

Figure S1. Laboratory-scale formulation system consisting of an acrylic mixing tank, a 3D-printed impeller, and a 3D-printed draft tube.

Table S1. Design parameters and dimensions of the agitation system.

Parameter	Symbol	Value	Unit
Liquid properties			
Density	ρ	997	$kg \cdot m^{-3}$
Dynamic viscosity	μ	0.001	Pa·s
Geometric design ratios			
Tank-to-impeller diameter ratio	Dt/Da	3.0	–
Tank diameter-to-liquid height ratio	Dt/H	1.0	–
Tank diameter-to-baffle width ratio	Dt/J	12.0	–
Impeller diameter-to-blade width ratio	Da/W	4.0	–
Impeller diameter-to-blade length ratio	Da/L	2.0	–
Impeller diameter-to-clearance ratio	Da/E	3.0	–
Scale factor	FH	1.25	–

Parameter	Symbol	Value	Unit
Tank dimensions			
Working volume	V	300.0	mL
Tank diameter	Dt	7.3	cm
Tank height	Ht	9.1	cm
Liquid height	Hliq	7.3	cm
Baffle width	J	0.6	cm
Impeller diameter	Da	2.4	cm
Blade length	L	1.2	cm
Blade width	W	0.6	cm
Impeller clearance	E	2.4	cm

Table S2. Geometric characteristics of the 3D-printed pitched-blade impeller.

Parameter	Value	Unit
Total impeller diameter	2.4	cm
Shaft hole diameter	0.5	cm
Hub diameter	0.6	cm*
Hub height	0.7	cm
Number of blades	4	–
Blade spacing	90	°
Blade height	0.6	cm
Blade thickness	~0.1	cm
Blade pitch angle	45	°
Direction of inclination	Clockwise	–

Table S3. Equipment nomenclature used in the process flow diagram.

Equipment code	Description
P-01	Nutrient solution pump
R-02	Raceway reactor
P-03	Centrifuge feed tank
T-04	Biomass transfer pump
S-05	Biomass centrifuge
P-06	Oil–biomass mixing tank transfer pump
T-07	Oil–biomass mixing tank
T-08	Emulsification tank

T-09	Dilute KNO_3 solution tank
P-10	Emulsification water supply pump
K-11	Air compressor

Table S4. Reactor constants and operating parameters of the raceway simulator

Parameter	Value	Origin / justification
Reactor width [m]	1	Raceway geometry (channel width)
Reactor length [m]	10	Raceway geometry
Liquid velocity [m s^{-1}]	0.2	Hydraulic design criterion to ensure turbulent flow ($Re \approx 4 \times 10^4$; ρ = 1000 kg m^{-3}, μ = 0.001 Pa·s, Rh = h = 0.15 m)
Sump length [m]	0.8	Defined in the simulator; does not affect loop hydrodynamics if unchanged
Paddlewheel length [m]	1.5	Simulator-defined paddle geometry
Sump depth [m]	1.12	Derived from geometric relationships
Sump radius [m]	0.4	Derived from geometric relationships
Initial reactor depth [m]	0.2	Prescribed operating depth
Harvest/dilution rate [-]	0.2	Operating parameter defined in the simulation model

Table S5. Initial physicochemical conditions for raceway simulation initialization

Parameter	Value	Source / Justification
Initial dissolved oxygen concentration [%]	88	Stable model value used for simulation start-up
Initial pH [-]	7.8	Initial value of the culture medium
TIC – Initial concentration [mol m^{-3}]	11.118	Calculated from the carbon/alkalinity balance implemented in the simulator
TIC – Inlet concentration [mol m^{-3}]	10.802	Defined according to the model configuration
Initial CO_2 concentration [mol m^{-3}]	3.40×10^{-1}	Initial concentration at the recorded operating temperature

Table S6. Growth model parameters used for raceway simulation

Model block	Parameter	Value	Origin / justification
Microalgae biomass	Initial biomass concentration [g L^{-1}]	0.5	Typical stable start-up value

Model block	Parameter	Value	Origin / justification
Biological model	Light extinction coefficient [$m^2\ g^{-1}$]	0.05	Typical range reported for Scenedesmus; calibrated within the simulator
	Light saturation intensity [$W\ m^{-2}$]	130	Internal calibration based on raceway geometry and operating conditions
	Light form parameter [-]	2	Internally calculated by the simulator
	Maximum specific growth rate [day^{-1}]	Fixed (model-scaled)	Model parameter scaled during formulation; modification disrupts predictive balance and pseudo-steady-state behavior
Respiration	Maximum / minimum respiration rate [day^{-1}]	1.999×10^{-6} / 9.838×10^{-7}	Default values defined in the growth model
Light (extra)	Light saturation / form parameter	130 / 2	Internally calculated by the simulator
Growth temperature	Minimum / optimum / maximum temperature [°C]	5 / 30 / 40	Optimal range reported for Scenedesmus
pH growth	Minimum / optimum / maximum pH [-]	6.5 / 8.0 / 9.0	Realistic growth window for Scenedesmus; optimum consistent with control conditions
Dissolved oxygen	Maximum DO saturation [%] / form parameter	500 / 3.150	Default anti-limitation control implemented in the simulator

