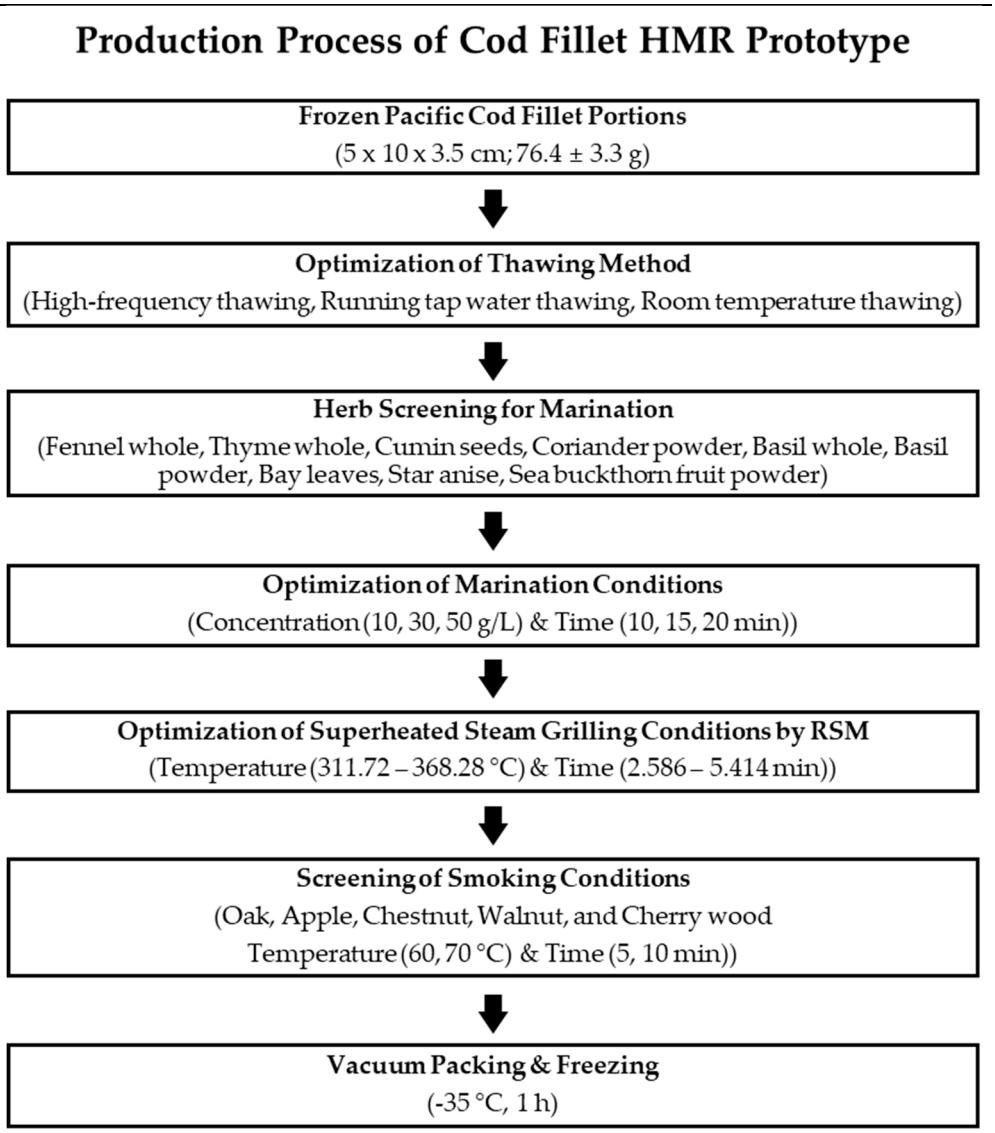


Figure S1. Production process of Pacific cod fillet Home Meal Replacement (HMR) prototype.

Table S1. Central composite design and responses for optimization of superheated steam treatment.

Symbol	Coded level				
	-1.414	-1	0	+1	+1.414
X_1	311.72	320	340	360	368.28
X_2	2.586	3	4	5	5.414

X_1: Temperature (°C); X_2: Time (min).

Table S2. Drip loss (%) and thawing time (min) of frozen cod fillets according to thawing method.

Parameter	Unit	HFD	RW	RT	F	df	η^2
Drip loss	%	11.91^{a} ± 2.44	24.46^{ab} ± 1.75	28.97^{b} ± 2.56	25.12	(2, 12)	0.81
Time	min	15.00^{a} ± 3.54	80.00^{b} ± 3.54	100.00^{c} ± 6.12	959.51	(2, 12)	0.99

Values are presented as means ± SD (n = 3). HFD: High-frequency thawing; RW: Running-water thawing; RT: Room temperature thawing; F: F-statistics; df: Degrees of freedom; η^2: Eta-squared; Different letters (a–c) within each parameter indicate significant differences among samples according to Tukey's test ($p < 0.05$).

