

Response Surface Modelling of Co-Collector Interactions in the Flotation of Great Dyke PGM Ores

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1 INTRODUCTION

The recovery of platinum group metals (PGMs) is cornerstone to the mining industry in countries such as South Africa, Russia and Zimbabwe, and is an essential contributor to their economies. PGMs such as platinum, palladium and rhodium are indispensable in industries ranging from automotive manufacturing to electronics and jewellery. However, the mining industry is increasingly challenged by global trends, including declining metal prices, diminishing ore grades, and the growing complexity of mineral deposits (Koek *et al.*, 2010; Thormann *et al.*, 2017; Zhang *et al.*, 2024). These challenges demand innovative and cost-effective approaches to maintain profitability and competitiveness in PGM production.

Sodium isobutyl xanthate (SIBX), one of the most used collectors in PGM flotation, has been proven effective in selectively recovering sulfide minerals (Lotter and Bradshaw, 2010; Corin *et al.*, 2021; Manono *et al.*, 2021). However, the occasional inefficiency of SIBX, as a single collector, in treating low-grade and complex ores (Lotter and Bradshaw, 2010), has prompted the need to explore alternative cost-effective reagents. The use of co-collectors was found to be effective in the beneficiation of PGM and base metal ores (Lee *et al.*, 2009; Becker, Wiese and Ramonotsi, 2014). Co-collectors, when used alongside, or in place of primary collectors like SIBX, can enhance metallurgical performance by improving recovery, increasing selectivity, lowering reagent consumption and costs (C.F. Vos, J.C. Davidtz and J.D. Miller, 2007). Thus, they provide an opportunity to address both the economic and technical challenges of PGM beneficiation while aligning with the industry's growing focus on sustainability.

The use of co-collectors in the extraction of PGMs from Zimbabwe's Great Dyke remains largely underexplored. This paper is an investigation on the potential of co-collectors to enhance the profitability of flotation operations in this region. By improving extraction efficiency and/or reducing reagent costs, the integration of co-collectors provides significant benefits to the flotation process in the beneficiation of Great Dyke ores.

2 EXPERIMENTAL

Approximately 300 kg of the plant feed material was collected from the Great Dyke. On receipt, the sample was stage crushed to 100% passing 3.35 mm, thoroughly blended then riffle and rotary split into representative sample portions.

A 4-point milling curve was developed by grinding representative sample portions of the feed samples in a laboratory scale rod mill for different predetermined milling times and wet/dry screening the products through the requisite screen, i.e., 75 μm . The data collected was used to plot a graph of $P_{80} = 75 \mu\text{m}$.

QA/QC: A representative portion of the ore was milled using the time established on the milling curve and screened through the requisite screen to test accuracy.

All flotation tests were carried out using a Denver D12 laboratory flotation machine, according to conditions shown in Table 1.

Table 1. Flotation test conditions.

Sample weight	1.343 kg
Pulp density	1.3 kg/L
Ore s.g.	3.2
Cell volume	4 L
Aeration rate	5 L/min
Impeller speed	1200 rpm
Cumulative flotation times	2, 6, 14 and 30 min
Scrapping intervals	15 s

This study employed the Response Surface Methodology (RSM) to optimise a response surface influenced by multiple process variables. The RSM approach followed a structured three-stage process:

1. Designing and conducting experiments
2. Developing a mathematical model
3. Identifying stationary points or the optimal set of experimental parameters

The primary responses evaluated were grade and recovery, with emphasis on understanding both main effects and interaction effects of three collectors. Design Expert™ version 23 was used to perform regression analysis and parameter optimisation. The significance of the model was assessed using analysis of variance (ANOVA).

The experimental results were fitted to suitable models to describe the relationship between the independent variables and the response. The coefficients of the regression models were estimated by fitting the flotation test work results. To validate the predictive accuracy of the model, additional flotation experiments were conducted under the predicted optimal reagent conditions.

3. RESULTS AND DISCUSSION

3.1. Model Fitting

The Response Surface Methodology (RSM) was used to model and optimise the parameter levels - in this case, collector dosages. Table 2 outlines how changes in collector dosages affected both 4E recovery and grade.

