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MATHEMATICAL MODELLING AND STATISTICAL ANALYSIS OF SUB GRADE IRON ORE BENEFICIATION USING WET HIGH INTENSITY MAGNETIC SEPARATOR (WHIMS)

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Abstract

Beneficiation of sub-grade iron ore from Bailadila, India (40.80% Fe, 40.90% SiO2, 0.24% Al2O3) was studied using Vertical Pulsating Wet High Intensity Magnetic Separation (VP-WHIMS). Fine grinding to 80% passing 150 microns enabled sufficient liberation of hematite and goethite from quartz. Thirty experiments were designed using a Central Composite approach and Response Surface Methodology, optimizing magnetic field intensity, pulp density, ring speed, and pulsating frequency. A quadratic model ($R^2 = 0.95$) was established using Minitab 17, and ANOVA confirmed that both individual parameters and their interactions significantly affected iron recovery and concentrate grade. Response surface plots visualized optimal operating conditions, offering practical insights for industrial application and effective process control.

Keywords: *Sub Grade Iron Ore, Beneficiation, VP-WHIMS, Bailadila, Anova and Surface plot*

1. INTRODUCTION

The world's iron feedstock is transitioning to low- and sub-grade resources such as ultrafine slimes, lean hematite, and complex ores, making robust recovery strategies essential. Conventional gravity and flotation are sub-optimal for such fines due to particle size, surface associations, and weak magnetic susceptibility. Extensive research exists for beneficiation of slimes and low-grade ores for pelletisation. Wet High-Intensity Magnetic Separation (WHIMS) selectively recovers weakly magnetic iron oxides engineered by key variables [4–6], and has re-emerged for slime treatment, tailings reprocessing, and low-grade fines upgrading [7–11]. However, most WHIMS studies are empirical and offer limited predictive ability for variable feed conditions . The mechanisms — magnetophoretic attraction, hydrodynamic transport, particle detachment, and liberation — act in complex ways. While modeling sub-systems with CFD or DEM is common, integrated mathematical frameworks that couple population balance models, magneto-hydrodynamic capture, and uncertainty quantification are rare, limiting predictive control and robust process design. Magnetization roasting and advanced magnetic separation approaches also add to the evolving beneficiation toolkit [13–19].

2. MATERIAL AND METHODS

2.1 The Sample

'As received' sub-grade iron ore from Bailadila, Chhattisgarh (ROM, -150 mm where–1 mm is 36%) was homogenized, sampled, and characterized (physical, chemical, mineralogical). The chemical composition (Table 1) and Minerological indicates Hematite is the main ore with Quartz as major gangue and the liberation particle size is ~150 microns.

Table 1. Size analysis of 'as received' ROM

Table 1. Chemical analysis of 'as received' ROM sample.

Constituent	Fe	FeO	SiO_2	Al_2O_3	LOI	P	S	TiO2	CaO	MgO	MnO
Assay %	40.80	0.30	40.90	0.24	0.22	0.05	<0.01	0.091	0.119	0.110	0.045

2.2 Experimental

2.2.1 Vertical Pulsating Wet High Intensity Magnetic Separator (VP-WHIMS)

A Longi LGS 500 VP-WHIMS (rotor Ø 500 mm, matrix gap 2 mm, semi-continuous) processed ore ground to 100 mesh (152 microns). Parameters varied: pulp density (15–35%), field intensity (2000–10000 G), ring speed (0.6–3 rpm), and pulsation (50–250 cpm). Batches of 10 kg ore were tested; concentrate, middlings, and tailings dried and analyzed.

