

Influence of MIBC- butyl glycol frother blends on two phase characterization and three phase flotation performance

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Abstract: Frother chemistry plays a key role in controlling bubble characteristics and flotation performance. This study investigated the effects of Methyl Isobutyl Carbinol (MIBC), Butyl Glycol, and their dual mixtures, representing two structurally different frother families, on the critical coalescence concentration (CCC), bubble size, light transmittance, dynamic froth stability, and microflotation performance. The dual blends reached the CCC at lower concentrations (7.5–9.0 ppm) than the single frothers (10.2–11.0 ppm). However, a lower CCC did not necessarily correspond to a smaller Sauter mean bubble diameter (d_{32}). Instead, the Sauter mean bubble diameter increased in the 25:75 and 75:25 MIBC–Butyl Glycol blends, indicating that the blending ratio had a pronounced influence on bubble size. Light transmittance showed a strong inverse relationship with the Sauter mean bubble diameter, and the second-order polynomial model provided the best fit, particularly for the dual blends. Among the single frothers, Butyl Glycol exhibited the highest dynamic froth stability, whereas the second-order polynomial model generally provided a better fit than the exponential model for the relationship between dynamic froth stability and the Sauter mean bubble diameter. Microflotation experiments revealed mineral-dependent flotation responses, with the MIBC-rich 75:25 blend producing the highest galena recovery (96.22%) and the Butyl Glycol-rich 25:75 blend producing the highest sphalerite recovery (97.88%). These results show that flotation performance depends on frother chemistry, blending ratio, particle characteristics, and bubble–particle interactions. Therefore, CCC and bubble size should be evaluated together with these factors when selecting frothers for flotation.

Keywords: frother, Sauter mean diameter, light transmittance, dynamic froth stability, frother blends, CCC

1. Introduction

The efficiency of flotation depends on the selective attachment of hydrophobic mineral particles to air bubbles and their transport to the froth phase. As particle size decreases, particularly below 10 μm , both flotation recovery and selectivity become increasingly difficult to achieve, making the optimization of hydrodynamic conditions and reagent chemistry essential (Gaudin et al., 1931; Rulyov, 2001). Among flotation reagents, frothers play a critical role by reducing surface tension, promoting the formation of suitably sized bubbles, stabilizing the froth, and increasing bubble residence time, thereby enhancing particle–bubble attachment and flotation kinetics (Wills and Finch, 2015; Cho and Laskowski, 2002; Khoshdast et al., 2023; Fathoni et al., 2026).

Industrial frothers are mainly classified into alcohols and polyglycol-based compounds, with MIBC remaining the most widely used because of its low cost and broad applicability (Tan et al., 2004; Gupta et al., 2007). Frother performance is strongly influenced by molecular structure, molecular weight, and surface activity. Generally, higher molecular weight frothers exhibit stronger foaming ability, whereas lower molecular weight frothers with higher CCC values tend to be more selective (Laskowski, 1993; Saavedra Moreno et al., 2022; Khoshdast et al., 2023).

Although frothers reduce the surface tension of water, flotation performance is governed primarily by dynamic interfacial properties rather than equilibrium surface tension. Dynamic surface tension and surface elasticity influence liquid film stability, suppress bubble coalescence, and control froth formation more effectively than static surface tension alone (Comley et al., 2002; Tan et al., 2004; Pan et al., 2022; Petkova et al., 2021). Consequently, the CCC is widely recognized as one of the most important frother parameters, representing the minimum concentration required to prevent bubble coalescence. Increasing frother concentration generally decreases the Sauter mean bubble diameter until the CCC is reached, after which bubble size becomes nearly independent of further concentration increases (Cho and Laskowski, 2002; Drzymala and Kowalczyk, 2018; Güven et al., 2024; Karakashev et al., 2021; Kowalczyk, 2013).

Bubble size and foam height are the two principal indicators used to characterize frother performance in two-phase systems. Bubble size is commonly expressed as the Sauter mean diameter (d_{32}), which reflects the available gas-liquid interfacial area for particle collection, while foam height represents the ability of a frother to generate and maintain a stable foam structure. These parameters are closely related to flotation kinetics, gas dispersion, and overall flotation performance (Gupta et al., 2007; Tan et al., 2005; Pan et al., 2022; Khoshdast et al., 2023; Fathoni et al., 2026).

In recent years, increasing attention has been devoted to dual frother systems because they offer greater flexibility than single frothers. Alcohol-type frothers, such as MIBC, generally produce smaller bubbles and favour fine-particle flotation, whereas polyglycol frothers generate stronger and more persistent froths that can improve the recovery of coarser particles. Combining these frother families therefore provides opportunities to optimize both bubble characteristics and froth stability (An et al., 2018; Cappuccitti and Finch, 2008; Laskowski et al., 2003; Khoshdast and Sam, 2011; Tan et al., 2004).

Despite extensive research on CCC, bubble size, foam height, and froth stability, these parameters have generally been investigated separately. In addition, most studies have focused on two-phase systems, while studies relating two-phase frother characterization to three-phase flotation performance remain limited. Therefore, this study investigates the effects of single and dual MIBC-Butyl Glycol systems on CCC, Sauter mean bubble diameter, foam height, and dynamic froth stability in a two-phase system, and relates these results to flotation performance obtained under three-phase conditions. This combined approach provides a more comprehensive evaluation of frother performance and contributes to a better understanding of the relationship between two-phase characterization and flotation behavior. The contribution of this work is therefore the measurement of CCC, Sauter mean bubble diameter, light transmittance and dynamic froth stability for a single alcohol-glycol ether blend pair within one consistent experimental system, and the direct comparison of the resulting two-phase ranking with pure-mineral microflotation performance.

2. Materials and methods

2.1. Materials

Two commercially available frothers representing different chemical classes were selected to investigate the influence of frother chemistry on bubble characteristics. Methyl isobutyl carbinol (MIBC), an aliphatic alcohol, and Butyl Glycol, a glycol ether, were used individually and in dual blends. Bubble generation and characterization were performed using a laboratory-scale microflotation system specifically designed for two-phase (air-water) experiments. Frothers and their blends were introduced into the microflotation cell at concentrations of 1, 3, 5, 8, 10, 15, 20, 25, 30, 40, and 50 ppm in a total volume of 100 cm³. Dual blends consisting of MIBC and Butyl Glycol were prepared at volumetric ratios of 75:25, 50:50, and 25:75 (MIBC:Butyl Glycol). Table 1 summarizes the chemical structures and physicochemical characteristics of the flotation frothers used in this study.

Table 1. Chemical classification and physicochemical characteristics of selected flotation frothers

Frothers	Chemical Formula	Chemical Class	Molecular Weight (g/mol)	HLB
Butyl Glycol	$\text{HOCH}_2\text{CH}_2\text{O}(\text{CH}_2)_3\text{CH}_3$	Glycol Ether (Solvent-type)	118.17	-
MIBC	$(\text{CH}_3)_2\text{CHCH}_2\text{CH}(\text{OH})\text{CH}_3$	Aliphatic Alcohol	102	6.1

MIBC used in this study is a low-molecular-weight aliphatic alcohol that is widely employed as a flotation frother. In contrast, Butyl Glycol belongs to the glycol ether group within the broader family of polyglycol-based frothers (Bulatovic, 2007) and differs from MIBC in its molecular structure and frothing characteristics. These two frothers were selected to compare their ability to control bubble size in flotation systems and to represent different chemical groups.

Based on the optimum frother conditions determined from the two-phase (air–water) experiments, three-phase (air–water–solid) microflotation tests were subsequently carried out using pure mineral samples. Galena (99.5% purity) and sphalerite (94% purity) were used as the pure mineral samples in the three-phase microflotation tests to evaluate flotation performance under particle–bubble interaction conditions. Table 2 presents the chemical compositions of the pure galena and sphalerite samples.

