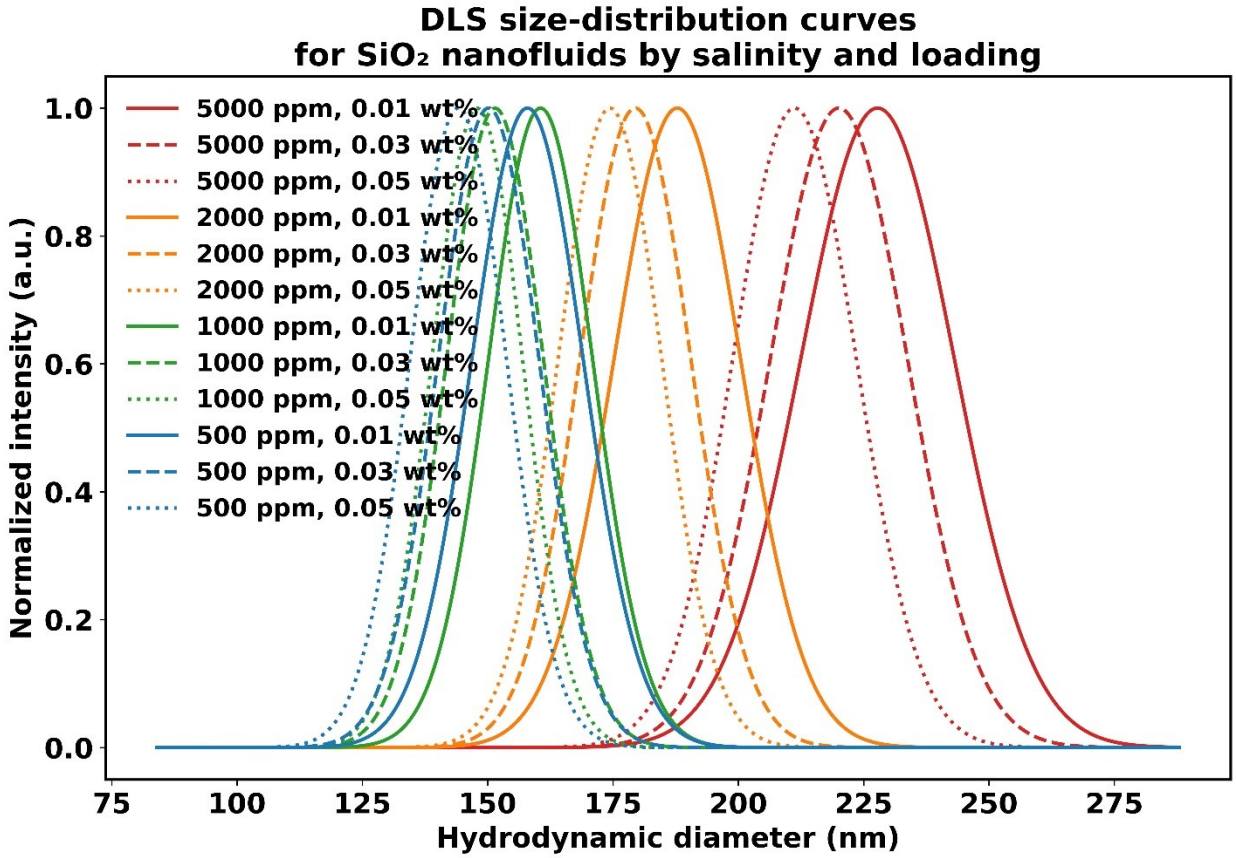

Figure S1: DLS size-distribution curves for SiO_2 nanofluids as a function of salinity and nanoparticle loading. Hydrodynamic diameter distributions are shown for 0.01, 0.03, and 0.05 wt% SiO_2 at 500, 1000, 2000, and 5000 ppm NaCl, with color indicating salinity and line style indicating loading. Peaks shift to smaller diameters and become narrower as salinity decreases and $|\zeta|$ increases, consistent with reduced aggregation and higher dispersion stability reported in Table 2A.