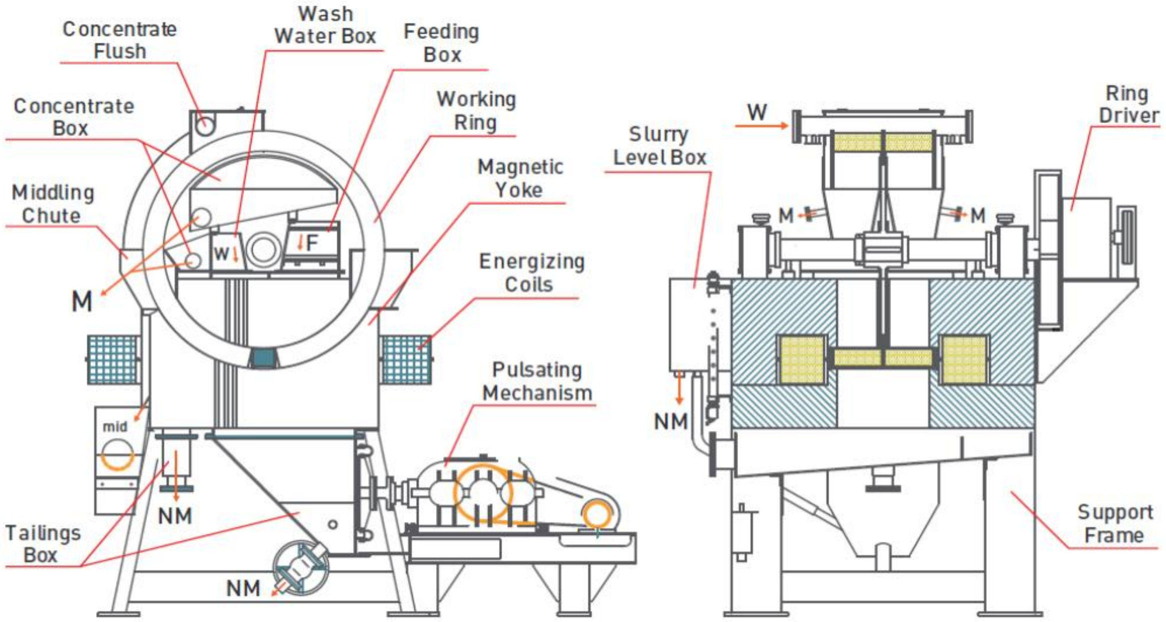

Figure 1. Schematic diagram of Vertical pulsating Wet High Intensity Magnetic Separator

2.2.2 Response Surface Methodology

RSM (Central Composite design, 4 variables, 5 levels, 30 runs) modeled the relationship between independent variables and process responses (Table 2), with equations and ANOVA generated by Minitab 17 [20–22].

Table 2. Experimental range and levels of independent process variables

Variable	Unit	Variable	(-2) Very Low	(-1) Low	0 Mid level	(+1) High	(+2) Very High
Magnetic Field Intensity	GAUSS	A	2000	4000	6000	8000	10000
Pulsating Frequency	Cycles/min	B	50	100	150	200	250
Ring Rotational Speed	RPM	C	0.6	1.2	1.8	2.4	3
Slurry concentration	%	D	15	20	25	30	35

3. RESULTS AND DISCUSSION

3.1 Results

Thirty experimental runs examined effects of the four main variables on concentrate grade, yield, and iron recovery (Tables 3). Mathematical models predicted performance; surface and contour plots were generated.

Table 3. Test results of Central Composite Design (CCD).