Table 2. The chemical compositions of the pure galena and sphalerite samples

Sample	Content (%)		
	Pb	Zn	Fe
Galena	86.2	0.02	0.49
Sphalerite	0.01	63.12	2.99

2.2. Methods

2.2.1. Two-phase measurements

The Sauter Mean Diameter, defined as the ratio of volume to surface area, is a standard metric for characterizing gas/liquid or liquid/liquid dispersions. As the concentration of the frother increases, the Sauter mean diameter progressively declines until it reaches the CCC—the specific point at which bubble coalescence is effectively eliminated.

Different effects were observed for each frother and their respective mixtures used in the study. After frother additions at predetermined intervals, all froth images were recorded and analyzed using the ImageJ software to determine bubble diameter. Bubble diameters were calculated from camera-captured images for each frother and concentration. The number of images analysed was varied according to the number of measurable bubbles available under each condition. Particularly at relatively low frother concentrations, multiple images were analysed to obtain a sufficient number of bubble measurements, whereas at higher concentrations fewer images were generally sufficient. Images were analysed until approximately 50–200 bubbles had been measured for each concentration, considering only bubbles that were fully visible within the field of view. The d_{32} values were then calculated using the average Feret diameters obtained for each concentration.

Bubble size measurements were conducted using a micro flotation cell with an internal diameter of 30 mm, a height of 220 mm, and a total volume of 170 cm³. A working volume of 100 cm³ was used in all experiments to prevent overflow of froth during bubble-size measurements. Nitrogen gas was introduced into the system through a 15 µm pore diameter frit located at the cell's base, while the flow rate was maintained at a constant superficial gas velocity of 0.23 cm/s using a Dwyer flow meter. All measurements were performed at the natural pH of distilled water (approximately pH 6.8–7.0).

Images of the froth phase were acquired with a 5 mm reference scale positioned on the microflotation cell. Before image analysis, the reference scale was calibrated in ImageJ software to convert pixel measurements to actual distances, enabling the accurate determination of bubble sizes. Visual data of the bubbles were captured from the froth zone using a computer-interfaced digital USB microscope (Bushman CMOS 8 LED) at 1000× magnification. The experiments involved both single frothers and dual blends across a concentration range of 1–50 ppm. The detailed experimental setup and procedure are illustrated in Fig. 1. All bubble diameters were measured using ImageJ software (version 1.8.0). Bubble size measurements were repeated 3 times independently for each frother system and concentration. Fig. 2 shows the ImageJ program interface during measurements.

Bubble size was characterized using the d_{32} , which represents the volume-to-surface area weighted average bubble diameter. The d_{32} values were calculated according to Eq. (1):

$$d_{32} = \frac{\sum n_i d_i^3}{\sum n_i d_i^2} \quad (1)$$

where n_i is the number of bubbles with diameter d_i .

The same calibrated images used for bubble size analysis were also employed to determine foam height. The vertical distance between the pulp–froth interface and the top of the froth layer was measured using ImageJ software (version 1.8.0).

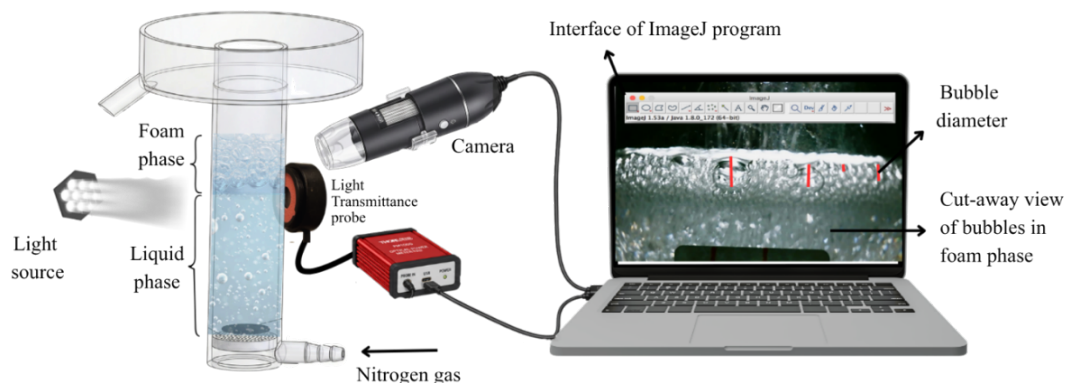


Fig. 1. Experimental setup for the measurements

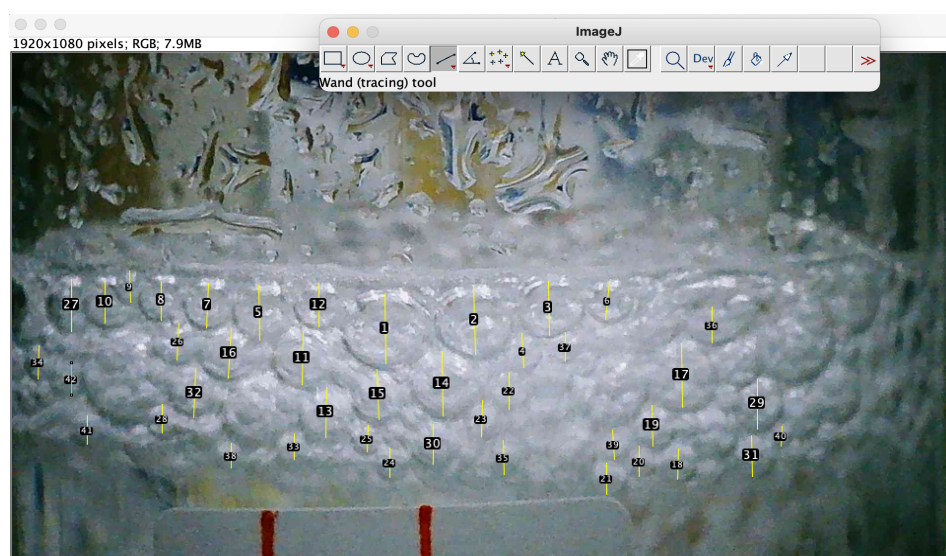


Fig. 2. Interface of ImageJ program

2.2.2. Three-phase measurements

Three-phase microflotation tests were performed using high-purity galena and sphalerite samples to evaluate the flotation performance of the selected frother systems. The sample was crushed to below 2 mm using a hammer to avoid introducing impurities from the crusher. The 1 g crushed sample required for the test was ground to 100 μm using an agate mortar before each flotation test. The microflotation cell, with a volume of 170 cm^3 , was aerated at 100 cm^3/min under a constant pressure of 1 bar. The mixing was performed using a hotplate stirrer and a magnet in the cell. The three-phase microflotation experiments were conducted at the natural pH of the pulp, consistent with the conditions used in the two-phase experiments. Distilled water was used as the aqueous medium in all three-phase microflotation experiments, consistent with the two-phase measurements. All microflotation tests were carried out in triplicate under identical conditions, and the reported recovery values represent the mean of three independent experiments. The corresponding standard deviations are shown as error bars.

Potassium amyl xanthate (KAX) was used as the collector at concentrations of $1 \cdot 10^{-7} \text{ mol/dm}^3$ for galena and $1 \cdot 10^{-3} \text{ mol/dm}^3$ for sphalerite. Frother dosages were selected according to the CCC values determined from the two-phase experiments. Accordingly, single frothers and dual blends with different mixing ratios were added to the pulp at their respective CCC concentrations, so that the total frother dosage varied between 7.5 and 11.0 ppm between the systems compared.