The polynomial coefficients were calculated from the experimental data to generate predictive models for 4E recovery and grade. These regression equations developed through RSM are shown in **Error! Reference source not found..** The predictive 4E recovery and grade values based on Equations 4 and 5 were plotted against the actual values as shown in Figure 1.

$$\text{Recovery} = 74.49 + 0.1390A + 1.040B + 0.02201C - 0.02155AB + 0.001238AC - 0.006227BC \quad (4)$$

$$\text{Grade} = 18.31 + 0.6112A + 3.756B + 0.1931C - 0.007269AB - 0.002168AC - 0.0062037BC - 0.008149A^2 - 0.2812B^2 - 0.004038C^2 \quad (5)$$

Table 2. Experimental design matrix showing SIBX and co-collector dosages with corresponding 4E recovery and grade responses.

Std	Run	Parameters			Responses	
		SIBX Dosage (g/t)	Co-collector A Dosage (g/t)	Co-collector B Dosage (g/t)	4E Recovery (%)	4E Grade (g/t)
Baseline	-	160	0	0	80.30	34.30
5	1	12	4	48	79.86	38.16
10	2	60	7	30	82.31	32.80
11	3	30	0	30	80.19	30.45
3	4	12	10	12	83.11	32.30
16	5	30	7	30	81.88	33.10
13	6	30	7	0	82.54	32.12
2	7	48	4	12	78.99	41.96
15	8	30	7	30	81.21	32.13
8	9	48	10	48	81.41	30.49
4	10	48	10	12	80.62	31.49
9	11	0	7	30	80.73	31.04
14	12	30	7	60	83.83	30.12
6	13	48	4	48	83.63	28.08
12	14	30	12	30	84.28	27.52
1	15	12	4	12	79.33	32.01
7	16	12	10	48	81.80	26.92
17	17	30	7	30	81.88	33.88

Figure 1a shows that for recovery, the points are closely scattered around the line, showing a good correlation between actual and predicted recovery. Minor deviations above or below the line indicate small prediction errors (either slight under- or over-predictions). For grade (Figure 1b), the points also followed a clear upward trend, meaning the model captured the relationship between actual and predicted grade reasonably well. However, the scatter is slightly wider than in the recovery plot, implying the model predicted grade with slightly less accuracy compared to recovery. Overall, Figure 1 shows that the developed regression models provided reasonable strong predictive accuracy for both recovery and grade in the batch flotation tests that were conducted.

Figure 2 presents normal probability plots of externally studentised residuals for both 4E recovery and 4E grade, to assess whether the residuals (differences between actual and

predicted values) follow a normal distribution - a key assumption for regression model validity.

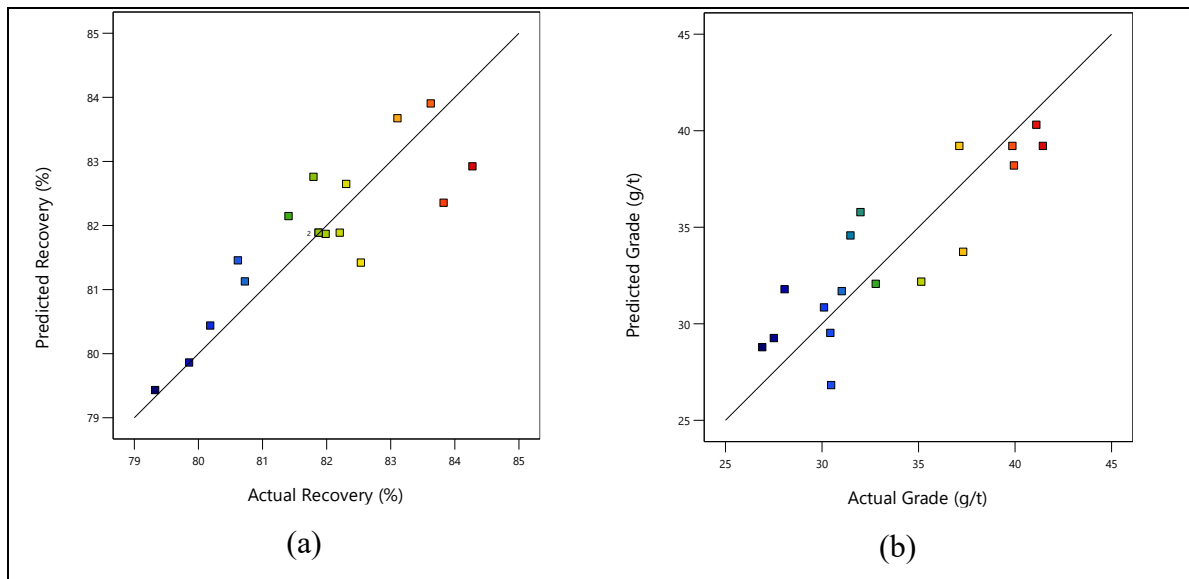


Figure 1. The plots of actual versus predicted values for 4E grade and recovery in batch flotation tests.