Test No.	Magnetic Field Intensity	Pulsating Frequency	Rotational Speed	Slurry concentration	% Yield	%Fe	% Iron Values recovery
	A	B	C	D	Yield	Grade	Recovery
1	0	-2	0	0	46.00	52.00	58.63
2	0	0	-2	0	32.00	55.50	43.53
3	0	2	0	0	50.00	55.00	57.40
4	0	0	0	2	40.00	55.50	54.41
5	0	0	0	-2	44.00	56.00	60.39
6	0	0	0	0	44.79	55.90	61.37
7	-2	0	0	0	40.50	58.00	57.57
8	0	0	0	0	44.79	55.90	61.37
9	2	0	0	0	54.00	55.00	72.79
10	0	0	2	0	39.00	56.00	53.53
11	0	0	0	0	44.79	55.90	61.37
12	1	1	1	1	53.70	55.00	72.39
13	-1	-1	1	1	42.50	55.00	57.29
14	0	0	0	0	44.79	55.90	61.37
15	1	-1	-1	1	39.40	53.50	51.66
16	-1	-1	-1	-1	44.00	55.00	59.31
17	-1	1	-1	1	35.64	56.80	49.62
18	-1	1	1	-1	40.00	56.20	55.10
19	1	-1	1	-1	43.50	55.00	58.64
20	1	1	-1	-1	50.00	54.70	67.03
21	1	-1	-1	-1	42.10	54.50	56.24
22	1	1	1	-1	56.00	54.50	74.80
23	-1	-1	-1	1	41.80	54.50	55.84
24	-1	1	1	1	38.20	56.20	52.62
25	-1	-1	1	-1	41.00	56.90	57.18
26	0	0	0	0	44.79	55.90	61.37
27	-1	1	-1	-1	33.00	56.80	45.94
28	1	1	-1	1	43.50	56.20	59.92
29	1	-1	1	1	44.00	53.60	57.70
30	0	0	0	0	44.79	55.90	61.37

$$\begin{aligned}\text{Concentrate Grade} = {} & 55.900-0.5750*A + 0.4917*B + 0.1667*C - 0.0500*D \\ & + 0.1604*A*A - 0.5896*B*B - 0.0271*C*C - 0.0271*D*D - 0.212*A*B \\ & + 0.037*A*C + 0.288*A*D - 0.513*B*C + 0.262*B*D - 0.012*C*D\end{aligned}$$

$$\begin{aligned}\text{Concentrate Yield} = {} & 44.790 + 3.440*A + 0.843*B + 1.790*C - 0.807*D \\ & + 0.582\ A*A + 0.770\ B*B - 2.355\ C*C - 0.730\ D*D + 3.572*A*B \\ & + 0.902*A*C - 0.728*A*D + 1.410*B*C - 0.285*B*D + 0.385*C*D\end{aligned}$$

$$\begin{aligned}\text{Iron Values recovery in Concentrate} = {} & 61.370 + 4.089*A + 0.787*B + 2.599*C - 1.123*D \\ & + 1.130*A*A - 0.662*B*B - 3.033*C*C \\ & - 0.815*D*D + 4.626*A*B + 1.214*A*C \\ & - 0.666*A*D + 1.401*B*C - 0.104*B*D + 0.499*C*D\end{aligned}$$

3.2 Discussion

Contour plots are two-dimensional visualizations showing how two factors simultaneously affect a response (such as yield, grade, or recovery), with response values indicated by lines or color bands of equal value—much like a topographic map. Surface plots offer a three-dimensional view, where the response surface is visualized as a "landscape" shaped by the two variables on the axes. These plots help identify response peaks, valleys, and ridges as the variables are varied. Contour and surface plots, built from the mathematical model, are powerful tools to visualize and optimize the complex relationships between operational variables in VP-WHIMS. Proper interpretation guides not only to the optimal settings but also highlights process sensitivity, robustness, and crucial interactions—ensuring the best possible balance between concentrate grade, yield, and iron recovery in continuous plant operation.