2.2.3. Light transmittance measurements

Light transmittance measurements were carried out in a two-phase system using a Thorlabs PM100USB power and energy meter equipped with an S121C light sensor. The measurement principle was based on the transmittance of light through the bubble dispersion, where variations in transmitted light intensity reflected changes in the characteristics of the bubble population. The sensor, with an aperture diameter of 9.5 mm, operates over a wavelength range of 400–1000 nm and a power range of 50 nW–50 mW.

As illustrated in Fig. 1, the light source was positioned opposite the sensor beneath the froth zone. Before each experiment, the incident light intensity was adjusted to 110–116 mW to ensure consistent measurement conditions and minimize errors due to light-source fluctuations. Light transmittance values (mV) were recorded for single frothers and dual blends over the investigated concentration range. The resulting data were subsequently plotted as light transmittance versus frother concentration.

2.2.4. Dynamic froth stability measurements

Dynamic froth stability measurements were performed in a two-phase (gas-liquid) system using the same laboratory-scale microflotation cell employed for the bubble size measurements, thereby ensuring identical operating conditions. Single frothers and their dual blends at various blending ratios were evaluated under steady-state aeration conditions. All measurements were conducted at a constant superficial gas velocity (J_g) of 0.23 cm/s.

The concept of dynamic froth stability was first introduced by Bikerman (1973) and later refined by Barbian et al. (2003). Dynamic froth stability (Σ) is defined as the ratio of froth volume to the air volumetric flow rate. Assuming a constant cross-sectional area of the flotation cell, this relationship can be expressed as the ratio of equilibrium froth height to superficial gas velocity, as given in Eq. (2).

$$\Sigma = \frac{V_f}{Q} = \frac{H_f}{J_g} \quad (2)$$

where Σ is the dynamic froth stability (s), V_f is the froth volume (cm³), Q is the volumetric air flow rate (cm³/s), H_f is the equilibrium froth height (cm), and J_g is the superficial gas velocity (cm/s).

The experimental setup used for dynamic froth stability measurements is illustrated in Fig. 3. The equilibrium froth height (H_f) was measured under steady-state conditions and used to calculate the dynamic froth stability according to Eq. (2).

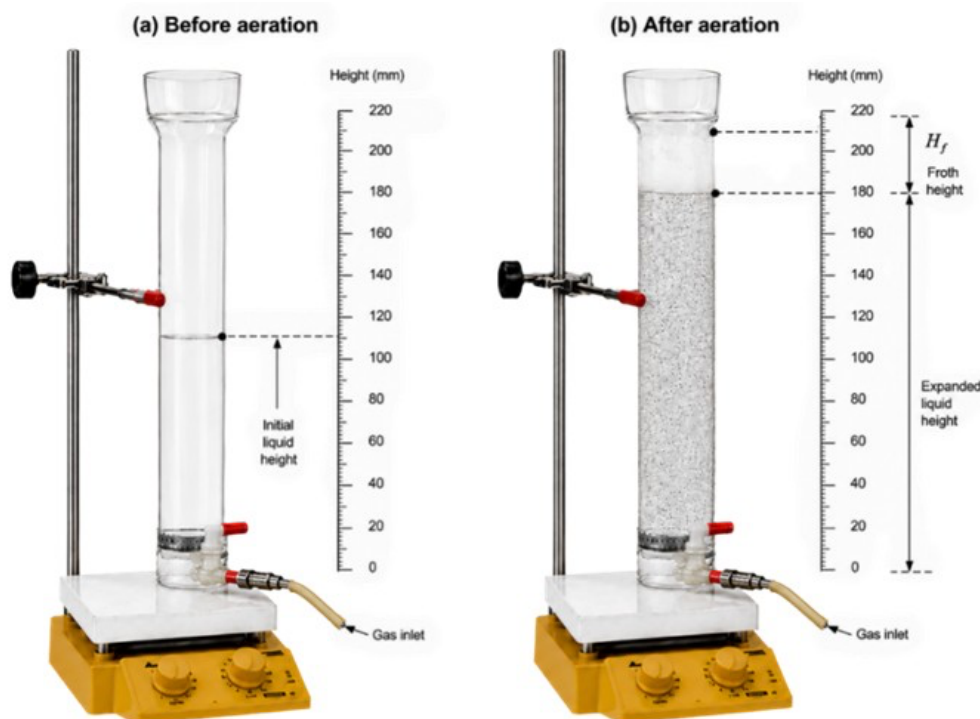


Fig. 3. Experimental setup for dynamic froth stability measurement

3. Results and discussion

3.1. Two-phase system

3.1.1. Bubble size measurements

The variation in bubble size with frother concentration was investigated for each frother and its dual blends. Fig. 4 shows the corresponding variation in d_{32} as a function of frother concentration, where the reported d_{32} values represent the means of these repeats and the variability is expressed as the standard deviation, shown as error bars. For all frother systems, the d_{32} decreased with increasing frother concentration until reaching the CCC, beyond which no significant change in bubble diameter was observed.

The CCC values determined for the single frothers were 11.0 ppm for MIBC and 10.2 ppm for Butyl Glycol, whereas the dual blends exhibited lower CCC values of 9.0, 8.0, and 7.5 ppm for the 75:25, 50:50, and 25:75 (MIBC:Butyl Glycol) mixtures, respectively. These results indicate that the dual blends reached the CCC at lower frother concentrations than the single frothers.

Although the dual blends exhibited lower CCC values, the bubble diameters measured at the CCC varied considerably with the blending ratio. The 50:50 blend produced the smallest bubble diameter among the dual blends ($d_{32} = 0.37$ mm), whereas the 25:75 and 75:25 mixtures generated larger bubble diameters of 0.61 mm and 0.90 mm, respectively. In comparison, Butyl Glycol produced smaller bubbles (0.35 mm) than MIBC (0.40 mm) when used individually. These findings suggest that a lower CCC does not necessarily result in a smaller equilibrium bubble diameter. Instead, the results suggest that the equilibrium bubble size is strongly influenced by the frother blending ratio, indicating that the CCC alone is insufficient to describe bubble size in dual blends.

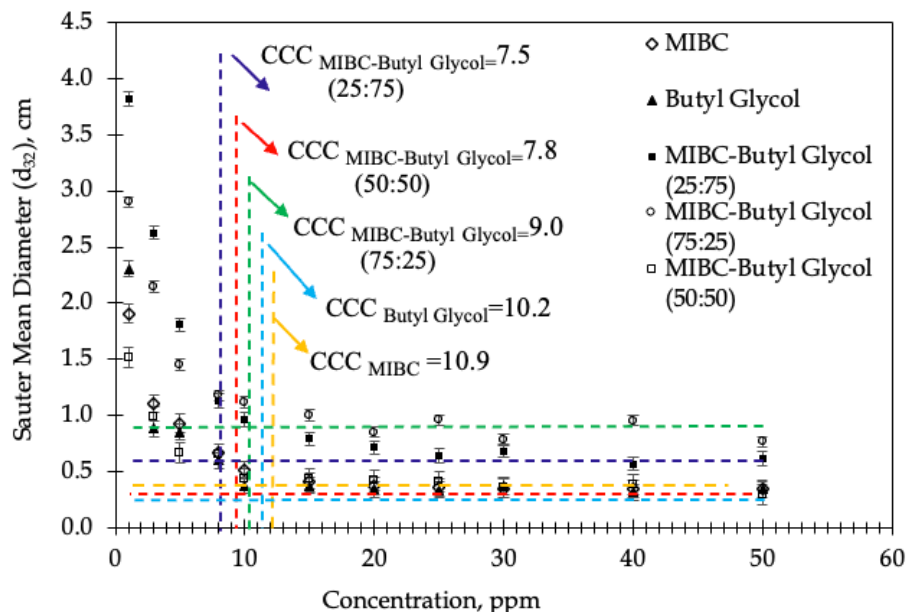


Fig. 4. Effect of frother concentration on the d_{32} of single frothers and dual blends

