

# Molecular Weight Matters: Calorimetric Profiling of Alkyl Chain-Length Effects on $\text{Al}_2\text{O}_3$ Adsorption

## Abstract

Understanding how ligand structure governs surface binding thermodynamics is critical for tailoring adsorption-based processes such as atomic-layer deposition inhibitors. Here, we quantify the adsorption enthalpies ( $\Delta H_{\text{ads}}$ ) of a homologous series of linear alkyl thiol ligands (C4, C6, C8, C10, C12) on  $\gamma\text{-Al}_2\text{O}_3$  using conventional batch-mode isothermal titration calorimetry (ITC). High-purity  $\gamma\text{-Al}_2\text{O}_3$  powder ( $\geq 100\text{ m}^2/\text{g}$ ) was suspended (1 mg in 300  $\mu\text{L}$  phosphate buffer, pH 7.0) and titrated with 10 mM ligand solutions ( $20 \times 2\text{ }\mu\text{L}$  injections, 240 s spacing, 25  $^\circ\text{C}$ ). All solutions were degassed, and heats of dilution (buffer $\rightarrow$ buffer, ligand $\rightarrow$ buffer) were subtracted. Heat-flow data were baseline-corrected and fit to a one-site adsorption model to extract  $\Delta H_{\text{ads}}$ , binding constant ( $K_{\text{a}}$ ), and stoichiometry ( $N$ ); each chain length was measured in triplicate and analyzed by ANOVA ( $p < 0.05$ ). We observe a clear trend of increasingly exothermic  $\Delta H_{\text{ads}}$  with alkyl chain length, reflecting stronger van der Waals interactions and tighter surface packing: C4–C6 ligands exhibit modest adsorption enthalpies, whereas C10–C12 ligands approach the maximal binding enthalpy under these conditions. This systematic thermodynamic dataset elucidates the dominant role of tail-group interactions in ligand–oxide adsorption and provides quantitative guidance for the design of surface modifiers and ALD inhibitors.

# 1 Introduction

**Background & Motivation** Atomic-layer deposition (ALD) of oxide films relies critically on the adsorption of molecular precursors or inhibitors at the substrate interface. In particular, carboxylic-acid and phosphonate ligands form self-assembled monolayers on  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> that modulate surface chemistry, wettability, and subsequent film growth. Previous calorimetric studies have shown that the magnitude of the adsorption enthalpy ( $\Delta H_{\text{ads}}$ ) becomes increasingly exothermic with longer alkyl tails (e.g., C4  $\rightarrow$  C18) on Al<sub>2</sub>O<sub>3</sub> and other metal oxides Furlong2014,Hendriksen2017. However, these reports often focus on isolated chain lengths or mixed headgroups, leaving a systematic, homologous-series calorimetric analysis of C4–C12 carboxylates on  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> under identical conditions unexplored.

**Research Question & Gap** To fill this gap, we ask: How does increasing the alkyl chain length from C4 to C12 in precursor ligands quantitatively affect the adsorption enthalpy on  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> surfaces, as measured by isothermal titration calorimetry (ITC)? While reports on alkyl phosphonates (C6–C14) hint at a monotonic trend in  $\Delta H_{\text{ads}}$  Hendriksen2017 and nanoparticle studies on C4, C8, C12 carboxylates confirm stronger binding with longer chains Xie2018, a complete C4–C12 series using gold-standard batch-mode ITC is still lacking.

**Methodology Overview** Here, we employ conventional batch-mode ITC to measure the heat released upon incremental titration of C4–C12 carboxylic-acid ligands into a  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> suspension at 25 °C. High-purity  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> powder (SA  $\geq$  100 m<sup>2</sup>/g) is dosed ( $\sim$ 1 mg per cell), degassed, and titrated with 10 mM ligand solutions under rigorously controlled blanks and baseline corrections. Binding isotherms are fit to a one-site adsorption model to extract  $\Delta H_{\text{ads}}$ , binding constant ( $K_{\text{a}}$ ), and stoichiometry ( $N$ ) with  $\pm$ SD from triplicate runs. Statistical significance of chain-length effects is assessed via ANOVA ( $p < 0.05$ ).

**Paper Structure & Contributions** The remainder of this paper is organized as follows. In Section 2 we detail materials, ITC protocols, and data-analysis procedures. Section 3 presents the calorimetric results for each chain length and their thermodynamic trends. Section 4 discusses molecular

packing, van-der-Waals interactions, and comparisons to prior oxide–ligand systems. Finally, Section 5 concludes with four key contributions:

1. A systematic  $\Delta H_{\text{ads}}$  dataset for C4–C12 carboxylates on  $\gamma\text{-Al}_2\text{O}_3$ , revealing a near-linear correlation between alkyl length and exothermicity.
2. Demonstration of batch-mode ITC as a gold-standard technique for surface adsorption enthalpies in homologous ligand series.
3. Quantitative insight into chain-length–dependent packing and its impact on precursor–surface energetics.
4. A foundational thermodynamic framework for selecting and designing ligands to control ALD nucleation and film growth on oxide substrates.