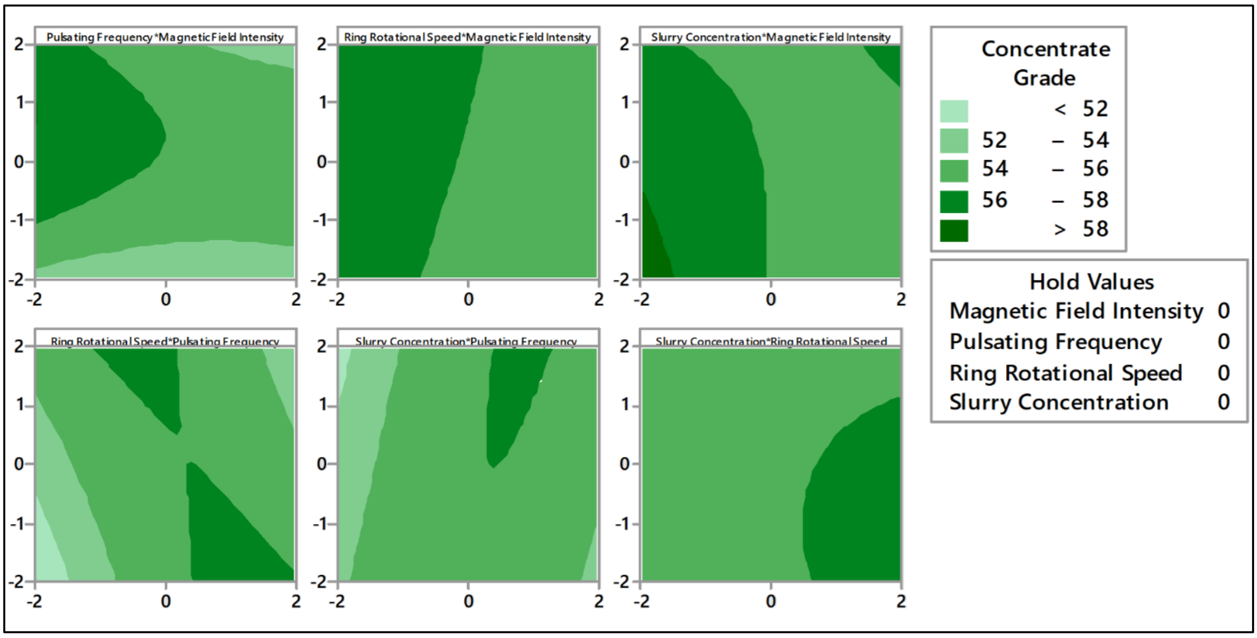

Figure 2. Contour plots of concentrate grade

3.2.1. Effects of magnetic field strength:

Increased field intensity raised yield and recovery but slightly reduced product quality at higher intensities, likely due to entrapment of non-magnetics.

3.2.2. Effects of Slurry concentration

Higher pulp density (>25%) reduced Fe recovery due to matrix overcrowding; lower densities (<30%) optimized recovery and grade.

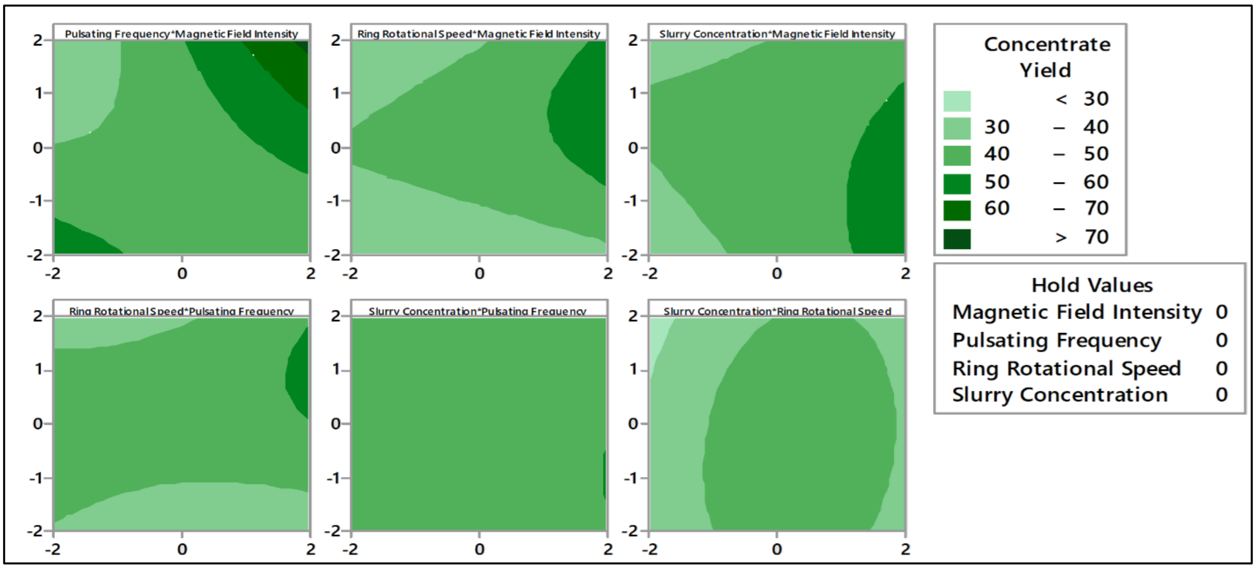

Figure 3. Contour plots of concentrate yield (weight percentage)