Table S7. Operational control parameters implemented in the raceway simulation

Control block	Parameter	Value	Justification
Temperature	Setpoint temperature [°C]	30	Optimal growth temperature for Scenedesmus
Harvest control	Control mode	Programmed	Time-based harvesting strategy
	Initial harvest time [h]	48	Periodic harvesting every 48 h
	Harvest duration [s]	3600	Harvest operation duration representative of raceway-scale systems
Dilution control	Control mode	Programmed	Time-based dilution strategy
	Initial dilution time [h]	49	Medium replenishment scheduled 1 h after harvesting
	Dilution duration [s]	3600	Dilution operation duration
Dissolved oxygen control	Control mode	Automatic	Feedback-based dissolved oxygen control
	DO setpoint [%]	150	Setpoint selected to avoid oxygen limitation during peak photosynthetic activity

Control block	Parameter	Value	Justification
pH control	Maximum air flow rate [L min^{-1}]	100.0 (upper limit)	Upper airflow limit consistent with the available aeration capacity
	Control mode	Automatic + PI	Proportional–integral control strategy
	pH setpoint [-]	8.0	Optimal pH for Scenedesmus growth
	Proportional gain [-]	0.001	Low gain selected to prevent oscillations in output variables
	Integral gain [s^{-1}]	2000	Moderate integral response

Table S8. Geometric calculations for the raceway system

Parameter	Value
Surface area	10 m^2
Volume	1.5 m^3
Aspect ratio	10
volume-surface ratio	0,15 m^3/ m^2
Length/width ratio	

Table S9. Hydraulic loss calculations in the raceway channel

Parameter	Value
Frictional head loss	—
Hydraulic radius	68cm
Flow velocity	—

Table S10. Paddlewheel design and power calculations

Parameter	Value
Actual diameter	—
Calculated diameter	68cm
Power	—
Rotational speed	—

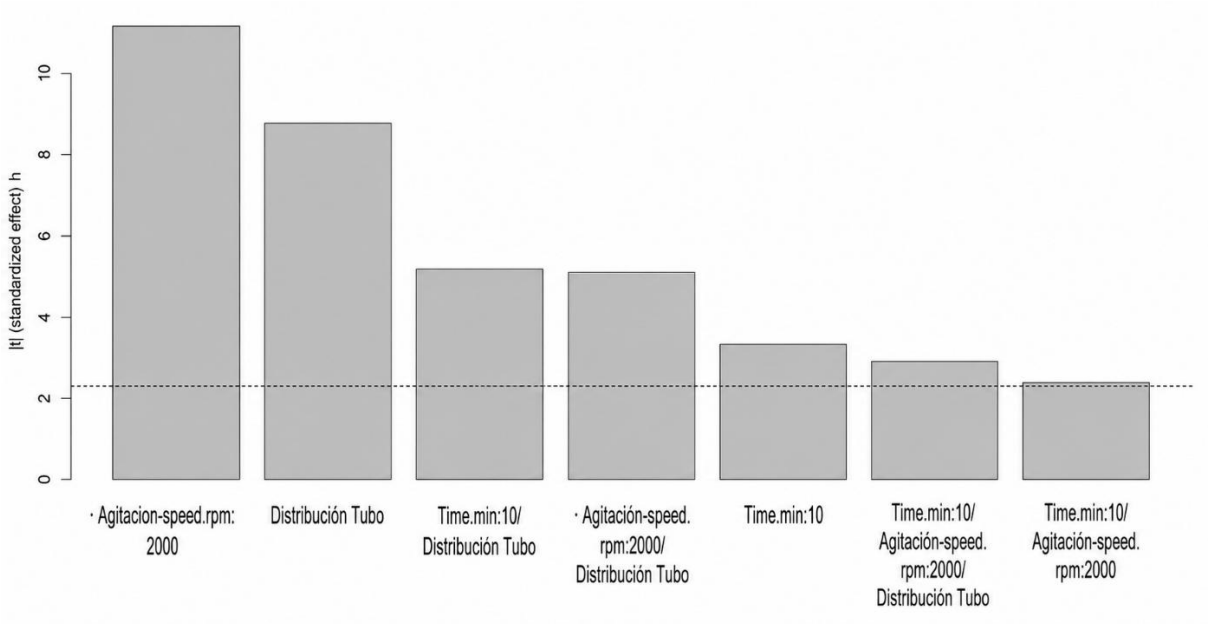


Figure S2. Pareto chart from the factorial analysis of emulsion formulation conditions after 1 h.