The results obtained for the dual MIBC–Butyl Glycol systems are consistent with the observations of Elmahdy and Finch (2013), who reported that blending alcohol- and glycol-based frothers produced non-linear hydrodynamic responses that could not be explained solely by the CCC. In particular, they observed that small additions of polyglycol to alcohol systems above the alcohol CCC unexpectedly increased bubble size, despite the lower coalescence tendency. They suggested that this behavior might be associated with changes in bubble coalescence, air break-up, or preferential partitioning of the frother at the gas–liquid interface, although no definitive mechanism could be established. Similar behavior was observed in the present study, where the dual blends reached lower CCC values than the individual frothers, but the equilibrium bubble size depended strongly on the blending ratio. In particular, the 75:25 and 25:75 MIBC–Butyl Glycol blends produced larger equilibrium bubbles than the 50:50 blend despite exhibiting lower CCC values. These findings further support that the hydrodynamic behavior

of blended frother systems cannot be interpreted based on CCC alone and is strongly influenced by molecular interactions between the two frother families.

3.1.2. Light transmittance measurements

The relationship between light transmittance and bubble size was investigated using single frothers and dual MIBC–Butyl Glycol blends with different ratios. Figs. 5 and 6 show the variations in light transmittance and the corresponding d_{32} as a function of frother concentration for the single and dual blends, respectively. Increasing frother concentration reduced both light transmittance and bubble diameter for all frother systems. The decrease became less pronounced as the CCC was approached, indicating that further frother addition had only a limited effect on bubble size. The similar concentration-dependent trends observed in both light transmittance and bubble diameter suggest a strong relationship between these two parameters.

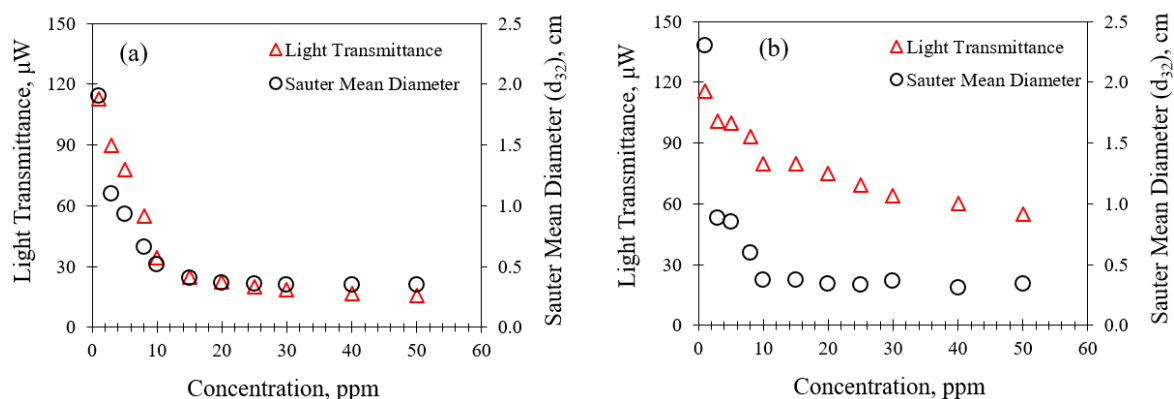


Fig. 5. Variation of light transmittance and d_{32} with frother concentration for the single frothers: (a) MIBC and (b) Butyl glycol

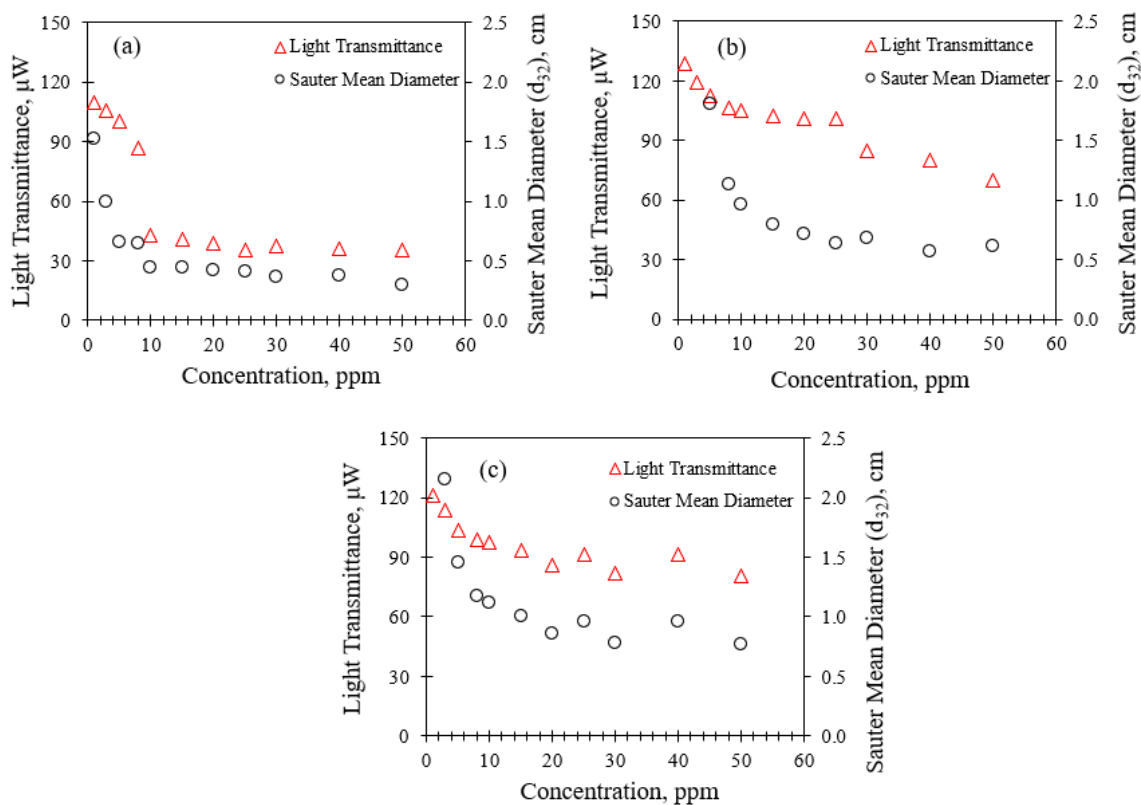


Fig. 6. Variation of light transmittance and d_{32} with frother concentration for the dual MIBC–Butyl glycol blends: (a) 50:50, (b) 25:75, and (c) 75:25

To further quantify the relationship between light transmittance and bubble size, linear, exponential, and second-order polynomial regression models were fitted to the experimental data (Figs. 7 and 8). Linear regression was performed using the Microsoft Excel Data Analysis Tool, while the nonlinear exponential and polynomial models were optimized using the Solver function to minimize the sum of squared errors (SSE) (Brown, 2001). The corresponding regression equations and goodness-of-fit statistics are summarized in Table 3. Model performance was evaluated using the coefficient of determination (R^2), the sum of squared errors (SSE), and the root mean square error (RMSE). The best-fitting model was identified based on the highest R^2 together with the lowest SSE and RMSE values. Among the evaluated models, the linear model consistently exhibited the lowest goodness-of-fit, indicating that the relationship between light transmittance and bubble size is inherently nonlinear.