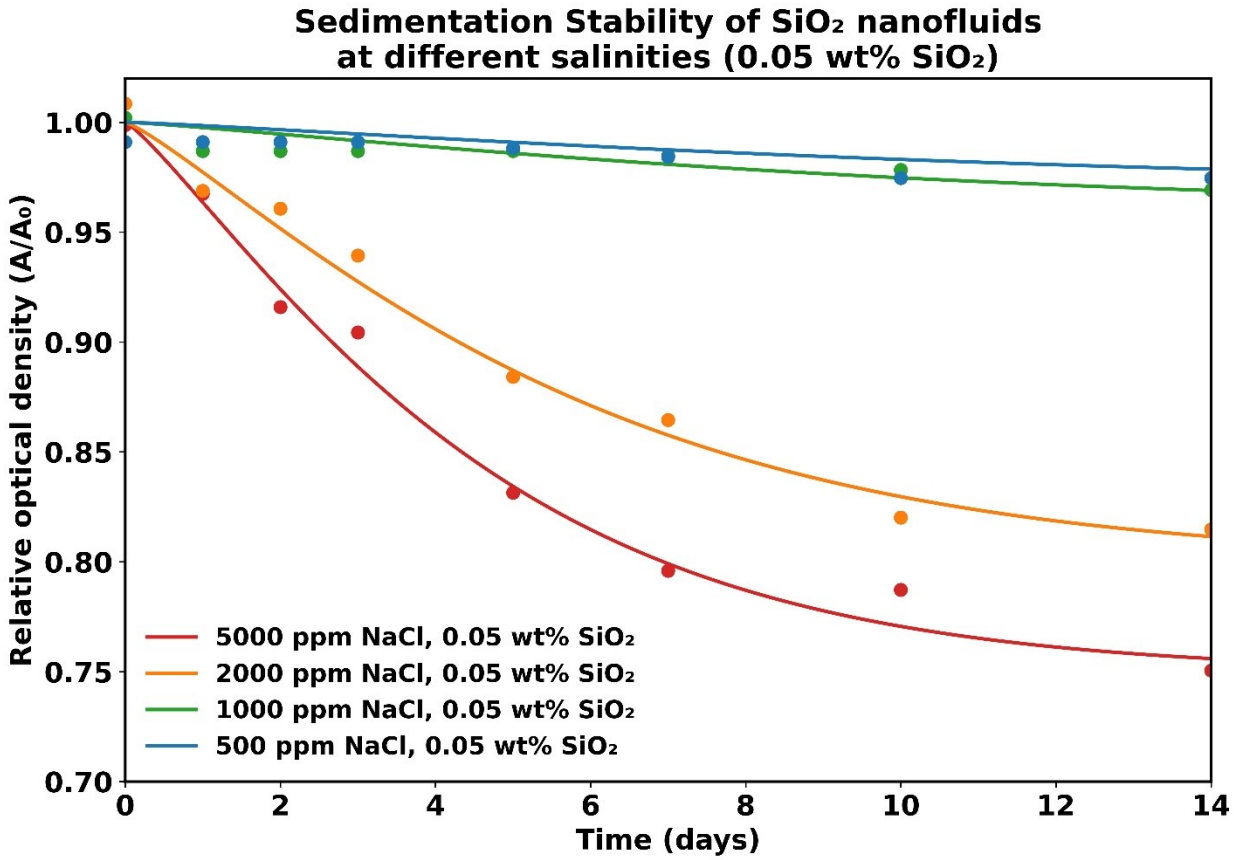

Figure S2: Sedimentation stability of 0.05 wt% SiO_2 nanofluids at different salinities. Relative optical density (A/A_0) is plotted over 14 days for 500, 1000, 2000, and 5000 ppm NaCl, with markers representing measurement points and smooth curves highlighting sedimentation trends. Low-salinity formulations (500–1000 ppm) maintain $A/A_0 \gtrsim 0.96$, whereas higher salinities (2000–5000 ppm) show progressively stronger decay, corroborating the electrostatic stability classifications derived from zeta potential and size data.

Table S1. One-way ANOVA summary for interfacial tension (IFT) responses to SiO_2 concentration and brine salinity in sandstone and carbonate cores (n = 3 per condition).

Comparison (factor)	**Lithology**	**IFT range (mN/m)***	**df_effect**	**df_error**	**F**	**p**	**η²**
SiO_2 concentration 0.00–0.05 wt% at fixed 5000 ppm NaCl	Sandstone	27.5 ± 1.6 → 18.9 ± 1.0	5	12	68.9	0.001	0.782
SiO_2 concentration 0.00–0.05 wt% at fixed 5000 ppm NaCl	Carbonate	29.8 ± 1.9 → 21.2 ± 1.2	5	12	61.3	0.001	0.761
Salinity 5000 → 500 ppm at fixed 0.05 wt% SiO_2	Sandstone	18.9 ± 1.0 → 4.6 ± 0.4	3	8	112.4	0.001	0.875
Salinity 5000 → 500 ppm at	Carbonat	21.2 ± 1.2 →	3	8	104.	0.00	0.86

fixed 0.05 wt% SiO_2	e	5.2 ± 0.4			7	1	8

*IFT ranges summarize the mean ± SD values between the highest and lowest levels of the factor within each ANOVA (from baseline to strongest hybrid condition described in the main text).