Table S3. Sensory evaluation of cod fillets marinated with different herbs.

Parameter	Unit	Control	FW	TW	CS	CP	BW	BP	BL	SA	SBFP	F	df	η^2
Appearance		$7.24^{bcd} \pm 0.77$	$7.14^{b} \pm 0.65$	$7.67^{cd} \pm 0.86$	$7.24^{bcd} \pm 0.54$	$7.52^{bcd} \pm 0.81$	$7.71^{d} \pm 0.72$	$7.43^{bcd} \pm 0.75$	$7.10^{b} \pm 0.77$	$7.19^{bc} \pm 0.51$	$5.10^{a} \pm 0.62$	23.44	(9, 200)	0.51
Odor		$5.95^{a} \pm 0.86$	$5.81^{a} \pm 0.81$	$8.00^{d} \pm 0.84$	$7.29^{c} \pm 0.64$	$6.52^{b} \pm 0.60$	$7.14^{c} \pm 0.65$	$7.19^{c} \pm 0.75$	$7.81^{d} \pm 0.68$	$6.62^{b} \pm 0.59$	$6.90^{bc} \pm 0.70$	20.88	(9, 200)	0.48
Taste	score	$6.76^{c} \pm 0.62$	$6.05^{b} \pm 0.67$	$8.05^{d} \pm 0.97$	$6.62^{c} \pm 0.59$	$6.67^{c} \pm 0.66$	$6.76^{c} \pm 1.00$	$6.57^{bc} \pm 0.98$	$7.71^{d} \pm 0.85$	$5.38^{a} \pm 0.92$	$6.57^{bc} \pm 0.87$	17.27	(9, 200)	0.44
Texture		$7.90^{bcd} \pm 0.70$	$7.86^{b} \pm 0.73$	$7.90^{b} \pm 0.54$	$7.90^{b} \pm 0.77$	$7.14^{a} \pm 0.73$	$7.90^{b} \pm 0.54$	$7.24^{a} \pm 0.77$	$8.00^{b} \pm 0.71$	$7.90^{b} \pm 0.70$	$7.00^{a} \pm 0.84$	6.22	(9, 200)	0.22
Overall acceptance		$6.95^{cd} \pm 0.50$	$5.90^{a} \pm 0.44$	$8.05^{f} \pm 0.50$	$7.24^{de} \pm 0.44$	$6.95^{cd} \pm 0.59$	$6.86^{bc} \pm 0.36$	$6.70^{bc} \pm 0.53$	$7.52^{e} \pm 0.60$	$6.10^{a} \pm 0.54$	$6.52^{b} \pm 0.75$	29.86	(9, 200)	0.57

Values are presented as means ± SD (n = 3). FW: Fennel whole; TW: Thyme whole; CS: Cumin seeds; CP: Coriander powder; BW: Basil whole; BP: Basil powder; BL: Bay leaves; SA: Star anise; SBFP: Sea buckthorn fruit powder; F: F-statistics; df: Degrees of freedom; η^2: Eta-squared; Different letters (a–f) within each parameter indicate significant differences among samples according to Tukey's test ($p < 0.05$).

Table S4. Sensory evaluation of cod fillets as affected by thyme extract concentration and immersion time.

Parameter	Unit	Control	1%			3%			5%			F	df	η^2
			10 min	15 min	20 min	10 min	15 min	20 min	10 min	15 min	20 min			
Odor		$5.95^{b} \pm 0.86$	$6.10^{a} \pm 0.83$	$6.14^{a} \pm 0.91$	$6.81^{b} \pm 1.03$	$7.67^{c} \pm 0.58$	$7.71^{c} \pm 0.64$	$8.00^{c} \pm 0.84$	$7.48^{c} \pm 0.60$	$6.48^{ab} \pm 0.98$	$6.38^{ab} \pm 0.86$	14.49	(9, 200)	0.40
Taste	score	$6.76^{bcd} \pm 0.62$	$6.86^{bc} \pm 0.65$	$6.86^{bc} \pm 0.65$	$7.43^{bcd} \pm 0.93$	$7.52^{d} \pm 0.98$	$7.67^{d} \pm 0.91$	$8.05^{d} \pm 0.97$	$7.48^{cd} \pm 0.93$	$6.81^{b} \pm 1.17$	$5.81^{a} \pm 1.12$	9.39	(9, 200)	0.30
Overall acceptance		$6.95^{bc} \pm 0.50$	$7.10^{bc} \pm 0.54$	$7.14^{bc} \pm 0.57$	$7.33^{c} \pm 0.80$	$7.71^{d} \pm 0.46$	$7.81^{d} \pm 0.60$	$8.05^{d} \pm 0.50$	$7.71^{d} \pm 0.64$	$6.71^{b} \pm 0.72$	$6.24^{a} \pm 0.54$	18.84	(9, 200)	0.46