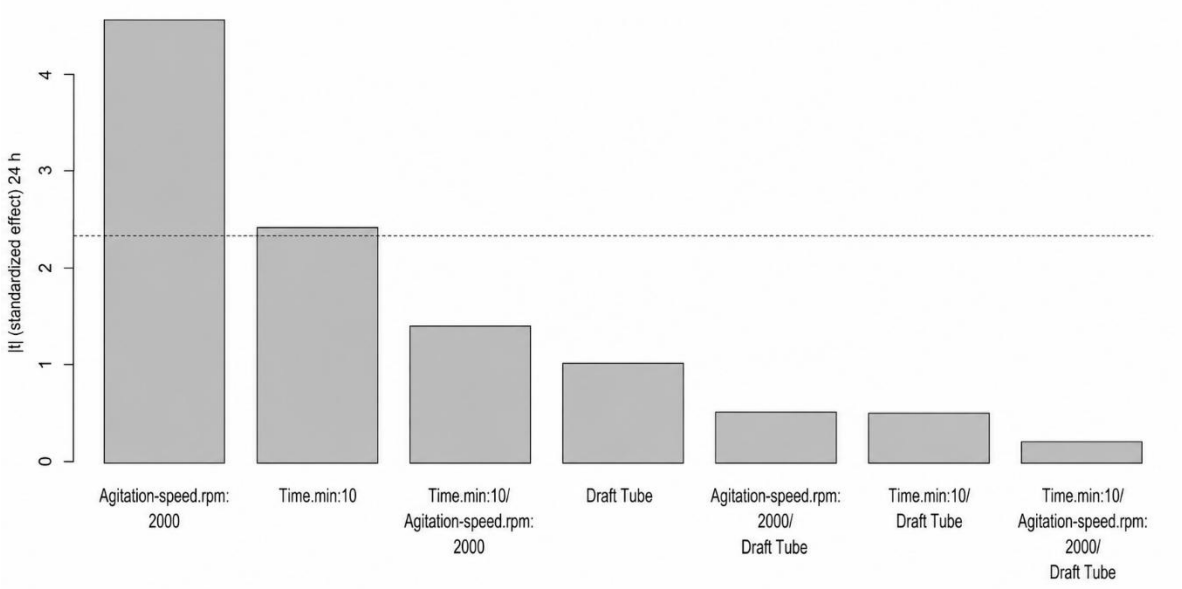


Figure S3. Pareto chart from the factorial analysis of emulsion formulation conditions after 24 h.

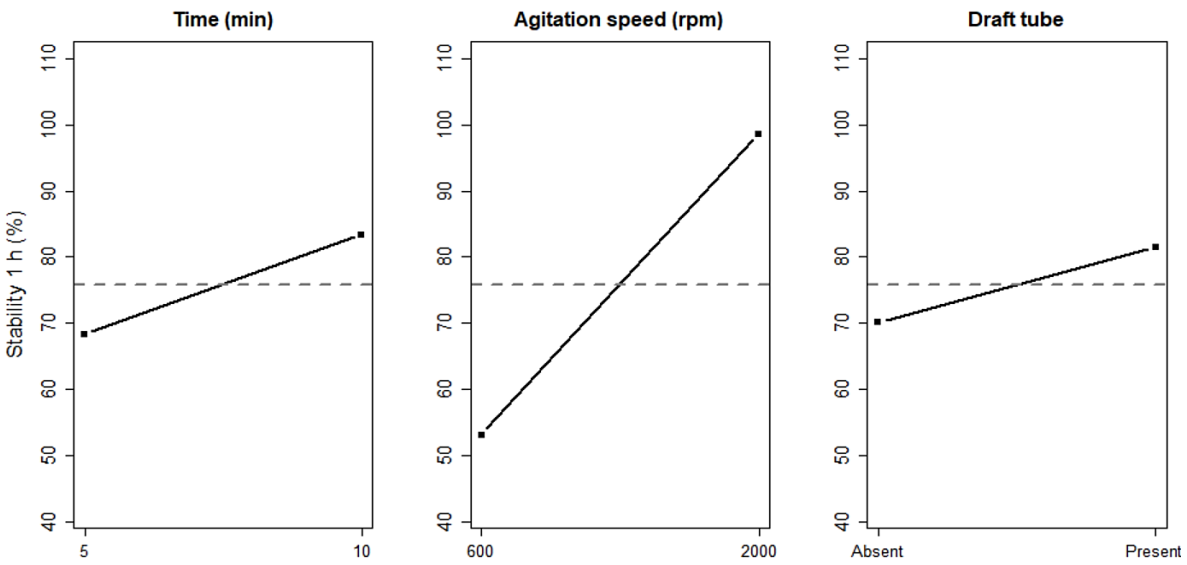


Figure S4. Main effects plot of factors affecting emulsion formulation after 1 h.