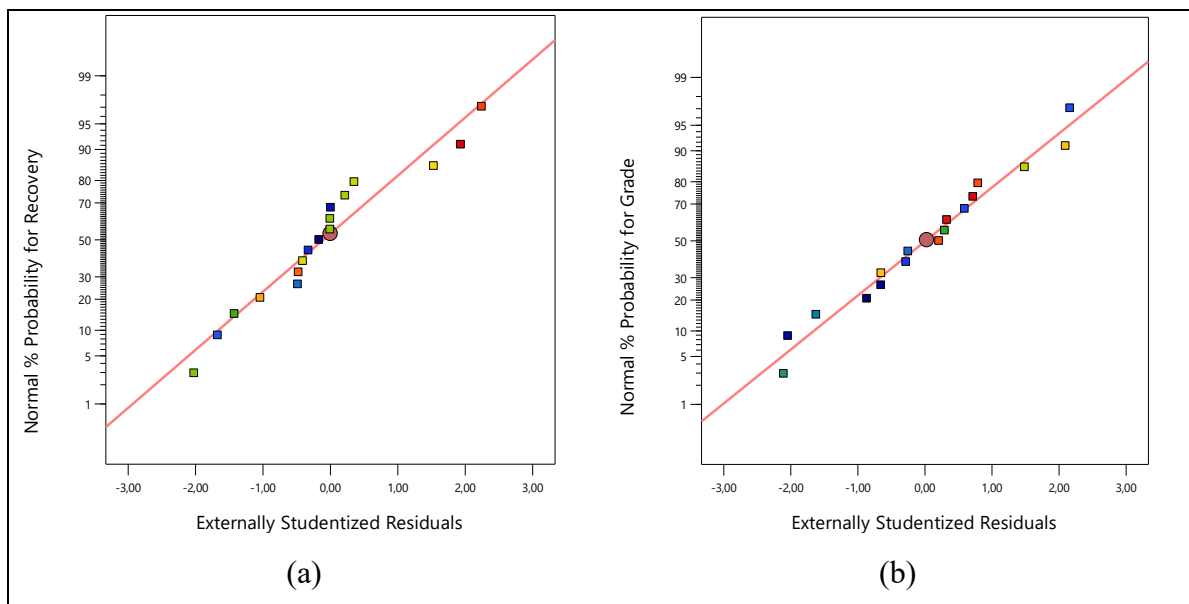


Figure 2. The plots of normal probability versus studentised residual for 4E recovery and grade.

For the recovery normal probability (Figure 2a), the points closely follow the red line, indicating that the residuals were approximately normally distributed. This suggests that the

model errors for recovery were random and unbiased, confirming that the model fit the data well. There were no extreme outliers or systematic deviations observed.

For grade (Figure 2b), the points also lied close to the red line, with only minor deviations at the ends. This indicated that the model residuals for grade also approximated a normal distribution. The absence of curvature or clustering confirms that there were no significant violations of the normality assumption.

Therefore, Figure 2 confirms that both 4E recovery and grade models exhibited randomly distributed residuals without systematic bias, with residuals following a near-normal pattern, and a good overall model validity for predictive use. In summary, the normal probability plots validated that the regression models for 4E recovery and grade were statistically sound and reliable.

3.2. Optimisation of collector dosages

Figures 3 and 4 show the 3D response surfaces illustrating the interactive effects of the three collectors. Figure 3a illustrates the interactive effect of co-collector A and SIBX dosages on 4E recovery. Recovery increased steadily with both reagents, with the maximum response occurring at moderate SIBX and mid-to-high co-collector A levels. This reflects strong synergy between the primary xanthate collector and the secondary co-collector, where co-collector A enhances the flotation of slow-floating PGM species that SIBX alone could not effectively recover. The surface curvature suggests an optimum zone beyond which reagent addition provides diminishing metallurgical returns.