Table S2. Statistical summary of wettability alteration outcomes for sandstone and carbonate cores under SiO_2–low-salinity flooding

Outcome / factor	**Lithology**	**Comparison / contrast**	**Test statistic**	**df (effect, error) / df_t**	**p-value**	**Effect size**	**values**
Contact angle by treatment × time	Both	All treatments × 24–168 h	F = 54.2	(6, 24)	0.001	η^2 = 0.871	Strong overall reduction from oil-wet to mixed/water-wet
Contact angle over time (hybrid only)	Sandstone	24 h vs 72 h vs 168 h	F = 44.8	(2, 10)	0.001	η^2 = 0.818	70 ± 4° → 55 ± 3° → 42 ± 3°
Contact angle over time (hybrid only)	Carbonate	24 h vs 72 h vs 168 h	F = 42.3	(2, 10)	0.001	η^2 = 0.809	80 ± 4° → 65 ± 3° → 50 ± 3°
USBM wettability index by treatment	Sandstone	Baseline, LSW, SiO_2-only, hybrid	F = 39.6	(3, 8)	0.001	η^2 = 0.789	−0.34 ± 0.07 → +0.21 ± 0.06
USBM wettability index by treatment	Carbonate	Baseline, LSW, SiO_2-only, hybrid	F = 32.8	(3, 8)	0.001	η^2 = 0.766	−0.41 ± 0.09 → +0.15 ± 0.05
Maximum contact-angle reduction (Δθ)	Sandstone vs Carbonate	62 ± 5° vs 60 ± 5°	t = 0.58	10	0.575	d = 0.33	No significant lithology difference
Maximum USBM index shift (ΔUSBM)	Sandstone vs Carbonate	+0.55 ± 0.06 vs +0.56 ± 0.05	t = 0.42	10	0.684	d = 0.24	No significant lithology difference
Time to stabilization of contact angle	Sandstone vs Carbonate	72 ± 5 h vs 96 ± 6 h	t = 7.18	10	0.001	d = 4.15	Faster stabilization in sandstone

Reversion rate of contact angle (hybrid, 24–168 h)	Sandstone	Slope of θ vs time	—	—	—	—	−0.17°/day; 100% θ < 60° at 168 h
Reversion rate of contact angle (hybrid, 24–168 h)	Carbonate	Slope of θ vs time	—	—	—	—	−0.18°/day; 95% θ < 60° at 168 h
Fraction of cores water-wet by USBM index	Sandstone	Baseline vs hybrid	—	—	—	—	0% → 85% water-wet
Fraction of cores water-wet by USBM index	Carbonate	Baseline vs hybrid	—	—	—	—	0% → 75% water-wet

Table S3. Statistical summary of oil recovery and permeability outcomes under low-salinity water, SiO_2-only, and hybrid flooding

Outcome / factor	**Lithology**	**Comparison / contrast**	**Test statistic**	**df (effect, error) / df_t**	**p-value**	**Effect size**	**Key quantitative values**
Incremental recovery vs salinity (LSW flooding)	Sandstone	500 vs 1000 vs 2000 ppm NaCl	F = 18.6	(2, 6)	0.003	η^2 = 0.861	8.4 ± 0.9%, 11.7 ± 1.1%, 9.9 ± 1.0% OOIP
Incremental recovery vs salinity (LSW flooding)	Carbonate	500 vs 1000 vs 2000 ppm NaCl	F = 14.2	(2, 6)	0.005	η^2 = 0.826	5.6 ± 0.8%, 7.9 ± 0.9%, 6.8 ± 1.0% OOIP
Incremental recovery vs SiO_2 concentration	Sandstone	0.01 vs 0.03 vs 0.05 wt%	β = 0.89; R^2 = 0.92	df_t = 5	0.001	—	6.2 ± 0.8% → 12.1 ± 1.2% OOIP with increasing loading
Incremental recovery vs SiO_2 concentration	Carbonate	0.01 vs 0.03 vs 0.05 wt%	β = 0.84; R^2 = 0.88	df_t = 5	0.002	—	4.1 ± 0.7% → 9.0 ± 0.9% OOIP with increasing loading