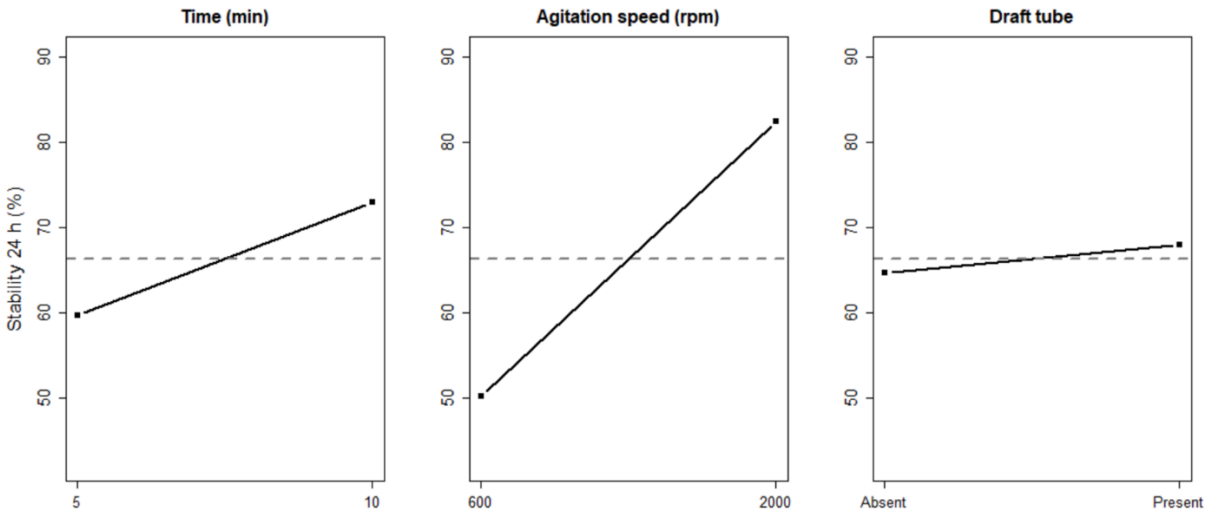


Figure S5. Main effects plot of factors affecting emulsion formulation after 24 h.

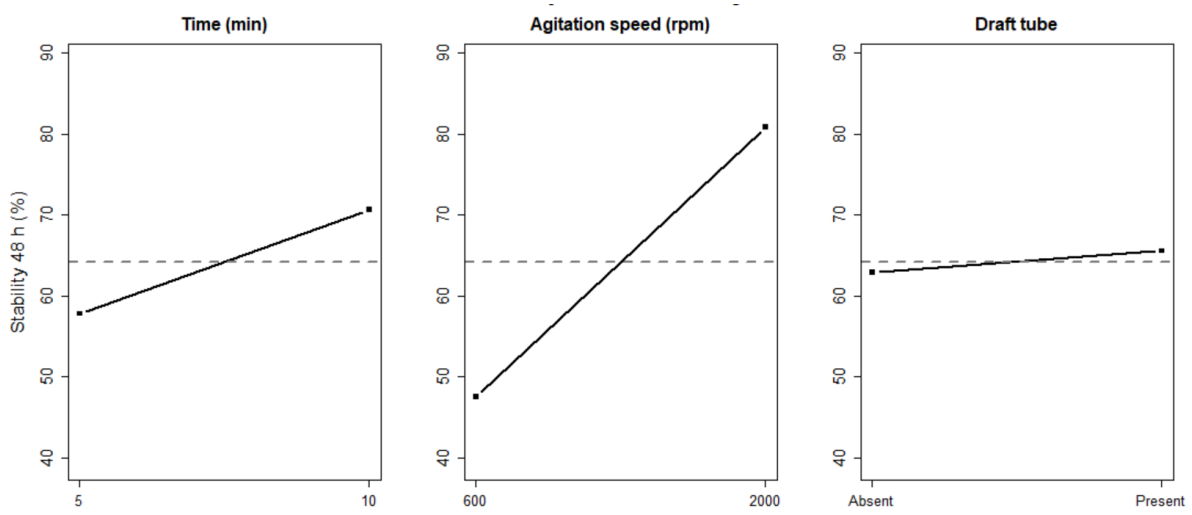


Figure S6. Main effects plot of factors affecting emulsion formulation after 48 h.