For the single frothers (Fig. 7), the exponential and polynomial models produced comparable fitting performance, indicating that both nonlinear models adequately describe the relationship between light transmittance and bubble size. The exponential model showed slightly higher R^2 values and lower error statistics for MIBC, whereas the polynomial model provided a marginally better fit for Butyl Glycol. These results suggest that the bubble size response of single frothers follows relatively simple nonlinear behavior that can be satisfactorily represented by either model.

More pronounced differences were observed in the dual-frother systems than in the single-frother systems (Fig. 8 and Table 3). The polynomial model consistently provided the best statistical performance for all blending ratios, with the highest R^2 values together with the lowest SSE and RMSE

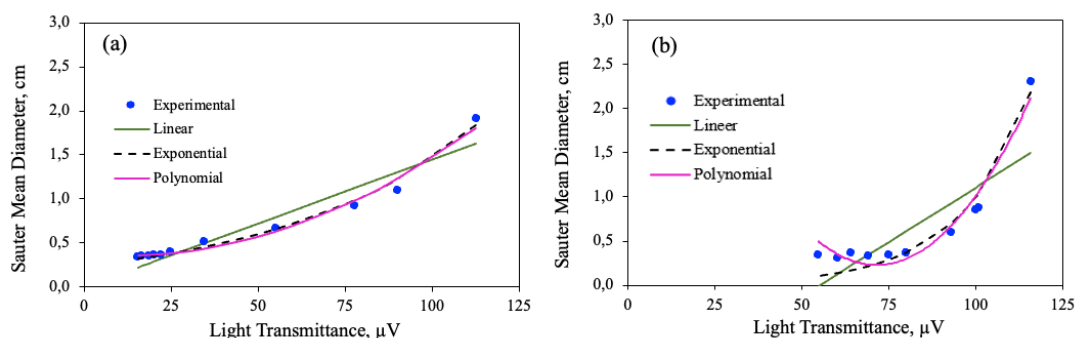


Fig. 7. Comparison of three models fitted to test data for single frothers: (a) MIBC, (b) Butyl glycol

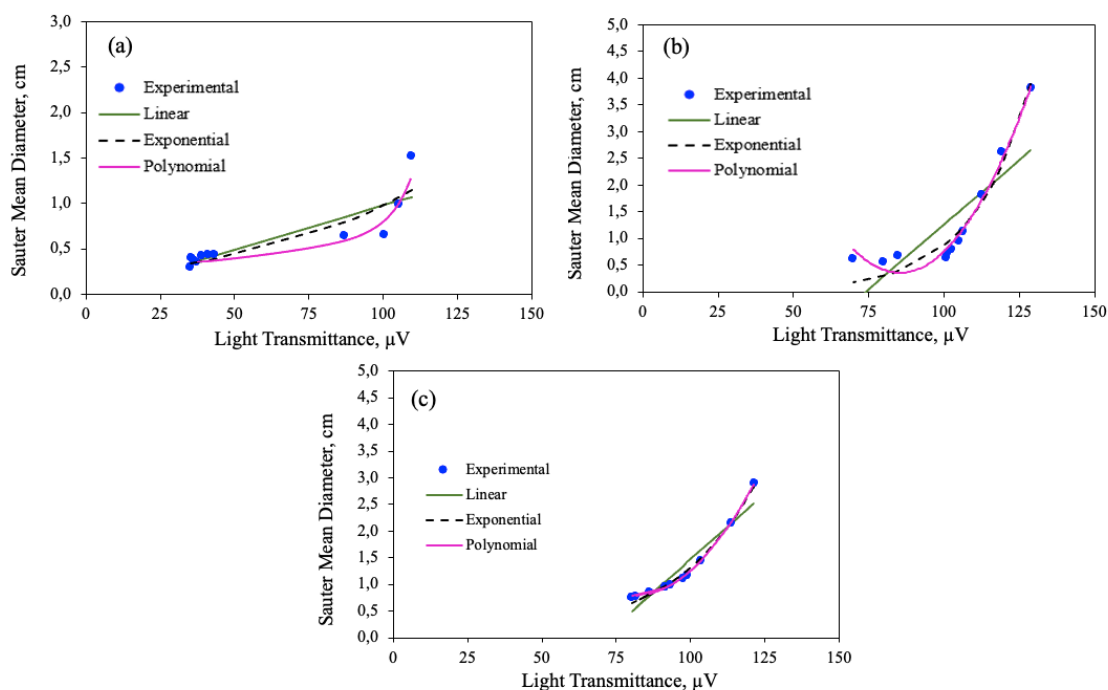


Fig. 8. Comparison of three models fitted to test data for dual MIBC-Butyl Glycol blends: (a) 50:50, (b) 25:75, and (c) 75:25

values. For the 75:25 MIBC–Butyl Glycol blend, the polynomial model achieved an R^2 value of 0.998. At the same time, the exponential model also showed a comparable fit ($R^2 = 0.989$), indicating that both nonlinear models adequately described the experimental data when MIBC was the dominant component. In contrast, the superiority of the polynomial model became more evident for the 25:75 blend, where the R^2 value increased from 0.943 to 0.977. For the 50:50 blend, although the polynomial model provided the best fit, the coefficient of determination remained comparatively low ($R^2 = 0.845$), suggesting that this blending ratio was less satisfactorily represented than the other dual blends. These results suggest that the relationship between light transmittance and bubble size depends not only on the frother type but also on the blending ratio. Therefore, although the polynomial model provides the best overall description of the dual blends, the exponential model also provides a comparable representation for the 75:25 MIBC–Butyl Glycol blend.

Table 3. Regression coefficients and goodness-of-fit statistics for the linear, exponential, and polynomial models fitted to the light transmittance–bubble size data

Model	MIBC	Butyl Glycol	MIBC-Butyl G. (50:50)	MIBC-Butyl G. (25:75)	MIBC-Butyl G. (75:25)
LINEAR					
Equation Coefficients	a=0.0003	a=-1.3636	a=0.0047	a=-3.5873	a=-3.4700
y=a+bx	b=0.0145	b=0.0247	b=0.0097	b=0.0485	b=0.0494
SSE	0.2021	1.2083	0.3570	3.9303	0.4415
RMSE	0.1355	0.3314	0.1802	0.5978	0.2003
R^2	0.915	0.651	0.732	0.640	0.900
EXPONENTIAL					
Equation Coefficients	a=0.2450	a=0.0070	a=0.1932	a=0.0050	a=0.0361
y=ab ^x	b=1.0180	b=1.0508	b=1.0164	b=1.0531	b=1.0366
SSE	0.0284	0.2153	0.2909	0.6215	0.0482
RMSE	0.0509	0.1399	0.1626	0.2377	0.0662
R^2	0.988	0.938	0.781	0.943	0.989
POLYNOMIAL					
Equation Coefficients	a=0.0001	a=0.0010	a=0.0004	a=0.0018	a=0.0361
	b=-0.0030	b=-0.1374	b=-0.0426	b=-0.3121	b=1.0366
y=ax ² +bx+c	c=0.3696	c=5.1361	c=1.4694	c=13.6655	c=8.9997
SSE	0.0389	0.1594	0.2066	0.2513	0.0057
RMSE	0.0594	0.1204	0.1370	0.1512	0.0227
R^2	0.984	0.954	0.845	0.977	0.998

Similar trends between light transmittance and bubble size were reported by Güven et al. (2024), who observed that changes in light transmittance closely followed changes in d_{32} across a range of frother concentrations. The intended purpose of the light-transmittance measurement in this study is to provide a rapid, low-cost, and non-intrusive indicator of relative changes in bubble dispersion during frother screening, rather than an absolute measurement of bubble size. Because the transmitted intensity depends on the total projected interfacial area, the optical path length, and the cell geometry, the regression coefficients obtained here apply only to the present configuration. Within a fixed configuration, the measurement was consistent with the image-analysis results and tracked the approach to the CCC, which suggests that it may be useful for comparing frothers or for monitoring changes in bubble dispersion over time.