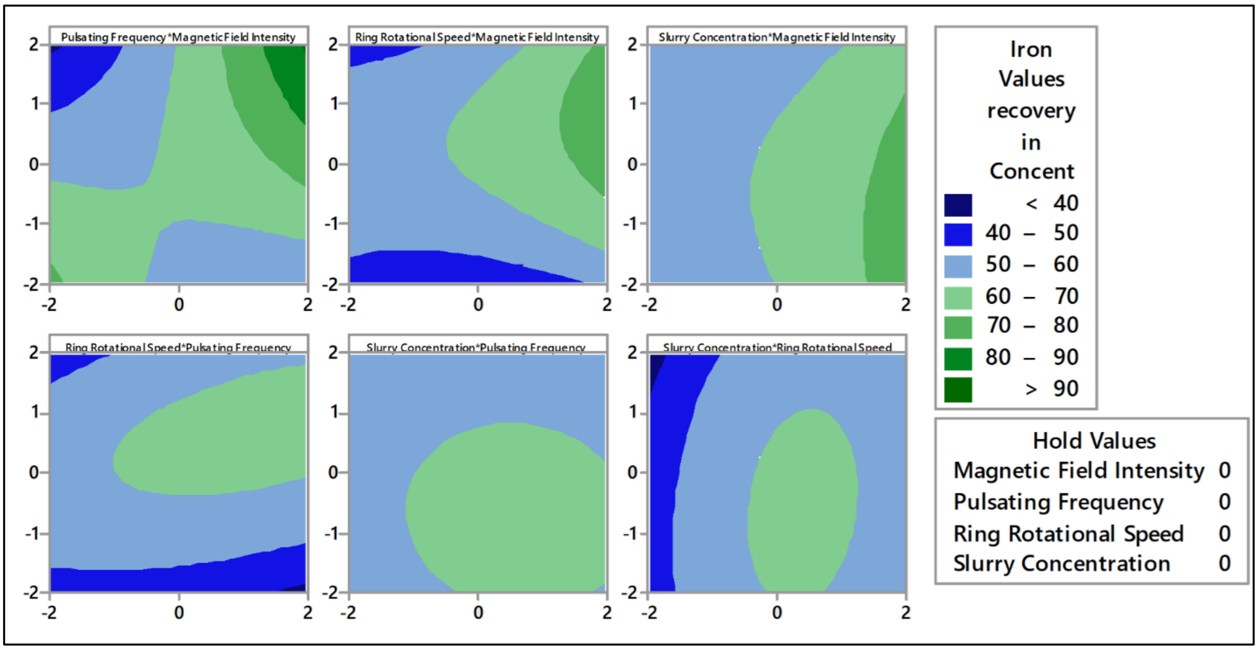

Figure 4. Contour plots of percent iron values recovery in concentrate

3.2.3. Effects of pulsation frequency

Higher frequency improved selectivity and minimized entrapment, increasing both yield and Fe grade.

3.2.4 Ring Rotational Speed (RPM)

Increased RPM elevated yield and recovery but marginally reduced grade unless compensated by pulsation/fine-tuned field intensity.

3.2.5 Statistical analysis:

ANOVA showed major effects from magnetic field intensity and pulsation frequency, and significant variable interactions. Optimal conditions (8,000 G, 200% pulsation, 2.4 rpm, 20% solids) maximized yield, grade, and Fe recovery, confirmed by response surface plots.