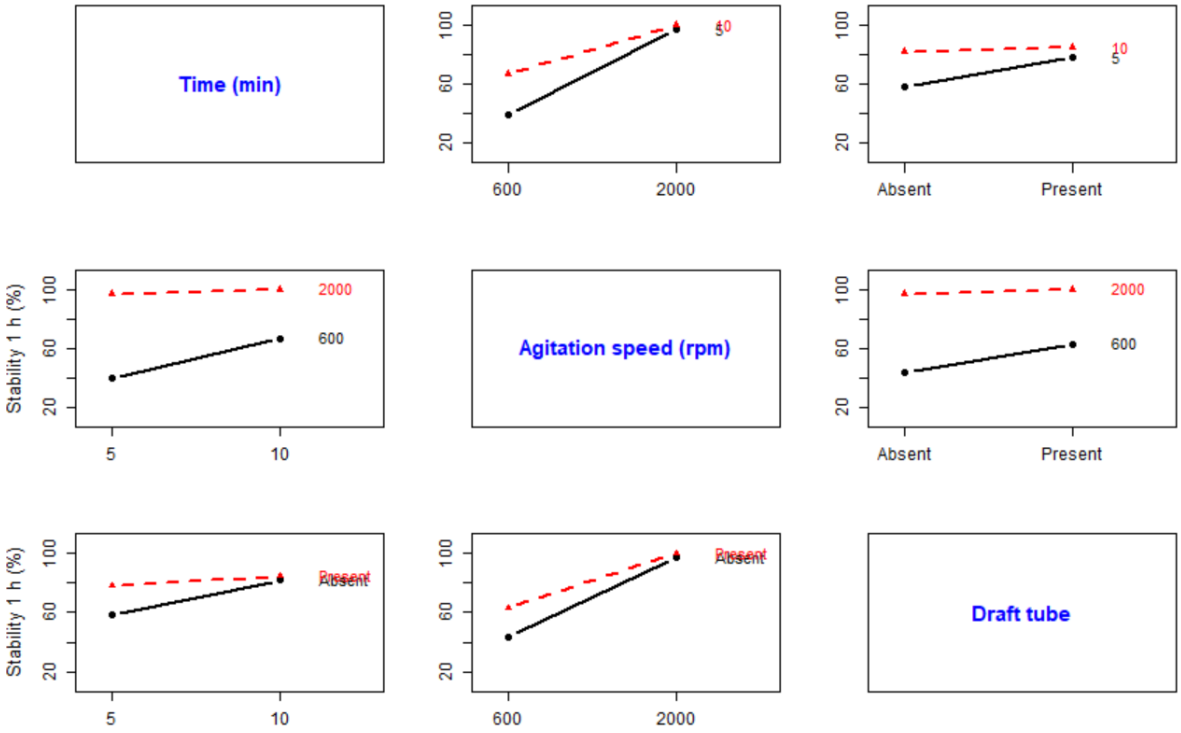


Figure S7. Interaction plots from the factorial analysis of emulsion formulation conditions after 1h.

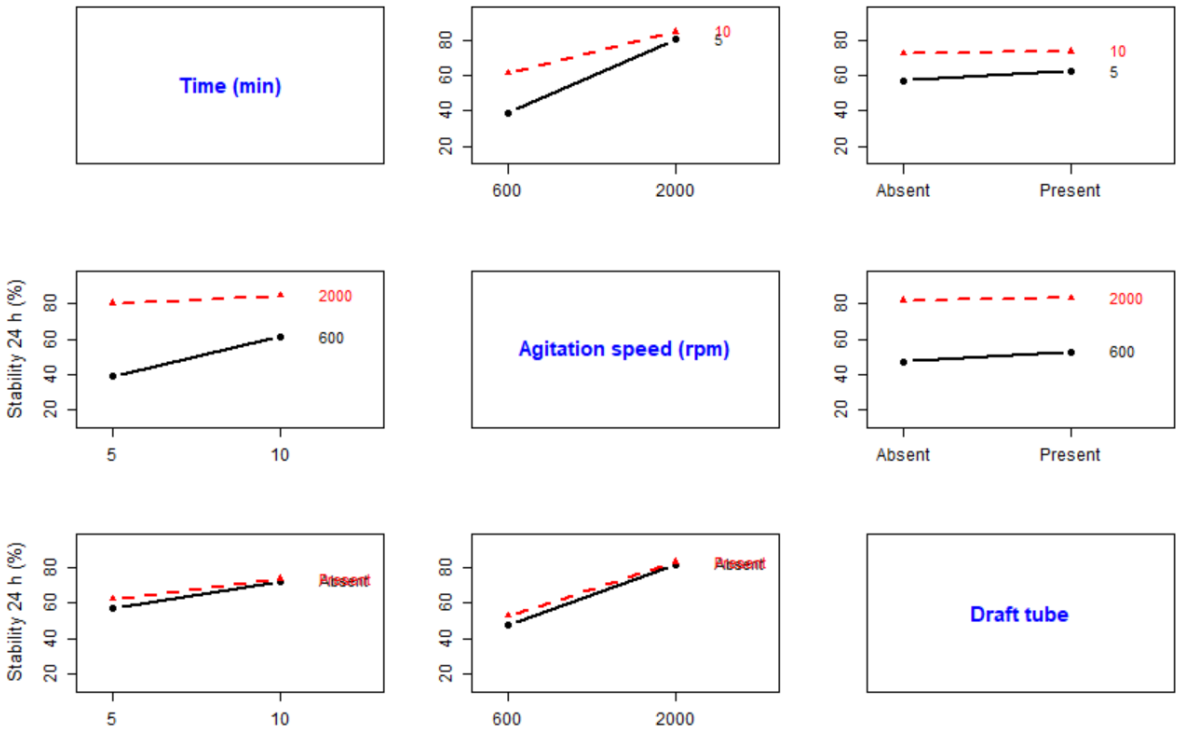


Figure S8. Interaction plots from the factorial analysis of emulsion formulation conditions after 24h.

