which depresses oxidised and sulfurised copper elements.

Recycling at 50% is acceptable because it allows for sufficient recovery (80%). This is due to the recycling of an acceptable amount of pre-conditioned and dissolved reagents, which converges towards an optimal quantity when added to the reagents added during flotation, and this result confirms what we obtained using the design of experiments (Figure 5).

Conclusion

While the use of 100% fresh water demonstrates high profitability in terms of metal recovery (87.55%), it is economically unsustainable due to its high

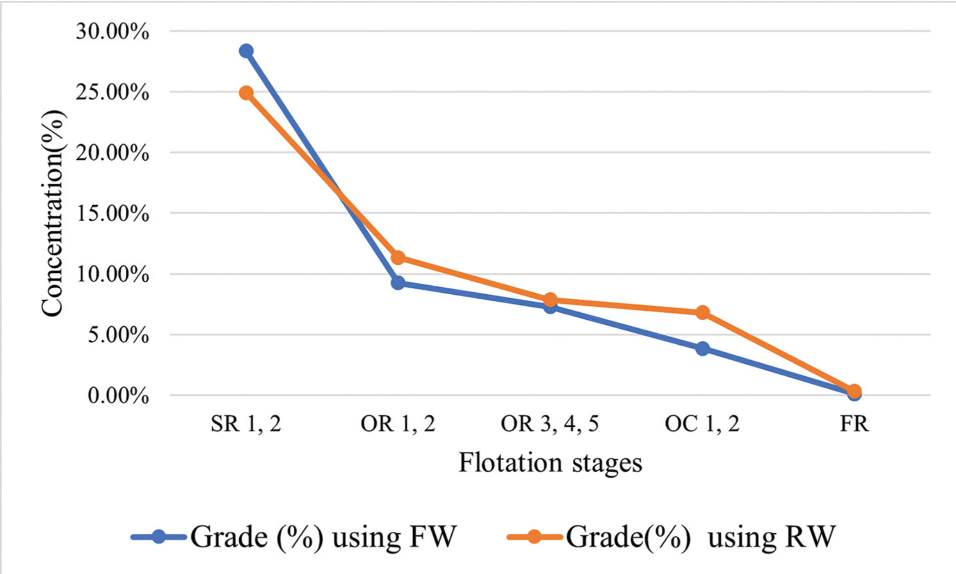

Figure 4: Grade kinetics as a function of flotation stages (FW = fresh water; RW = recycled water).

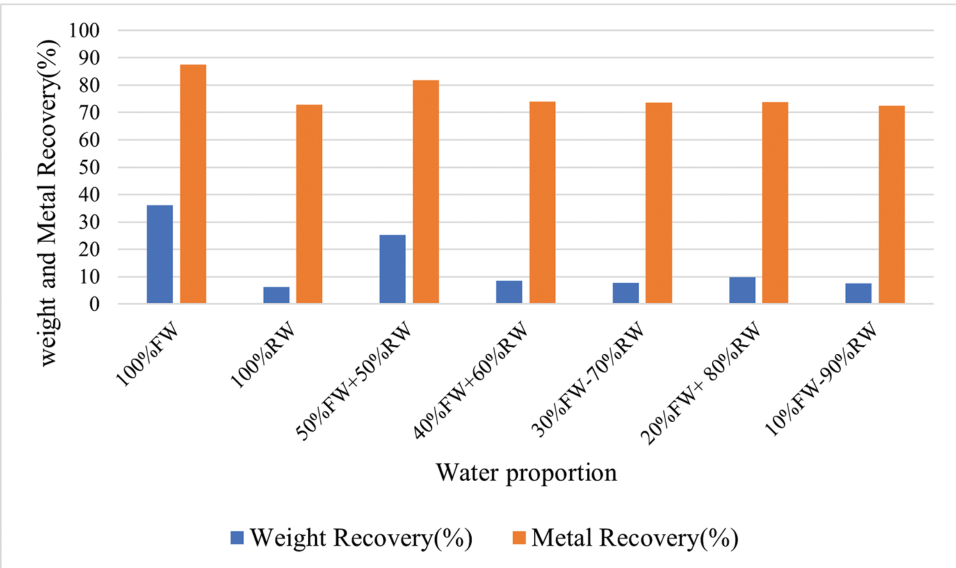

Figure 5: Impact of recycled water on metal recovery (FW = fresh water; RW = recycled water).

Table 6: Weight recovery and metal recovery as a function of water type

Water type	Grade (%)	Metal recovery (%)
Fresh water (FW)	36.14	87.55
Recycled water (RW)	6.3	72.82
50%FW + 50%RW	25.2	81.73
40%FW + 60%RW	8.45	73.94
30%FW + 70%RW	7.7	73.56
20%FW + 80%RW	9.74	73.8
10%FW + 90%RW	7.48	72.48

costs and the environmental challenges associated with declining water reserves. However, the use of 50% fresh water and 50% recycled water is both profitable, given a sufficient recovery, and economical as 50% of water used is recycled from the dike. Thus, this approach of combining the design of experiments and machine learning represents not only a good way to manage water resources, but also a sustainable and profitable solution for mining industries while minimising their environmental impact.

Acknowledgements

We acknowledge the Marrakech Mining Institute professors, the Bleida laboratory team and the exceptional team of the Faculty of Science and Technology for their expertise and collaborative spirit that played a big role in our collective success.

Data availability

The data and code supporting the results of this study are available upon request to the corresponding author.

Declarations

We have no competing interests to declare. We have no AI or LLM use to declare.

Authors' contributions

R.E-B.: Collected and curated the data; performed the methodology, analysis and interpretation; and drafted the manuscript. A.S.: Aided in writing and revising the manuscript. H.A.: Supervised the work. S.R.: Supervised the work and contributed to interpreting the results. All authors discussed the results and read and approved the final manuscript.

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