3.1.3. Dynamic froth stability measurements

The relationship between dynamic froth stability, frother concentration, and bubble size was investigated for single and dual MIBC–Butyl Glycol systems. Fig. 9 (a,b) shows the variation of dynamic froth stability with frother concentration and d_{32} . Dynamic froth stability increased with increasing frother concentration for all single and dual blends (Fig. 9a). In contrast, dynamic froth stability

decreased with increasing bubble diameter (Fig. 9b), indicating that smaller bubbles produced more stable froths. Among the single frothers, Butyl Glycol exhibited the highest dynamic froth stability, whereas the dual blends showed intermediate behavior depending on the blending ratio.

The observed increase in dynamic froth stability with increasing frother concentration is consistent with previous studies. Malysa (1992) demonstrated that foam retention time increased with frother concentration until reaching a maximum value. Laskowski et al. (2003) reported that the dynamic foamability index (DFI) increased with the number of propylene oxide groups in the frother molecule, with MIBC and dipropylene glycol methyl ether (DPM, $m = 2$, containing two propylene oxide units) showing comparable DFI values. Similarly, Tan et al. (2005) observed that foaminess increased with increasing frother concentration before reaching a plateau. Saavedra Moreno et al. (2021) observed that dynamic foam stability increased with increasing frother concentration for a wide range of non-ionic flotation frothers. The present results are in agreement with these findings and further demonstrate that, for both single and dual blends, increasing frother concentration enhances dynamic froth stability while simultaneously reducing the d_{32} in the froth phase.

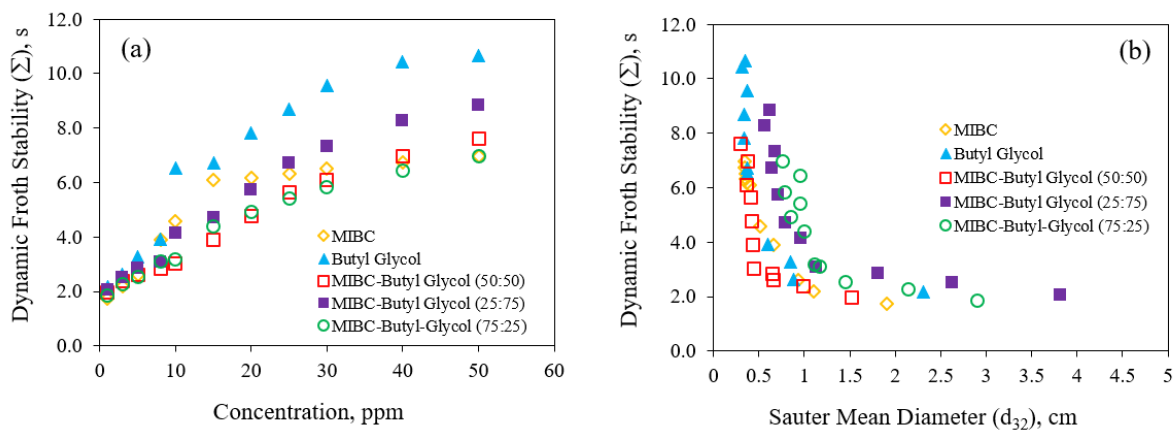


Fig. 9. Dynamic froth stability as a function of (a) frother concentration and (b) Sauter mean bubble diameter for single and dual blends

The relationship between dynamic froth stability and bubble size was quantitatively analyzed using exponential and second-order polynomial regression models fitted to the experimental data (Figs. 10 and 11). The corresponding regression equations and goodness-of-fit statistics are presented in Table 4. Model performance was evaluated using the coefficient of determination (R^2), the sum of squared errors (SSE), and the root mean square error (RMSE).

For the single frothers (Fig. 10 and Table 4), both nonlinear models adequately described the overall experimental trend. The polynomial model provided the best fit for MIBC ($R^2 = 0.982$), whereas only a slight improvement over the exponential model was observed for Butyl Glycol ($R^2 = 0.845$ and 0.822 , respectively). These results indicate that the relationship between dynamic froth stability and bubble size for single frothers can be satisfactorily represented by either nonlinear model.

A similar trend was observed for the dual blends (Fig. 11 and Table 4). The polynomial model consistently showed higher R^2 values, together with lower SSE and RMSE values than the exponential model for all blending ratios. Though the improvement was relatively limited, with R^2 values ranging from 0.770 to 0.805. This indicates that the relationship between dynamic froth stability and bubble size was weaker than that observed for the light transmittance–bubble size relationship. Among the dual blends, the highest goodness of fit was obtained for the 75:25 MIBC–Butyl Glycol blend ($R^2 = 0.805$), whereas the lowest was obtained for the 50:50 blend ($R^2 = 0.770$).

Previous studies have shown that froth-phase bubble size can be used to characterize several important froth properties, including froth stability, bubble coalescence, and froth mobility (Ata et al., 2003; Bhondayi et al., 2018; Bhondayi, 2022). Building on these findings, the present study quantitatively evaluates the relationship between dynamic froth stability and the d_{32} in the froth phase using nonlinear regression models. Although bubble size alone cannot fully explain the observed variations in dynamic froth stability, the polynomial model consistently provided the closest fit to the experimental data for

both single and dual blends. The comparatively lower goodness-of-fit values obtained for the dynamic froth stability models suggest that froth stability is influenced not only by bubble size but also by other physical and physicochemical factors governing froth behaviour.

MIBC exhibited a considerably better correlation between dynamic froth stability and the froth-phase d_{32} than Butyl Glycol. This difference may be associated with the distinct molecular characteristics of the two frother families. MIBC is a branched aliphatic alcohol with a relatively low molecular weight, whereas Butyl Glycol belongs to the glycol ether family and possesses a comparatively higher molecular weight. Branched alcohols generally exhibit higher water solubility

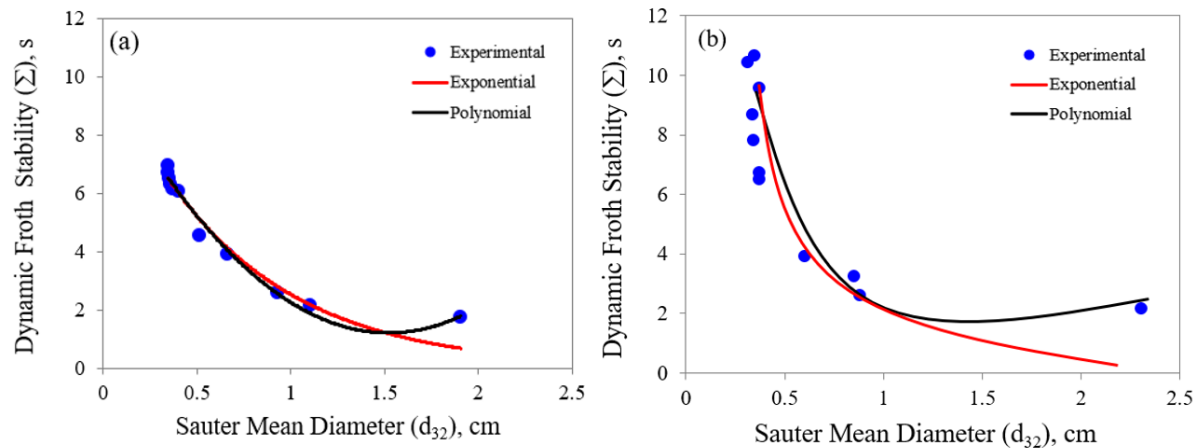


Fig. 10. Comparison of exponential and second-order polynomial models fitted to the relationship between dynamic froth stability and Sauter mean bubble diameter for single frothers: (a) MIBC and (b) Butyl Glycol