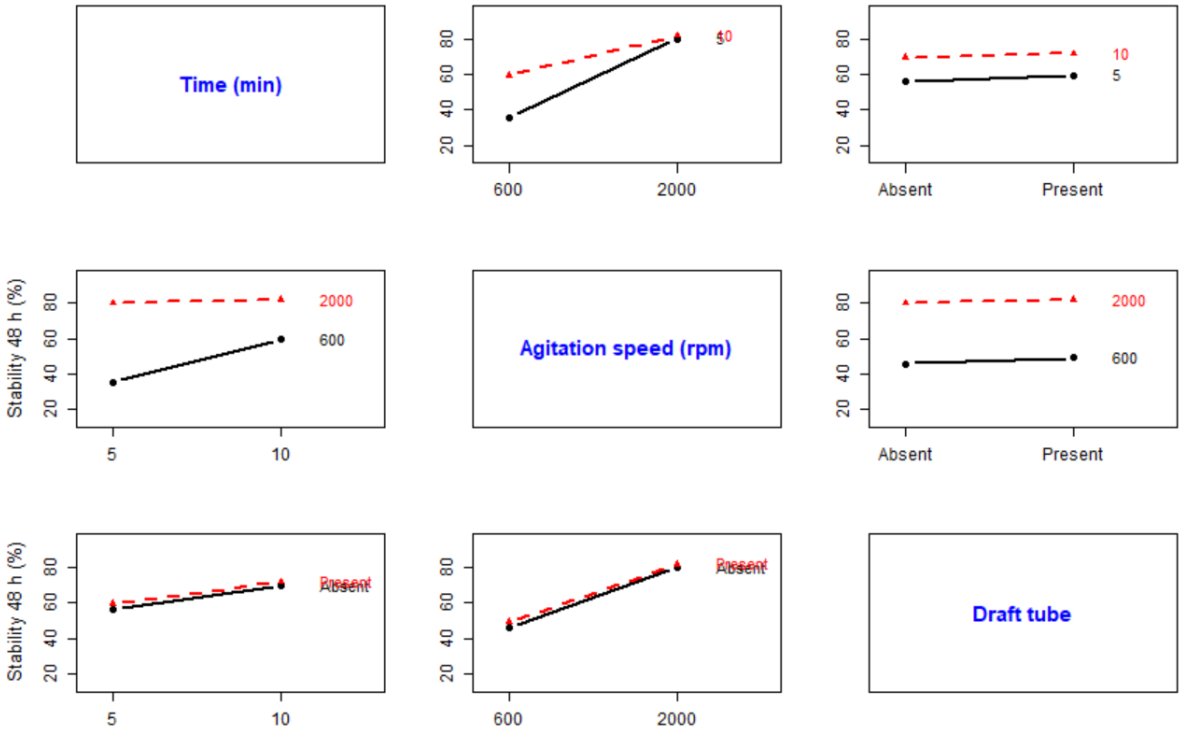


Figure S9. Interaction plots from the factorial analysis of emulsion formulation conditions after 48h.

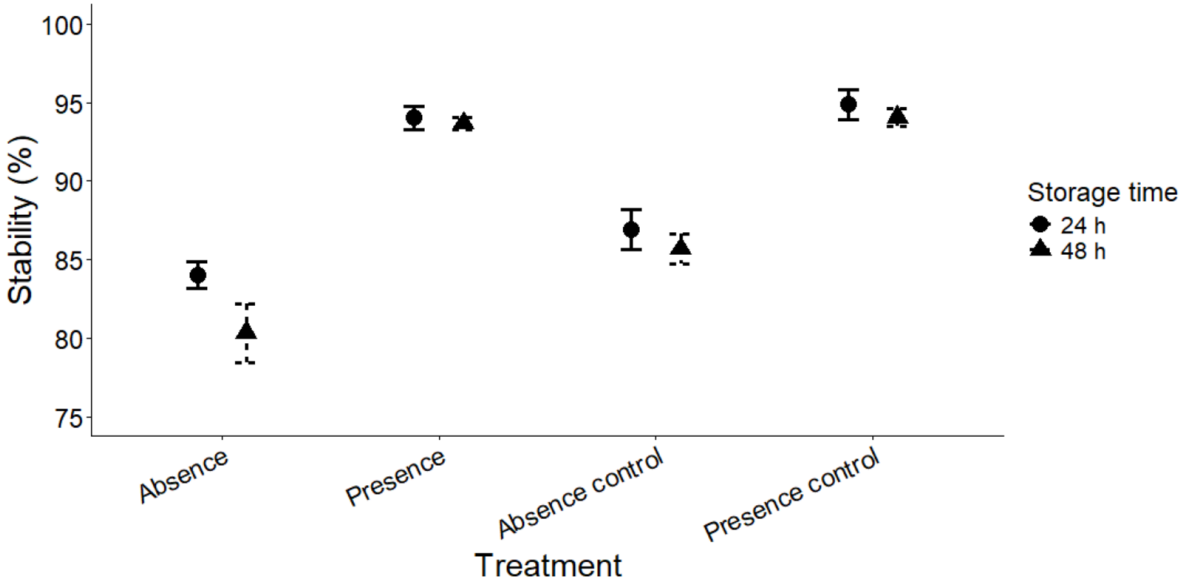


Figure S10. Comparison of the Original and Validation Experiments for the Optimized Pickering Emulsion