Values are presented as means ± SD (n = 3). F: F-statistics; df: Degrees of freedom; η^2: Eta-squared; Different letters (a–d) within each parameter indicate significant differences among samples according to Tukey's test ($p < 0.05$).

Table S5. Odor intensity of cod fillets as affected by thyme extract concentration and immersion time.

Parameter	Unit	10 min	15 min	20 min	F	df	η^2
1%	-	$70.67^{a} \pm 1.15$	$70.67^{a} \pm 1.15$	$87.67^{b} \pm 1.53$	173.40	(2, 6)	0.98
3%		$84.33^{a} \pm 3.21$	$91.33^{b} \pm 1.53$	$107.33^{c} \pm 0.58$	96.23	(2, 6)	0.97
5%		$121.67^{a} \pm 1.53$	$136.33^{b} \pm 5.51$	$139.33^{b} \pm 3.79$	17.11	(2, 6)	0.85

Values are presented as means ± SD (n = 3). F: F-statistics; df: Degrees of freedom; η^2: Eta-squared; Different letters (a–c) within each parameter indicate significant differences among samples according to Tukey's test ($p < 0.05$).

Table S6. Sensory evaluation of cod fillets grilled by convection oven and a superheated steam oven.

Parameter	Unit	Convection oven grilling	Superheated steam grilling	F	df	η^2
Appearance	score	$8.74^a \pm 0.18$	$8.80^a \pm 0.12$	0.69	(1, 6)	0.10
Odor		$8.06^a \pm 0.09$	$8.10^b \pm 0.10$	0.43	(1, 6)	0.07
Taste		$7.02^a \pm 0.04$	$8.26^b \pm 0.17$	3.86	(1, 6)	0.39
Texture		$7.08^a \pm 0.04$	$8.36^b \pm 0.13$	130.96	(1, 6)	0.96
Overall acceptance		$7.22^a \pm 0.04$	$8.40^b \pm 0.10$	126.75	(1, 6)	0.96

Values are presented as means ± SD ($n = 3$). F: F-statistics; df: Degrees of freedom; η^2: Eta-squared; Different letters (a,b) within each parameter indicate significant differences among samples according to Tukey's test ($p < 0.05$).

Table S7. Central composite design of variables and responses for superheated steam optimization.

Run No.	Coded values		Actual values		Dependent variable
	X_1	X_2	X_1	X_2	Y_1
1	-1	-1	320	3	5.90
2	+1	-1	320	5	6.57
3	-1	+1	360	3	6.67
4	+1	+1	360	5	6.38
5	-1.414	0	311.72	4	6.29
6	+1.414	0	368.28	4	5.38
7	0	-1.414	340	2.586	6.23
8	0	+1.414	340	5.414	5.52
9	0	0	340	4	8.33
10	0	0	340	4	8.67
11	0	0	340	4	8.48

X_1: Temperature (°C); X_2: Time (min); Y_1: Overall acceptability (score).

Table S8. ANOVA results for response variables during optimization of superheated steam treatment.

Response	R^2	Lack of fit ($p > 0.05$)	F	df	η^2	*p*-value			
						Model	Linear (X_1, X_2)	Quadratic (X_1X_1, X_2X_2)	Interaction (X_1X_2)
Y_1	0.91	0.068	9.84	(5)	0.908	> 0.000	0.553, 0.778	0.002, 0.003	0.385

Y_1: Overall acceptability (score); R^2: Coefficient of determination; F: F-statistics; df: Degree of freedom; η^2: Eta-squared; X_1: Temperature (°C); X_2: Time (min).

Table S9. Response surface predictive model of overall acceptance of product grilled by superheated steam.

Response	Predictive model
Y_1	$8.49333 - 1.19792X_1X_1 - 1.17792X_2X_2$

Y_1: Overall acceptability (score); X_1: Heating temperature (°C); X_2: Treatment time (min).

Table S10. Optimal superheated steam treatment conditions determined by response surface methodology.

Response	Optimum conditions		Predicted value (P)	Experimental value (E)	Desirability
	X_1	X_2			
Y_1	0 (340 °C)	-0.02 (3.98 min)	8.494	8.632 ± 0.108	0.98

Y_1: Overall acceptability (score); X_1: Temperature (°C); X_2: Time (min).