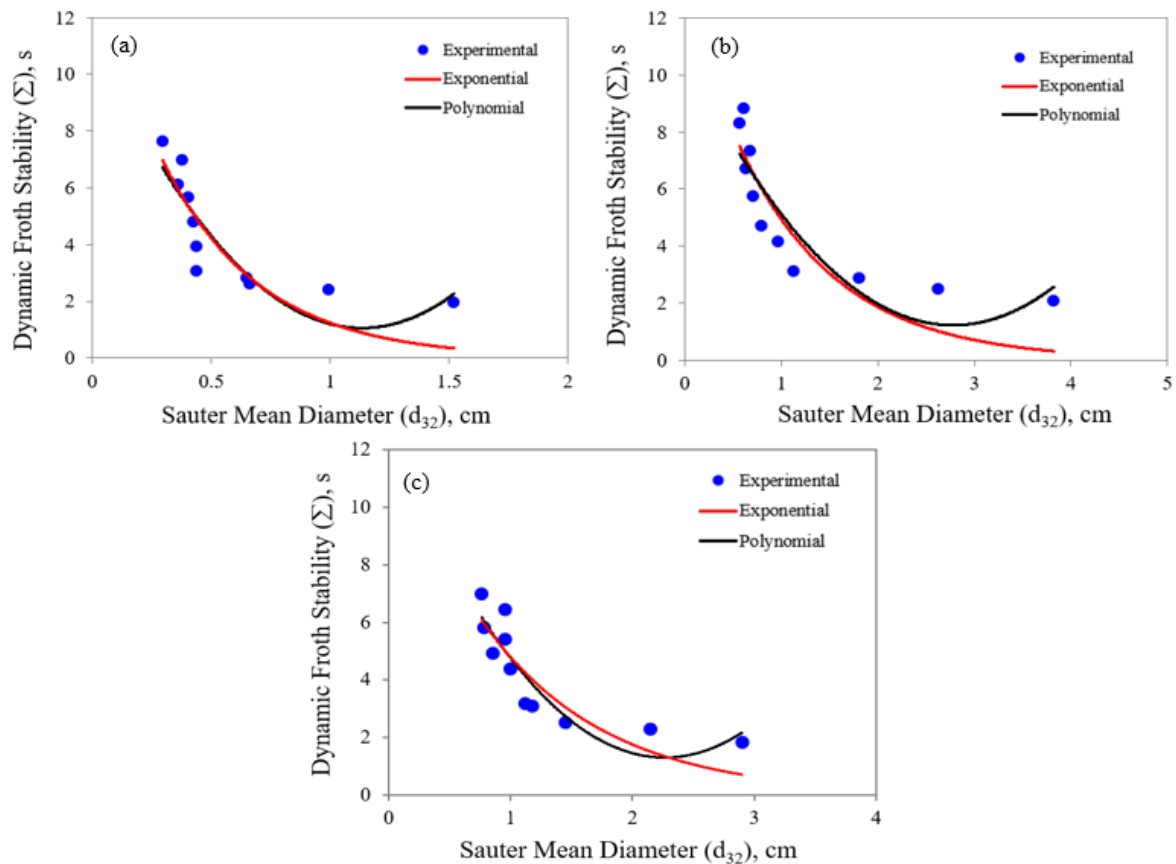


Fig. 11. Comparison of exponential and second-order polynomial models fitted to the relationship between dynamic froth stability and Sauter mean bubble diameter for dual MIBC–Butyl Glycol blends: (a) 50:50, (b) 25:75, and (c) 75:25

Table 4. Regression coefficients and goodness-of-fit statistics for the exponential and second-order polynomial models fitted to the dynamic froth stability-bubble size data

Model	MIBC	Butyl Glycol	MIBC-Butyl G. (50:50)	MIBC-Butyl G. (25:75)	MIBC-Butyl G. (75:25)
EXPONENTIAL					
Equation Coefficients	a=10.7467	a=20.3459	a=14.3790	a=13.0341	a=13.0893
$y=ab^x$	b=0.2363	b=0.0858	b=0.0861	b=0.3785	b=0.3667
SSE	1.7983	17.7557	10.6133	14.3011	7.7962
RMSE	0.4043	1.2705	0.9823	1.1402	0.8419
R ²	0.954	0.822	0.728	0.754	0.753
POLYNOMIAL					
Equation Coefficients	a=3.8543	a=6.0260	a=8.0450	a=1.2312	a=2.1574
	b=-11.7230	b=-19.2377	b=-18.2437	b=-6.8392	b=-9.7743
$y=ax^2+bx+c$	c=10.1325	c=14.5645	c=11.4008	c=10.7243	c=12.3782
SSE	0.6905	15.4820	8.9844	12.8861	6.1483
RMSE	0.2505	1.1864	0.9038	1.0823	0.7476
R ²	0.982	0.845	0.770	0.778	0.805

and more rapid adsorption at the gas-liquid interface, whereas glycol ether frothers are characterized by slower adsorption kinetics and the formation of mechanically more persistent froths (Amidon et al., 1974; Phan et al., 2012; Melo and Laskowski, 2006, 2007; Javor et al., 2015; Pawliszak et al., 2024). Consequently, in glycol ether systems, dynamic froth stability is likely influenced not only by the bubble size in the froth phase but also by interfacial film properties, froth drainage, and other structural characteristics of the froth. These findings are in agreement with those reported by Saavedra Moreno et al. (2021), who showed that the dynamic and static foam stability of alcohol- and glycol-based frothers is strongly dependent on molecular structure, particularly the number of hydrocarbon and propylene oxide groups. Accordingly, the lower correlations observed for Butyl Glycol and the dual blends may be attributed to the combined influence of froth-phase bubble size and the physicochemical characteristics of the frother molecules.

3.2. Three-phase system measurements

Microflotation experiments were conducted using pure galena and sphalerite samples. The particle size distributions of the mineral samples were determined using a Malvern Mastersizer 2000 laser-diffraction particle-size analyzer and are shown in Fig. 12. The d_{80} values were approximately 68 μm for galena and 98 μm for sphalerite, indicating that the galena sample was finer than the sphalerite sample. Fig. 13 shows the flotation recoveries obtained with the single and dual blends.

MIBC was the dominant component in the 75:25 MIBC-Butyl Glycol blend, the recovery increased further to 96.22%, indicating that galena flotation benefited from MIBC-rich systems. In contrast, sphalerite exhibited the opposite trend. Butyl Glycol produced a substantially higher recovery (94.72%) than MIBC (78.68%), and the highest sphalerite recovery (97.88%) was obtained with the Butyl Glycol-dominant 25:75 blend. These results demonstrate that increasing the proportion of MIBC preferentially enhanced galena recovery, whereas increasing the proportion of Butyl Glycol preferentially improved sphalerite recovery.