Figures 3 and 4 show the 3D response surfaces illustrating the interactive effects of the three collectors. Figure 3a illustrates the interactive effect of co-collector A and SIBX dosages on 4E recovery. Recovery increased steadily with both reagents, with the maximum response occurring at moderate SIBX and mid-to-high co-collector A levels. This reflects strong synergy between the primary xanthate collector and the secondary co-collector, where co-collector A enhances the flotation of slow-floating PGM species that SIBX alone could not effectively recover. Previous work reported that addition of co-collectors increases hydrophobicity of the target minerals (C.F. Vos, J.C. Davidtz and J.D. Miller, 2007). This increased hydrophobicity might be because of the co-adsorption of co-collectors (Wang et al.,

2018). The surface curvature suggests an optimum zone beyond which reagent addition compromises recovery.

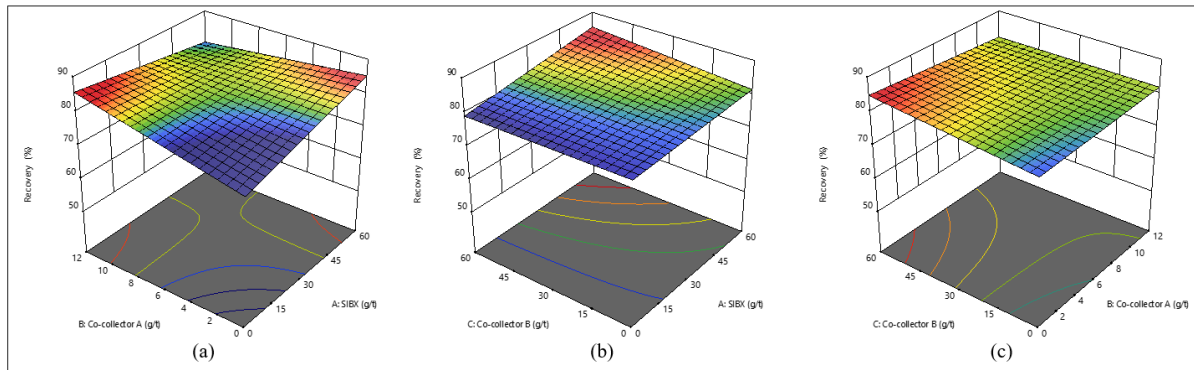


Figure 3. Response surface plots showing the effect of SIBX and co-collectors A and B on 4E recovery.

Figure 3b shows the combined influence of co-collector B and SIBX dosages on 4E recovery. Recovery improved primarily with increasing SIBX dosage, while changes in co-collector B had a comparatively smaller effect. This indicated limited synergistic behaviour between co-collector B and SIBX, suggesting that co-collector B contributed less to overall PGM activation under the tested conditions. The relatively flat surface implies that SIBX dosage was the dominant factor controlling recovery in this reagent combination.

Figure 3c depicts the interaction between co-collector A and co-collector B dosages on 4E recovery. The surface shows moderate curvature, with recovery improving as both co-collectors increase but reaching a plateau at higher levels. This suggests that the two co-collectors provided overlapping functions rather than additive benefits. The optimal recovery region lies at mid-range dosages of both reagents, highlighting that excessive combined dosing does not further enhance metallurgical response.

Figure 4a shows the interactive effect of co-collector A and SIBX dosages on 4E grade. Grade increased with moderate increases in both reagents, reaching a maximum at intermediate SIBX and co-collector A levels before declining at higher dosages. The curved surface indicates a strong interaction between the two collectors, where excessive reagent addition compromises grade. This confirms that balanced dosages yielded the best metallurgical performance, optimising both recovery and concentrate grade.