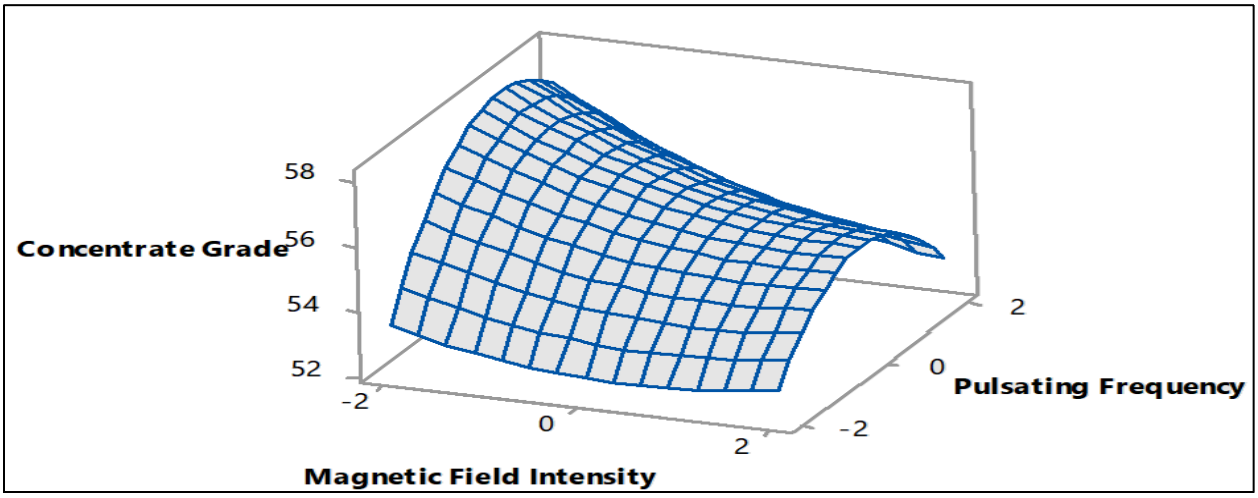

Figure 5. Concentrate Grade Plot (Ring rotational speed and Slurry concentration are at Mid level)

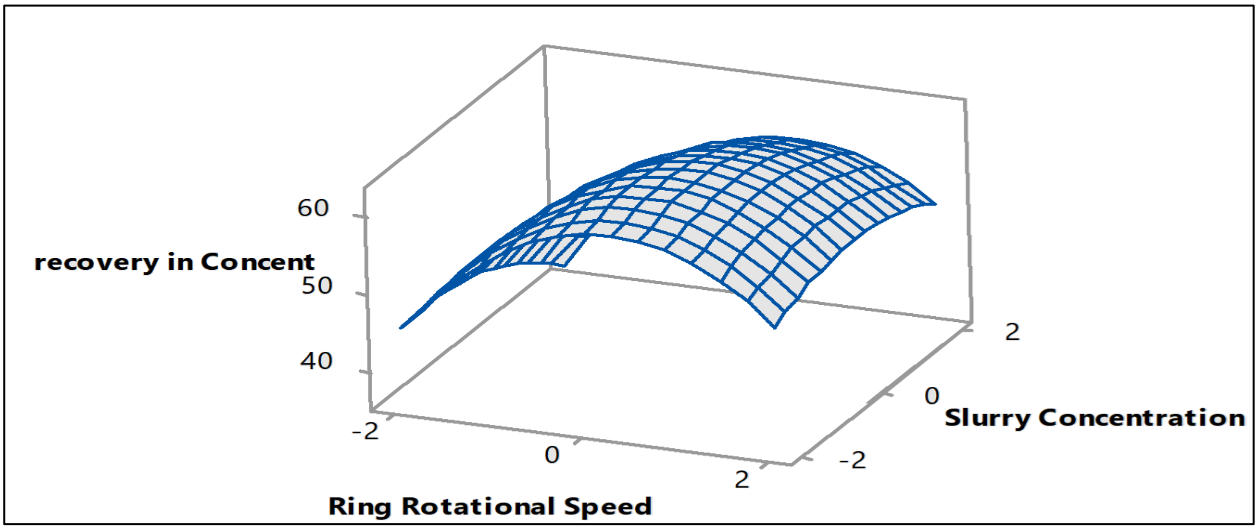

Figure 6. Percent recovery of Iron values in Concentrate plot (Magnetic Field Intensity and Pulsating frequency are at mid-levels)