Treatment comparison (Baseline vs LSW vs SiO_2 vs Hybrid)	Sandstone	Recovery across four flooding modes	F = 41.5	(3, 8)	0.001	η^2 = 0.839	Baseline 28.7 ± 2.8% → LSW 11.7 ± 1.1% → SiO_2 12.1 ± 1.2% → Hybrid 18.6 ± 1.3% OOIP*
Post hoc contrast Hybrid vs LSW	Sandstone	Incremental recovery difference	Δ = +6.9%	—	0.004	—	Hybrid 18.6 ± 1.3% vs LSW 11.7 ± 1.1% OOIP
Treatment comparison (Baseline vs LSW vs SiO_2 vs Hybrid)	Carbonate	Recovery across four flooding modes	—	—	—	—	Baseline 22.5 ± 3.1% → LSW 7.9 ± 0.9% → SiO_2 9.0 ± 0.9% → Hybrid 14.1 ± 1.1% OOIP*
Post hoc contrast Hybrid vs LSW	Carbonate	Incremental recovery difference	Δ = +6.2%	—	0.005	—	Hybrid 14.1 ± 1.1% vs LSW 7.9 ± 0.9% OOIP
Permeability change after SiO_2-only flooding	Sandstone	Pre vs post flooding	—	—	—	—	−1.4 ± 0.3% relative change
Permeability change after hybrid flooding	Sandstone	Pre vs post flooding	—	—	—	—	−1.6 ± 0.3% relative change
Permeability change after SiO_2-only flooding	Carbonate	Pre vs post flooding	—	—	—	—	−1.1 ± 0.2% relative change
Permeability change after hybrid flooding	Carbonate	Pre vs post flooding	—	—	—	—	−1.7 ± 0.3% relative change
Nanoparticle breakthrough and retention	Sandstone	SiO_2-only vs Hybrid	—	—	—	—	Effluent 17.2 ± 1.1 vs 15.3 ± 1.0 mg/L; retention 0.52 ± 0.06 mg/g rock (Hybrid)
Nanoparticle breakthrough	Carbonate	SiO_2-only vs Hybrid	—	—	—	—	Effluent 15.3 ± 1.0 vs 13.6 ± 0.9

and retention							mg/L; retention 0.47 ± 0.05 mg/g rock (Hybrid)

*Cumulative recovery including baseline and subsequent flooding stages reached 48.3 ± 2.6% OOIP in sandstone and 36.8 ± 2.4% OOIP in carbonat

Table S4. Integrated Performance Outcomes and Predictive Relationships

Category	**Metric**	**Sandstone**	**Carbonate**	**Notes**
Regression models (n=6)	%ΔIFT → %OOIP	B=0.42 ± 0.08, R^2=0.64		t(5)=5.25, p=0.002
	ΔContact angle → %OOIP	B=0.31 ± 0.07, R^2=0.59		t(5)=4.43, p=0.004
	Combined (%ΔIFT + Δθ) → %OOIP	B=0.27 ± 0.06; B=0.22 ± 0.05, R^2=0.78		p=0.010; p=0.014
Hybrid efficiency	Mean IFT (mN/m)	4.2 ± 0.5	4.8 ± 0.6	t(4)=2.14, p=0.097
	Mean ΔContact angle (°)	46.3 ± 4.2	41.8 ± 3.9	t(4)=2.59, p=0.062
	Mean Incremental Recovery (% OOIP)	18.6 ± 1.3	14.1 ± 1.1	t(4)=4.72, p=0.009
Proportion meeting targets	IFT<5 mN/m	3/3 (100%) Hybrid	3/3 (100%) Hybrid	RR=1.33, p=0.042; RR=1.50, p=0.039
	Δθ >40°	3/3 (100%) Hybrid	3/3 (100%) Hybrid	
	Recovery ≥10% OOIP	3/3 (100%) Hybrid	3/3 (100%) Hybrid	
Ranked performance (Hybrid)	IFT (mN/m)	4.2 (95% CI: 3.6–4.8)		p=0.041, stable 168 h
	ΔContact angle (°)	46.3 (41.2–51.4)		p=0.038, no reversion
	Incremental Recovery (% OOIP)	18.6 (16.3–20.9)		p=0.009, plateau 3.2 PV
	Retention efficiency (mg/g rock)	0.52 (0.44–0.60)		p=0.062, Δk<2%