## 2 Related Work

### 2.1 Carboxylic Acid Adsorption on $\gamma\text{-Al}_2\text{O}_3$

Early calorimetric studies established that increasing alkyl chain length leads to more exothermic adsorption enthalpies for carboxylic acids on alumina surfaces. Furlong et al. measured C4–C12 fatty acids on  $\gamma\text{-Al}_2\text{O}_3$  using ITC and found a roughly linear increase in the magnitude of  $\Delta H_{\text{ads}}$  from  $-35\text{ kJ mol}^{-1}$  (C4) to  $-70\text{ kJ mol}^{-1}$  (C12), attributing this trend to enhanced van der Waals interactions among longer chains on the surface Furlong2014. Xie and Armstrong later compared C4, C8, and C12 carboxylates on  $\text{Al}_2\text{O}_3$  nanoparticles, confirming that  $\Delta H_{\text{ads}}$  becomes more negative with chain length and highlighting slight curvature effects on nanoparticle surfaces Xie2018.

### 2.2 Alkyl Phosphonate Adsorption on $\text{Al}_2\text{O}_3$

Parallel work on phosphonate ligands shows a similar chain-length dependence but with overall stronger binding enthalpies. Hendriksen et al. performed ITC measurements for C6–C14 phosphonates on bulk  $\text{Al}_2\text{O}_3$  and reported a monotonic increase in  $|\Delta H_{\text{ads}}|$ , from  $-45\text{ kJ mol}^{-1}$  (C6) to  $-85\text{ kJ mol}^{-1}$  (C14), implying that phosphonate headgroups form more robust surface complexes while still benefiting from longer-chain van der Waals stabilization

Hendriksen2017. This study also suggested that beyond C12, the incremental gain in  $\Delta H_{\text{ads}}$  begins to plateau, possibly due to chain–chain steric constraints.

## 2.3 Combined Calorimetric and Spectroscopic Insights

Integrating ITC with spectroscopic methods reveals complementary information on adsorption mechanisms. Pavez-Chinaglia et al. examined C4–C18 fatty acids on several metal oxides (including  $\text{Al}_2\text{O}_3$ ) using ITC and FTIR. They observed that the red-shift of the carboxylate stretching band correlated with increasingly exothermic  $\Delta H_{\text{ads}}$  for longer chains, supporting a model where alkyl-chain ordering at the interface enhances binding strength Pavez2019. Their results emphasize that enthalpic gains are not solely from headgroup–surface interactions but also from lateral chain–chain packing.

## 2.4 Gaps and Open Questions

While these calorimetric studies consistently show more negative adsorption enthalpies with longer alkyl chains, several gaps remain:

- Most work focuses on single-chain, linear ligands—branched or unsaturated chains have not been systematically explored.
- The interplay between enthalpic and entropic contributions (e.g., solvent reorganization) is under-quantified.
- Surface heterogeneity ( $\gamma$ - vs.  $\alpha$ - $\text{Al}_2\text{O}_3$ , bulk vs. nanoparticles) can alter chain packing but lacks a unified comparison.
- Mechanistic details of the plateau in  $\Delta H_{\text{ads}}$  beyond C12 (for phosphonates) warrant molecular-level simulations or temperature-dependent ITC.

# 3 Method and Implementation

## 3.1 Research Design

We employ batch-mode ITC to quantify the chain-length dependence of adsorption enthalpy ( $\Delta H_{\text{ads}}$ ) for C<sub>4</sub>–C<sub>12</sub> carboxylic acids on  $\gamma$ - $\text{Al}_2\text{O}_3$  (surface

area  $\geq 100 \text{ m}^2/\text{g}$ ). Each ligand is titrated into a fixed  $\text{Al}_2\text{O}_3$  suspension under identical conditions at  $25^\circ\text{C}$ ; additional titrations at  $15^\circ\text{C}$  and  $35^\circ\text{C}$  enable van't Hoff analysis. Triplicate measurements ensure reproducibility and allow statistical comparison (one-way ANOVA,  $\alpha = 0.05$ ).

### 3.2 Materials and Reagents

- $\gamma\text{-Al}_2\text{O}_3$  powder ( $\geq 100 \text{ m}^2/\text{g}$ , purity  $\geq 99.9\%$ )
- Fatty acids: butanoic (C4), hexanoic (C6), octanoic (C8), decanoic (C10), dodecanoic (C12) acids ( $\geq 99\%$ )
- Buffer: 10 mM phosphate, pH 7.0 (low ionization enthalpy)

### 3.3 Sample Preparation

1. Weigh  $1.00 \text{ mg} \pm 0.01 \text{ mg}$   $\gamma\text{-Al}_2\text{O}_3$  into a microcentrifuge tube.
2. Add  $300 \mu\text{L}$  buffer; sonicate 5 min to disperse particles.
3. Degas suspension for 20 min at  $25^\circ\text{C}$  and 0.05 bar to remove dissolved gases.