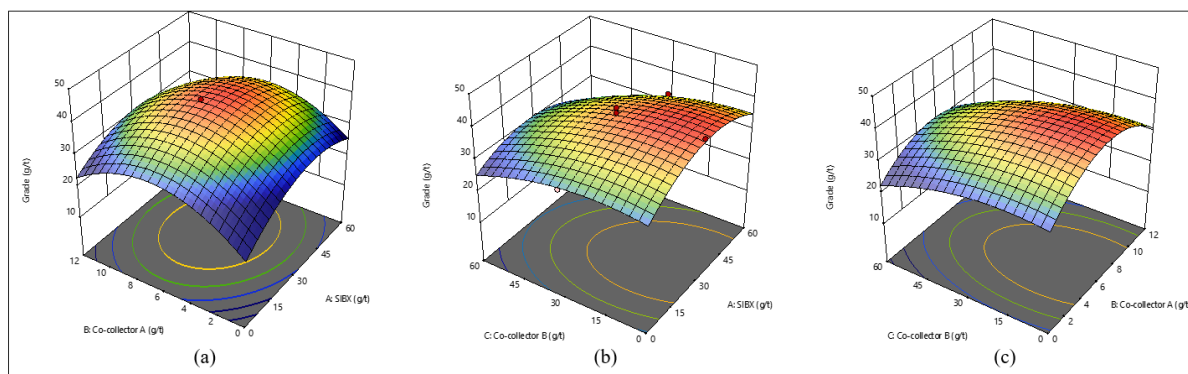


Figure 4. Response surface plots showing the effect of SIBX and co-collectors A and B on 4E grade.

Figure 4b shows the dual impact of co-collector B and SIBX on 4E grade. Grade increased with SIBX dosage up to a midpoint, after which it decreased slightly, while changes in co-collector B had a little effect. The surface curvature suggests that high SIBX levels might promote non-selective flotation or gangue entrainment, leading to a drop in grade. Overall, SIBX was a more dominant contributor to concentrate grade than co-collector B.

Figure 4c shows the interaction between co-collector A and co-collector B dosages on 4E grade. Grade increased as both co-collectors increased to moderate levels, forming a broad optimum region before decreasing at higher dosages. The shape of the 3D surface indicated overlapping functionality between the two reagents - both promoted 4E recovery, but compromised concentrate grade at higher dosages. The optimum zone lies where moderate levels of co-collector A and co-collector B are blended, providing a balanced trade-off between grade and recovery.

Numerical optimisation was then executed using the desirability function of the Design Expert Software. The goals selected for the optimisation of flotation performance were minimum levels of collector dosages to obtain maximum 4E recovery and grade. The solution with maximum desirability value was selected as the optimised reagent dosages. The optimum reagent dosages were 42 g/t SIBX, 6 g/t co-collector A and 25 g/t co-collector B.

3.3. Verification of RSM Model

Optimised collector dosages were validated by performing flotation tests under predicted conditions. The predicted and experimental 4E recovery and grade at these optimised collector dosages are shown in Table 4. It can be deduced from Table 4 that the predicted and actual 4E recovery and grade values were in reasonable agreement. Thus, the predictive model was successfully validated.

Table 4. Optimum conditions and the corresponding responses (experimental and predicted)

Response	Predicted Values	Actual Values
4E Recovery (%)	82.1	83.5
4E Grade (g/t)	39.0	36.5

3.4. Comparison with baseline

The experimental 4E grade and recovery obtained with the optimised dosages (Table 4) were compared to the baseline values (Table 2). It can be deduced that there was a 3.2% increase in 4E recovery and 6% increase in 4E grade. Furthermore, a cost analysis, was done, comparing the baseline and optimised conditions as shown in Table 5. It can be deduced from Table 5 that the introduction of co-collectors results in savings on reagents of R 1.7 M per month (~US\$ 100 000). Thus, the RSM was successfully used for reagent optimisation, performance and cost improvement.

Table 5. Cost analysis of two scenario analysis: with and without co-collectors.

Monthly throughput (tons):	457200				
FLOTATION REAGENTS		Reagent Strength %	kg per month	Price (R/kg)	Total Cost (P)
Baseline Reagent Suite					
SIBX	0,160	40	182880	R 21,94	R 4 012 387,20
					R 4 012 387,20
Reagent Suite with co-collectors					
SIBX	0,042	40	48006	R 21,94	R 1 053 251,64
co-collector A + co-collector B	0,031	100	14173	R 91,34	R 1 294 580,09
TOTAL					R 2 347 831,73
Monthly cost saving on reagents with co-collectors					R 1 664 555,47
Annual cost savings on reagents					R19 974 665,66
Additional revenue based on 3.1% recovery improvement with new suite					

4. CONCLUSIONS

The study demonstrated that Response Surface Methodology (RSM) can effectively optimise collector interactions in the flotation of Great Dyke PGM ores. Significant synergy between SIBX and co-collector A improved 4E recovery by 3.2% and concentrate grade by 6%, while reducing SIBX consumption by about 74%. The validated RSM model proved statistically robust, and the optimised reagent suite delivered substantial cost savings on reagents of approximately R1.7 million per month. These outcomes confirm that statistically guided reagent optimisation can simultaneously enhance metallurgical efficiency and reduce operating costs in PGM flotation.

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