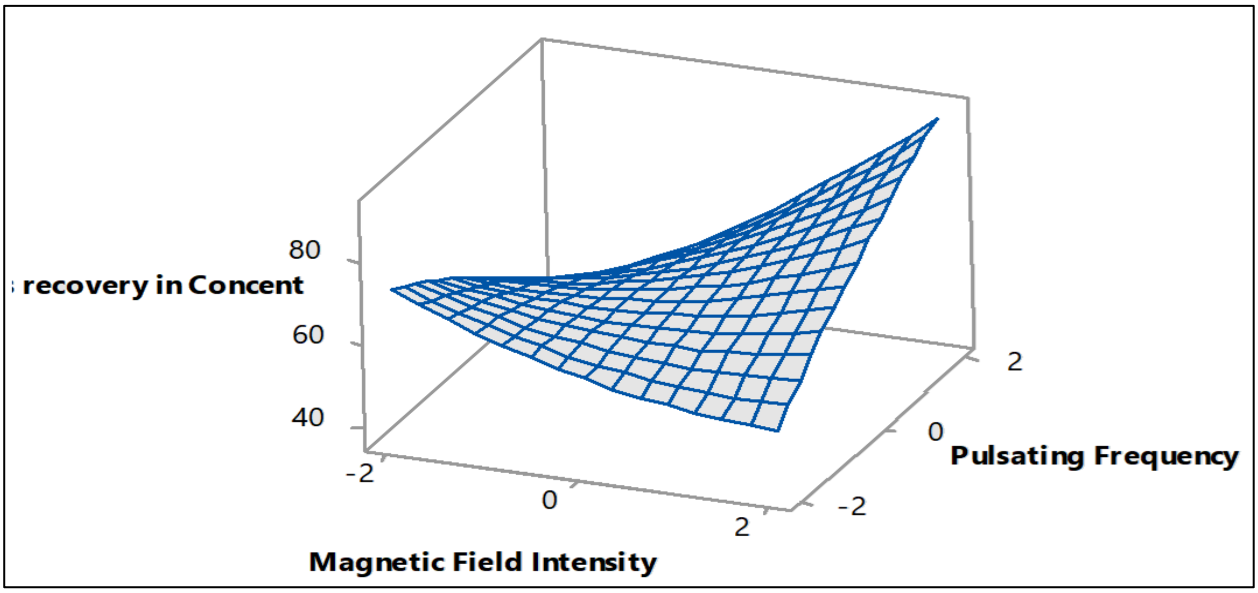

Figure 7. Percent recovery of Iron values in Concentrate plot (Slurry concentration and Ring rotational Speed are at mid-levels)

Table 4. Model Summary

Product	S	R-Sq	R-Sq (adj)	R-Sq (pred)
Concentrate grade	0.414667	93.86%	86.30%	53.68%
Concentrate yield	0.966838	98.63%	96.94%	89.51%
Percent recovery of Iron Values	1.86850	96.77%	92.79%	74.41%