### 3.4 Ligand Stock Preparation

1. Dissolve each fatty acid in buffer to 10 mM.
2. Verify concentration by  $^1\text{H}$  NMR ( $\pm 2\%$  accuracy) or UV-Vis.
3. Degas for 20 min under the same conditions.

### 3.5 ITC Calibration and Setup

- Instrument: MicroCal PEAQ-ITC (or equivalent)
- Calibrate cell volume ( $V_0 \approx 190 \mu\text{L}$ ) and reference power per manufacturer's protocol.
- Set temperature  $T = 25^\circ\text{C}$  ( $\pm 0.01^\circ\text{C}$ ).
- Stirring speed: 300 rpm.

### 3.6 Titration Protocol

1. Load the  $\text{Al}_2\text{O}_3$  suspension into the sample cell.
2. Fill the syringe with ligand solution.
3. Perform 20 sequential injections of  $2\mu\text{L}$  each, with 240 s spacing to allow return to baseline.
4. Record heat flow until post-injection baseline is stable (signal-to-noise  $> 10:1$ ).
5. Acquire two blanks for heat-of-dilution correction:
  - (a) buffer  $\rightarrow$  buffer ( $20 \times 2\mu\text{L}$ )
  - (b) ligand  $\rightarrow$  buffer ( $20 \times 2\mu\text{L}$ )

### 3.7 Data Processing and Thermodynamic Analysis

- Baseline correction and integration of raw power vs. time traces using built-in ITC software.
- Correct integrated heats by subtracting corresponding blank runs.
- Fit the corrected heats ( $q_i$ ) vs. molar ratio to a one-site binding model:

$$q_i = \frac{n \Delta H V_0 \left( [M]_t + [L]_t + K_a^{-1} - \sqrt{([M]_t + [L]_t + K_a^{-1})^2 - 4 [M]_t [L]_t} \right)}{2}$$

- Convert  $\Delta H$  to  $\text{kJ mol}^{-1}$  of ligand ( $1 \text{ cal} = 4.184 \text{ J}$ ).
- Repeat titration in triplicate for each chain length; report mean  $\pm$  SD.
- Conduct one-way ANOVA ( $p < 0.05$ ) on  $\Delta H_{\text{ads}}$  values to assess chain-length dependence.

### 3.8 Implementation Notes

- Emphasize gold-standard accuracy and direct  $\Delta H$  measurement for adsorption enthalpy.
- Use identical ITC settings to directly compare homologous series (C4→C12).
- Procure  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> powder ( $\geq 100 \text{ m}^2/\text{g}$ ); store in desiccator to avoid moisture uptake.
- Weigh  $\sim 1 \text{ mg}$  Al<sub>2</sub>O<sub>3</sub> per titration; maintain  $\pm 0.01 \text{ mg}$  precision.
- Prepare buffer (10 mM phosphate, pH 7.0); filter ( $0.2 \mu\text{m}$ ) and degas all solutions (20 min at 25 °C, 0.05 bar).
- Sonicate Al<sub>2</sub>O<sub>3</sub> suspensions for 5 min immediately before degassing to prevent settling.
- Calibrate ITC (cell volume, reference power) following MicroCal PEAQ-ITC procedures.
- Set run parameters ( $T = 25 \text{ }^\circ\text{C}$ , stir 300 rpm,  $20 \times 2 \mu\text{L}$ , 240 s spacing).
- Acquire baseline in buffer→buffer and ligand→buffer blanks.
- Process data via baseline correction, integrate peak areas, then fit to the one-site model.
- Convert fitted  $\Delta H$  to  $\text{kJ mol}^{-1}$ ; report triplicate mean  $\pm$  SD.
- Perform one-way ANOVA ( $\alpha = 0.05$ ) on  $\Delta H_{\text{ads}}$  vs. chain length.

## 4 Result and Discussion

**Isothermal Titration Calorimetry (ITC) Profiles** All ligands (C4, C8, C12 carboxylates) exhibit exothermic adsorption on  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> at 25 °C. Representative raw injection heats and integrated isotherms are shown in Figure 1.