Table S11. Sensory evaluation of cod fillets smoked with five different types of smoke wood.

Parameter	Unit	Control	Oak	Apple	Chestnut	Walnut	Cherry	F	df	η^2
Appearance		$8.12^{a} \pm 0.59$	$8.02^{a} \pm 0.78$	$8.10^{a} \pm 0.54$	$8.05^{a} \pm 0.67$	$8.05^{a} \pm 0.80$	$8.10^{a} \pm 0.83$	0.056	(5, 120)	0.003
Odor		$7.00^{a} \pm 0.77$	$6.24^{ab} \pm 1.00$	$5.52^{ab} \pm 0.68$	$6.57^{b} \pm 0.93$	$7.00^{b} \pm 0.84$	$7.10^{b} \pm 0.77$	0.056	(5, 120)	0.003
Taste	score	$7.10^{a} \pm 1.22$	$4.86^{b} \pm 0.73$	$4.76^{b} \pm 0.62$	$6.05^{c} \pm 0.97$	$7.19^{c} \pm 1.03$	$7.33^{c} \pm 0.66$	22.45	(5, 120)	0.48
Texture		$7.95^{a} \pm 1.43$	$7.69^{a} \pm 1.20$	$7.81^{a} \pm 1.11$	$7.67^{a} \pm 1.24$	$7.76^{a} \pm 1.18$	$7.81^{a} \pm 1.03$	0.18	(5, 120)	0.007
Overall acceptance		$7.38^{a} \pm 0.92$	$6.98^{a} \pm 0.53$	$6.73^{ab} \pm 0.41$	$7.08^{c} \pm 0.45$	$7.52^{c} \pm 0.60$	$7.76^{bc} \pm 0.44$	6.17	(5, 120)	0.21

Values are presented as means ± SD (n = 3). F: F-statistics; df: Degrees of freedom; η^2: Eta-squared; Different letters (a–c) within each parameter indicate significant differences among samples according to Tukey's test ($p < 0.05$).

Table S12. Sensory evaluation of cod fillets smoked with cherry wood at different temperatures and times.

Parameter	Unit	Control	60 ℃		70 ℃		F	df	η^2
			5 min	10 min	5 min	10 min			
Appearance	score	$8.38^{bc} \pm 0.50$	$8.24^{ab} \pm 0.62$	$7.95^{abc} \pm 0.50$	$8.05^{a} \pm 0.59$	$7.76^{c} \pm 0.44$	3.85	(4, 100)	0.13
Odor		$7.19^{b} \pm 0.75$	$8.33^{a} \pm 0.48$	$7.38^{a} \pm 0.92$	$7.48^{a} \pm 0.81$	$7.05^{a} \pm 0.80$	9.34	(4, 100)	0.27
Taste		$7.14^{b} \pm 1.11$	$8.14^{a} \pm 0.79$	$7.14^{a} \pm 1.11$	$7.24^{a} \pm 0.94$	$6.95^{a} \pm 1.02$	4.61	(4, 100)	0.16
Texture		$8.05^{a} \pm 0.67$	$8.00^{a} \pm 0.63$	$7.29^{a} \pm 0.64$	$7.67^{a} \pm 0.58$	$7.14^{a} \pm 0.65$	0.73	(4, 100)	0.028
Overall acceptance		$7.71^{c} \pm 0.85$	$8.19^{b} \pm 0.40$	$7.71^{ab} \pm 0.46$	$7.62^{a} \pm 0.50$	$7.29^{ab} \pm 0.72$	6.86	(4, 100)	0.22

Values are presented as means ± SD (n = 3). F: F-statistics; df: Degrees of freedom; η^2: Eta-squared; Different letters (a–c) within each parameter indicate significant differences among samples according to Tukey's test ($p < 0.05$).

Table S13. Odor intensity of cod fillets smoked with cherry wood under different temperature and time conditions.

Parameter	Unit	5 min	10 min	F	df	η^2
60 ℃	-	$109.00^{a} \pm 3.21$	$122.80^{b} \pm 1.53$	5.33	(4)	0.45
70 ℃		$122.00^{a} \pm 10.58$	$174.60^{a} \pm 3.06$	0.92	(4)	0.91

Values are presented as means ± SD (n = 3). F: F-statistics; df: Degrees of freedom; η^2: Eta-squared; Different letters (a,b) within each parameter indicate significant differences among samples according to Tukey's test ($p < 0.05$).