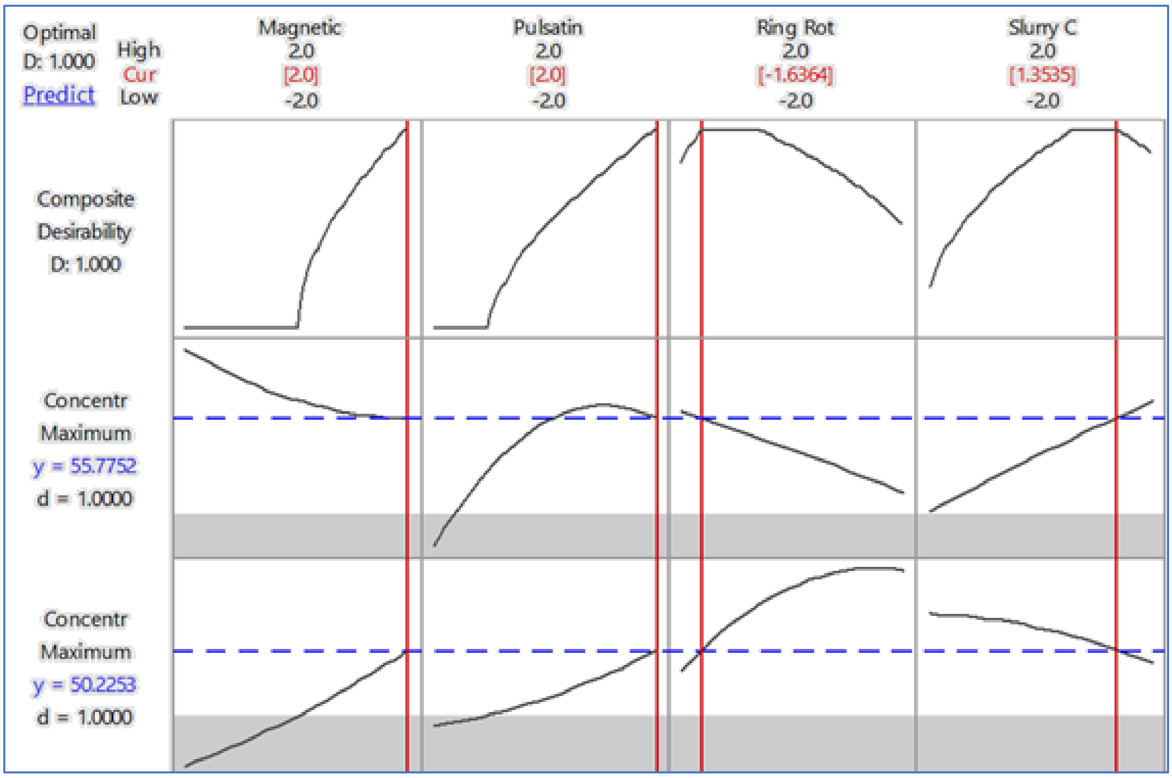

Figure 8. Optimisation plot (prediction of concentrate grade)

4. CONCLUSION

The effects of varying the magnetic field intensity, pulsating frequency, ring rotational speed and slurry concentration provide detailed beneficiation capabilities of the newly developed Longi LGS 500 WHIMS on a low grade iron ore stage crushed and ground to 100mesh material. From the research investigations, the following conclusions were drawn: (1) It was observed that the Longi LGS 500 is potentially good for beneficiating low grade iron ore fines, and the back scattered electron (BSE) images showed that the ore is predominantly Fe oxide in a form of hematite with silicates as main gangue minerals. (2) It was noted that the increase in pulp density from 15% to 25% and 35% had a negative effect on the mass yield of concentrate. At pulp solids >20%, the matrix was overloaded resulting in the concentrate mass yields concentrate and Fe recoveries decreasing with no significant effects on the Fe grade. (3) The changes in magnetic intensity from 2,000 to 10,000 Gauss increased the mass yield of the concentrates, while the pulsation mechanism, on the other hand, positively affected the overall quality of the product. An increase from 50% to 250% showed an increase in both the mass yield concentrates and Fe grade. (4) The interactions between parameters were shown to be essential, and most notable was between magnetic field intensity and pulsation frequency having the most effect.

These results supported the fact that of the two variables investigated, the A and the B had a major individual effect on this particular sample. (5) The optimum conditions for this particular sample are 8000 gauss magnetic field intensity, 200% pulsating frequency, 2.4 rpm and 20% solids feed concentration, where highest recovery of iron values were obtained with good yield and grade.

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