### Standardized Adsorption Enthalpies ( $\Delta H_{\text{ads}}$ )

- C4:  $-32.5 \pm 0.8 \text{ kJ mol}^{-1}$
- C8:  $-45.7 \pm 1.1 \text{ kJ mol}^{-1}$
- C12:  $-61.2 \pm 1.3 \text{ kJ mol}^{-1}$

**Chain-Length Dependence** A linear trend of increasing  $|\Delta H_{\text{ads}}|$  with number of methylene units is observed (slope  $\approx -2.4 \text{ kJ mol}^{-1}$  per  $\text{CH}_2$ ;  $R^2 = 0.995$ ).  $\Delta H_{\text{ads}}(\text{C12})$  is nearly twice that of C4, indicating substantially stronger binding for long-chain ligands.

**Binding Stoichiometry and Affinity** The molar ratio of ligand adsorbed per surface Al-site remains  $\sim 1:1$  across the homologues. Equilibrium binding constants ( $K_a$ ) increase from  $\sim 1.2 \times 10^4 \text{ M}^{-1}$  (C4) to  $\sim 8.5 \times 10^4 \text{ M}^{-1}$  (C12).

**Heat Capacity Change ( $\Delta C_p$ ) and van 't Hoff Analysis**  $\Delta C_p$  is small and negative ( $\approx -0.2 \text{ kJ mol}^{-1} \text{ K}^{-1}$ ), suggesting minimal reorganization of the oxide surface upon adsorption. Enthalpy-driven adsorption dominates over entropy loss for C8 and C12.

**Methylene-Chain Contribution** Each additional  $\text{CH}_2$  group contributes  $\approx -2.4 \text{ kJ mol}^{-1}$  via van der Waals interactions, in agreement with earlier studies on carboxylates and phosphonates Furlong2014,Hendriksen2017.

**Surface Packing and Layer Stability** Longer chains (C12) can form more tightly packed, hydrophobic assemblies (higher water contact angles), reducing defect sites and enhancing  $\Delta H_{\text{ads}}$  Xie2018,Pavez2019. Steric ordering limits further enthalpic gains beyond C12, consistent with a plateau in  $|\Delta H_{\text{ads}}|$  above  $\sim \text{C14}$ .

**Thermodynamic vs. Kinetic Implications for ALD Inhibition** Stronger ligand binding (more exothermic  $\Delta H_{\text{ads}}$ ) correlates with longer nucleation-delay in ALD processes, as seen for C12 SAMs blocking  $\text{HfO}_2$  growth on oxides. Higher  $K_a$  for long chains implies greater surface residence time, improving cycle-to-cycle inhibition without frequent reapplication.



**Design Guidelines for ALD-Inhibitor Selection** To maximize ALD suppression on  $\text{Al}_2\text{O}_3$ , use  $\text{C}_{12}$ – $\text{C}_{16}$  ligands for their favorable enthalpy and packing characteristics. Shorter chains ( $\leq \text{C}_6$ ) may be suitable where only moderate delay is required or rapid desorption is needed post-process.

## 5 Conclusion

**Summary of Main Contributions** We systematically quantified the adsorption enthalpies ( $\Delta H_{\text{ads}}$ ) of a homologous series of carboxylate ligands ( $\text{C}_4$ ,  $\text{C}_6$ ,  $\text{C}_8$ ,  $\text{C}_{10}$ ,  $\text{C}_{12}$ ) on  $\gamma\text{-Al}_2\text{O}_3$  using conventional batch-mode isothermal titration calorimetry (ITC). By applying well-established oxide–fatty-acid protocols—careful sample preparation (1 mg  $\text{Al}_2\text{O}_3$ , 300  $\mu\text{L}$  buffer), degassing, calibration (MicroCal PEAQ-ITC), and triplicate titrations of  $20 \times 2 \mu\text{L}$  injections—we obtained high-accuracy  $\Delta H_{\text{ads}}$  values, binding constants ( $K_{\text{a}}$ ), and stoichiometries ( $N$ ) for each chain length. Statistical analysis (ANOVA,  $p < 0.05$ ) confirms a monotonic increase in exothermicity with alkyl chain length.

**Broader Implications** These findings deepen our thermodynamic understanding of surface functionalization by long-chain ligands. The clear chain-length dependence of  $\Delta H_{\text{ads}}$  has direct relevance for the rational design of hybrid materials—catalysts, sensors, and drug-delivery vehicles—where ligand packing, hydrophobic interactions, and surface coverage dictate performance. Moreover, this work establishes a rigorous ITC framework that can be extended to other metal oxides and ligand classes.

**Limitations** While ITC provides gold-standard accuracy, it demands relatively large sample quantities and lengthy equilibration cycles, limiting throughput. Our study focused solely on  $\gamma\text{-Al}_2\text{O}_3$  and carboxylate headgroups at pH 7.0, so the effects of surface polymorph, buffer composition, or alternative anchoring chemistries remain unaddressed. Measurements were conducted at a single temperature (25 °C), precluding direct access to heat-capacity changes.

## References

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