These results suggest that flotation performance was not explained by the CCC or the froth-phase bubble size alone. For example, the 75:25 MIBC-Butyl Glycol blend produced the largest froth-phase bubbles ($d_{32} = 0.90$ mm) but exhibited the highest galena recovery, whereas the 25:75 blend, despite producing smaller bubbles ($d_{32} = 0.61$ mm) and having the lowest CCC (7.5 ppm), provided the highest sphalerite recovery. Therefore, neither the lowest CCC nor the smallest bubble size consistently corresponded to the highest flotation recovery. As described by Khoshdast and Sam (2011), frothers can be classified as selective or powerful depending on their primary function during flotation. Selective frothers mainly enhance the probability of particle-bubble attachment, whereas powerful frothers increase froth carrying capacity and therefore improve the recovery of coarse particles. This concept is

consistent with the present results. The d_{80} of sphalerite (98 μm) was considerably larger than that of galena (68 μm). Consequently, Butyl Glycol-rich systems, which exhibited greater frothing power, produced substantially higher Zn recoveries by improving the transport of the coarser sphalerite particles through the froth phase. In contrast, MIBC-rich systems yielded the highest Pb recoveries, suggesting that enhanced particle-bubble attachment was sufficient for recovering the finer galena particles. These findings indicate that flotation recovery is governed not only by frother chemistry but also by the interaction between frother characteristics, particle size, mineral characteristics, and bubble-particle interactions, rather than by CCC or froth-phase bubble size alone.

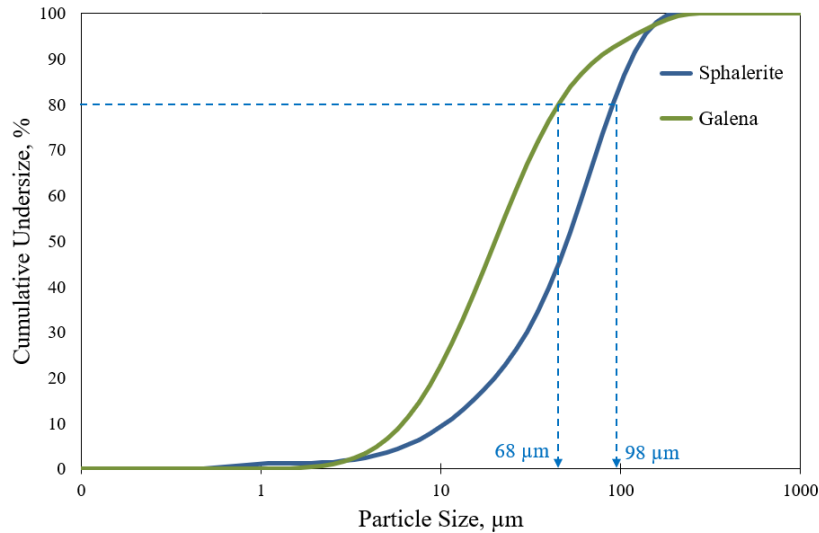


Fig. 12. Particle size distributions of the pure galena and sphalerite samples

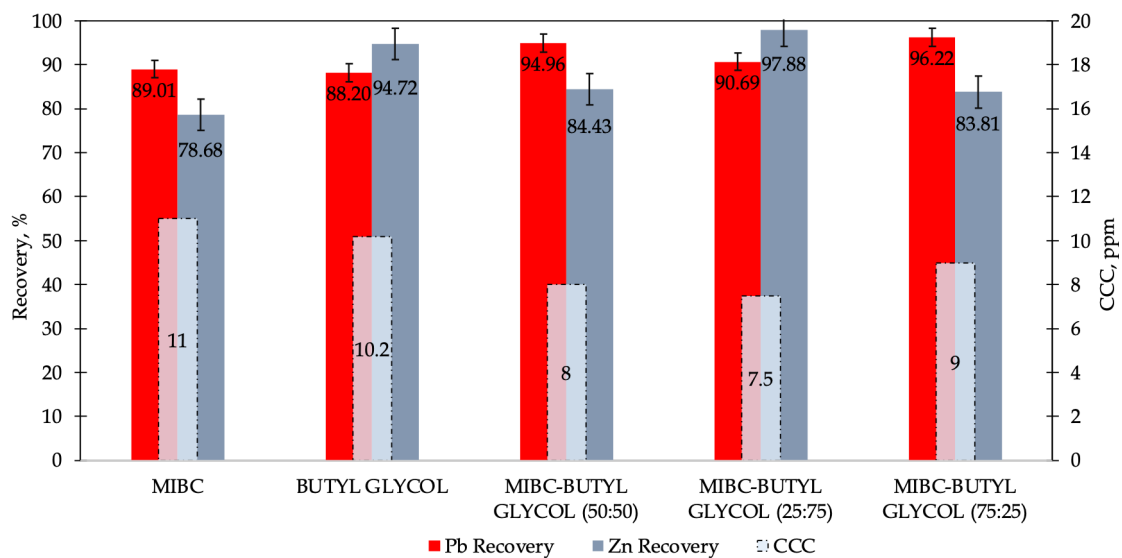


Fig. 13. Effect of single and dual blends on CCC and recovery of galena – sphalerite

For galena, MIBC provided a slightly higher recovery (89.01%) than Butyl Glycol (88.20%). When the present results are consistent with previous studies showing that the molecular structure of frothers affects not only froth stability but also the particle size range recovered during flotation. In particular, alcohol-based frothers generally show higher selectivity for finer particles, whereas polyglycol-based frothers, because of their higher molecular weight and more persistent froths, can recover a wider particle size range, although with lower selectivity (Melo and Laskowski, 2006, 2007; Grau and Laskowski, 2006; Gupta et al., 2007, 2009; Dey et al., 2014; Jávors et al., 2015).

Although frother blending influenced CCC, bubble size, light transmittance, and dynamic froth stability in the two-phase system, the corresponding trends were not directly reflected in the three-

phase microflotation results. For example, the 50:50 blend produced the smallest equilibrium bubble size but did not provide the highest recovery, whereas the 75:25 blend produced relatively larger bubbles and yielded the highest galena recovery. Similarly, the lowest CCC obtained with the 25:75 blend did not correspond to the highest recovery for both minerals. These observations are consistent with the concept proposed by Cappuccitti and Nasset (2009) that flotation performance depends on an appropriate balance between hydrodynamic characteristics rather than on a single parameter. The present results therefore indicate that CCC and bubble size alone were not sufficient to predict the flotation response after the introduction of the mineral phase and collector.

4. Conclusions

This study investigated the influence of single and dual blends composed of structurally different alcohol-based (MIBC) and glycol ether-based (Butyl Glycol) frothers on gas dispersion characteristics in two-phase systems and mineral flotation behavior in three-phase systems.

The dual MIBC–Butyl Glycol systems reached the CCC at lower concentrations than the single frothers. However, the equilibrium Sauter mean bubble diameter varied markedly with the blending ratio, increasing in both the 75:25 and 25:75 MIBC–Butyl Glycol blends despite their similarly low CCC values. This behavior emphasizes the importance of the blending ratio in controlling bubble characteristics in dual blends.

Light transmittance was consistent with the changes observed in bubble size. While the nonlinear models showed similar performance for the single frothers, the improved performance of the second-order polynomial model for the dual MIBC–Butyl Glycol blends indicate that the blending ratio influences the relationship between light transmittance and bubble size.

The correlation between dynamic froth stability and bubble size was highest for the single MIBC system, but decreased with the incorporation of Butyl Glycol in both the single Butyl Glycol system and the dual MIBC–Butyl Glycol blends. This suggests that the different molecular structure of Butyl Glycol may be responsible for the lower correlation between dynamic froth stability and bubble size.

The three-phase microflotation results indicated that both frother chemistry and the MIBC–Butyl Glycol blending ratio significantly influence the flotation behavior of galena and sphalerite.

The present results indicate that the critical coalescence concentration and bubble size are insufficient to explain flotation performance in single and dual blends. Frother chemistry and blending ratio should also be considered.

These findings suggest that optimizing flotation performance requires a holistic evaluation of frother chemistry, blending ratio, bubble characteristics, and froth properties rather than relying on CCC alone.

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