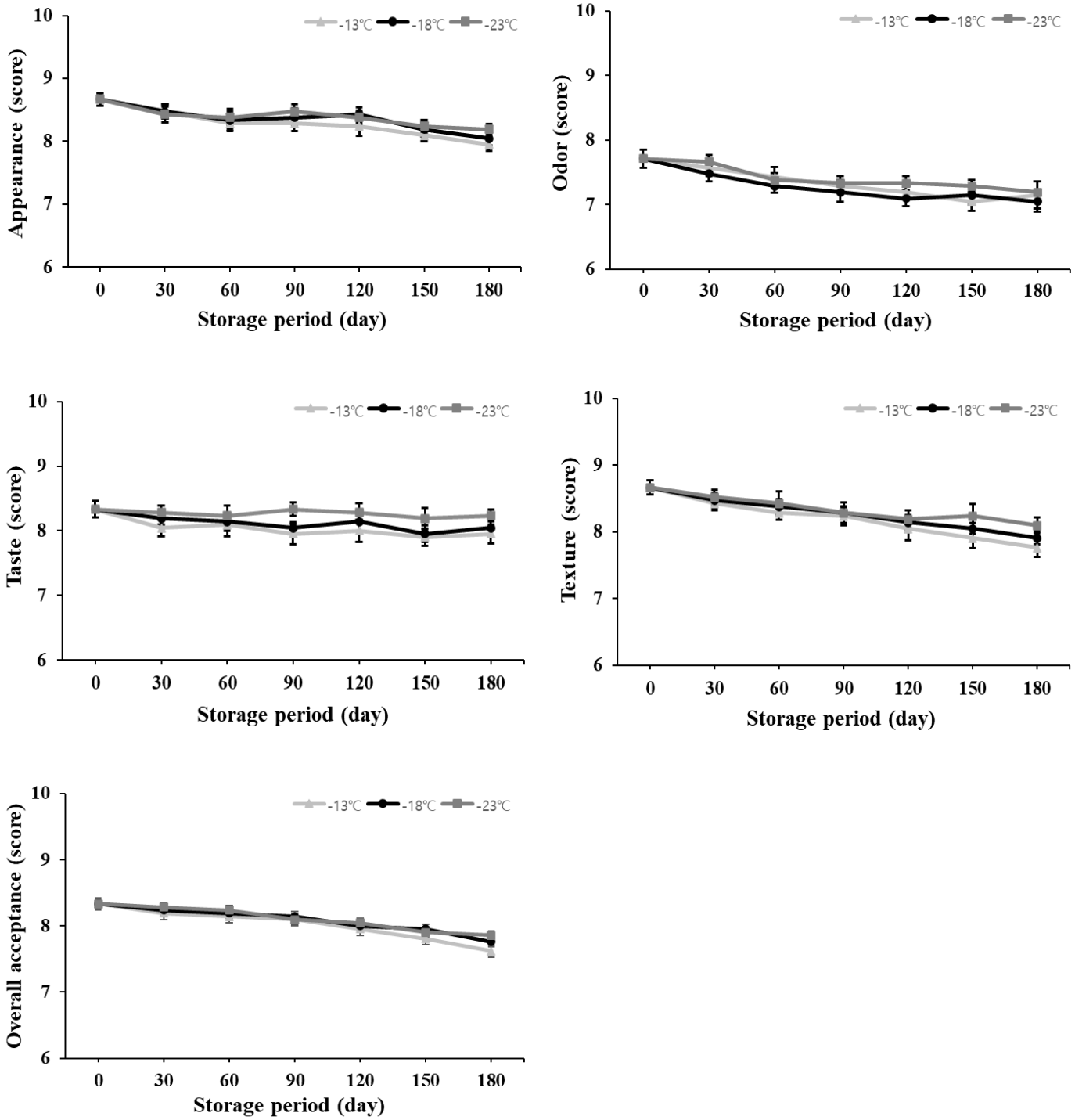


Figure S2. Sensory evaluation of final products stored at different temperatures for 180 days.

Table S14. Statistical parameters of the VSLSF model for predicting the shelf-life of grilled Pacific cod fillets at different reaction orders.

Quality Indicator	Order	R^2	Ea	Predicted Shelf-life (at –18 °C, months)
Bacterial Count	0	0.0077	1091.08	1853.33
	1	0.0052	-1057.14	1107.49
pH	0	0.8203	-11290.45	22.70
	1	0.8228	-11427.34	23.54
VBN	0	0.8117	-7645.48	22.65
	1	0.8117	-5941.46	14.99
Sensory	0	0.8444	-3273.90	34.87
	1	0.8520	-3463.18	43.00

VBN: Volatile basic nitrogen; R^2: Coefficient of determination; Ea: Activation energy.