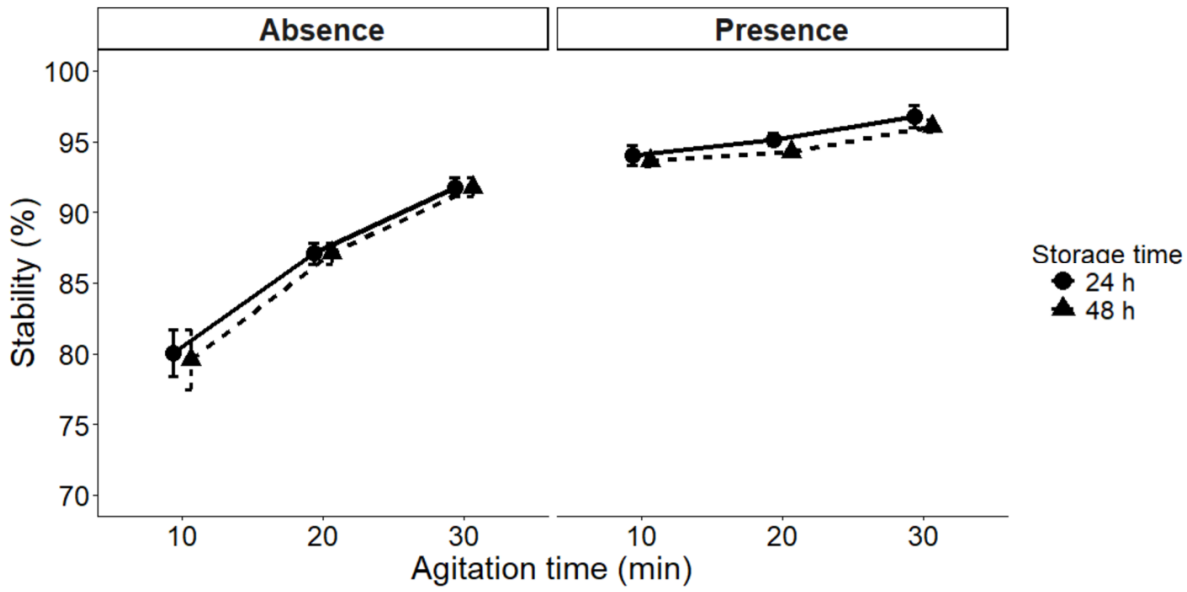


Figure S11. Effect of Mixing Time and Draft Tube Configuration on Formulation Stability after (a) 24 h and (b) 48 h of Storage.

Table S11. Two-Way ANOVA Results for Formulation Stability after 24 h of Storage

Source of variation	df	F	p-value
Mixing time	2	31.11	1.79×10^{-5}
Draft tube	1	144.47	4.75×10^{-8}
Mixing time × Draft tube	2	12.38	0.00121
Residual	12	—	—

Table S12. Two-Way ANOVA Results for Formulation Stability after 48 h of Storage

Source of variation	df	F	*p*-value
Mixing time	2	27.38	3.37×10^{-5}
Draft tube	1	111.43	1.99×10^{-7}
Mixing time × Draft tube	2	13.00	0.000991
Residual	12	—	—

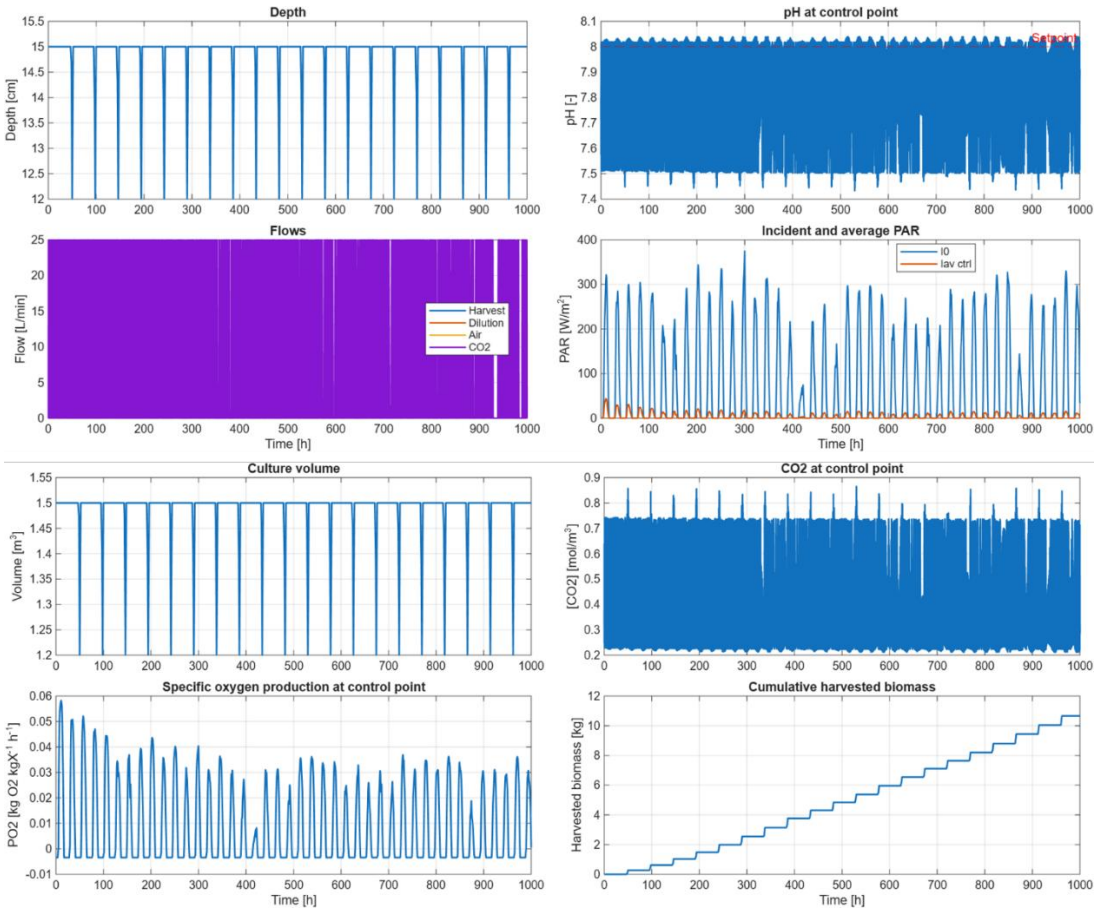


Figure S12. Control parameters in the raceway system

Table S13. Raw experimental data from the factorial designs conducted to evaluate Pickering **emulsion stability**

Experiment number	Tiempo (min)	Velocidad (rpm)	Draff Tube	Formulation Hours	Stability 1 h	Stability 24 h	Stability 48 h
1	20	2000	Without	10:43am	100 %	83,3	80,8
2	20	600	With	11:14 a. m	64 %	60,5	60,0
3	10	600	With	11:33 a. m	53 %	39,5	32,0
4	10	2000	With	11:49 a. m	100 %	75,6	75,6
5	10	600	Without	12:05 p. m	25 %	21,3	21,2
6	20	2000	With	12:36 p. m	100 %	84,2	81,6
7	10	2000	Without	1:33pm	94 %	77,0	76,5
8	10	600	Without	1:49 p. m	20 %	48,7	46,7
9	20	2000	Without	2:18 p. m	100 %	85,9	82,4
10	20	600	Without	2:44 p. m	58 %	55,3	50,6
11	10	2000	Without	2:59 p. m	94 %	81,2	80,0
12	10	2000	With	3:15 p. m	100 %	87,5	87,5
13	20	600	Without	3:49 p. m	70 %	64,7	64,7
14	20	2000	With	4:13 p. m	100 %	85,0	82,5
15	20	600	With	4:40 p. m	72 %	64,7	62,4
16	10	600	With	5:00 p. m	60 %	46,7	42,6

Table S14. Raw experimental data from the Pickering emulsion validation experiments at 24h.

	Mixing Time (min)	ht (cm)	he (cm)	Rh (%)	Average	Standart deviation
Without Draft tube	10	7,0	1,0	85,7	84,0	1,2
	10	6,0	1,0	83,3		
	10	5,9	1,0	83,1		
Draft tube	10	8,0	0,5	93,8	94,0	1,0
	10	8,5	0,6	92,9		
	10	8,7	0,4	95,4		
Without Draft tube	10	7,4	1,1	85,14	86,9	1,8
	10	8,5	0,9	89,41		
	10	8,7	1,2	86,21		
Draft tube control	10	8,0	0,3	96,3	94,9	1,4
	10	8,5	0,4	95,3		
	10	8,6	0,6	93,0		

Table S15. Raw experimental data from the Pickering emulsion validation experiments at 48h

	Mixing Time (min)	ht (cm)	he (cm)	Rh (%)	Average	Standart deviation
Without Draft tube	10	7,0	1,2	82,9	80,3	2,6
	10	6,0	1,4	76,7		
	10	5,9	1,1	81,4		
Draft tube	10	8,0	0,5	93,8	93,6	0,5
	10	8,5	0,6	92,9		
	10	8,7	0,5	94,3		
Without Draft tube	10	7,4	1,2	83,78	85,7	1,4
	10	8,5	1,1	87,06		
	10	8,7	1,2	86,21		
Draft tube control	10	8,0	0,4	95,0	94,0	0,8
	10	8,5	0,5	94,1		
	10	8,6	0,6	93,0		

Table S16. Raw experimental data used for the analysis of variance (ANOVA) of Pickering emulsion stability at 24 h, evaluated at different mixing times

	Mixing Time (min)	ht (cm)	he (cm)	Rh (%)	Average	Standart deviation
Without Draft tube	10	7,3	1,7	76,71	80,0	2,3
	10	8,2	1,5	81,71		
	10	8,7	1,6	81,61		
	20	8,7	1,1	87,36	87,1	1,0
	20	8,4	1,2	85,71		
	20	8,5	1,0	88,24		
	30	8,5	0,6	92,94	91,8	1,0
	30	8,5	0,7	91,76		
	30	8,5	0,8	90,59		
Draft tube	10	8,0	0,5	93,8	94,0	1,0
	10	8,5	0,6	92,9		
	10	8,7	0,4	95,4		
	20	9,2	0,4	95,7	95,2	0,6
	20	8,7	0,5	94,3		
	20	9,0	0,4	95,6		
	30	10,0	0,3	97,0	96,8	1,1
	30	9,8	0,2	98,0		
	30	8,6	0,4	95,3		

Table S17. Raw experimental data used for the analysis of variance (ANOVA) of Pickering emulsion stability at 48 h, evaluated at different mixing times

	Mixing Time (min)	ht (cm)	he (cm)	Rh (%)	Average	Standart deviation
Without Draft tube	10	7,3	1,8	75,34	79,6	3,0
	10	8,2	1,5	81,71		
	10	8,7	1,6	81,61		
	20	8,7	1,1	87,36	87,1	1,0
	20	8,4	1,2	85,71		
	20	8,5	1,0	88,24		
	30	8,5	0,6	92,94	91,8	1,0
	30	8,5	0,7	91,76		
	30	8,5	0,8	90,59		
Draft tube	10	8,0	0,5	93,8	93,6	0,5
	10	8,5	0,6	92,9		
	10	8,7	0,5	94,3		
	20	9,2	0,5	94,6	94,2	0,3
	20	8,7	0,5	94,3		
	20	9,0	0,6	93,9		
	30	10,0	0,4	96,0	96,1	0,7
	30	9,8	0,3	96,9		
	30	8,6	0,4	95,3		