Image-Driven Analysis of Bubble Dynamics and Foam Stability

Microscopy Hackathon 2025 — AISCIA Informatics
Author: Hesham Eina Abdalla, Electrical Engineer
Affiliation: Qatar University (Alumni)
GitHub: https://github.com/hdaw1905/AI_Microscopy_FoamDynamics

---

1. Introduction and Motivation

Foam stability emerges from microscopic bubble-scale processes such as coarsening, rupture, and spatial rearrangement, which collectively determine macroscopic foam lifetime. Conventional approaches typically rely on chemical composition or empirical correlations, limiting interpretability and generalization. This project demonstrates that foam stability can be quantified, compared, and predicted using **microscopy images alone**, by extracting interpretable bubble-level features and analyzing their temporal evolution in a chemistry-agnostic manner.

---

2. Experimental Dataset and Conditions

Time-resolved segmented microscopy images were analyzed for three experimental conditions: a surfactant-only baseline foam (E138), a graphene oxide–stabilized foam with 150 ppm GO (E130), and a nano–graphene oxide–stabilized foam with 1500 ppm NGO (E142). Each experiment contains between 149 and 188 sequential frames, from which binary bubble masks and bubble center coordinates were used to compute image-derived geometric, statistical, and spatial descriptors.

---

3. Image-Driven Analysis Pipeline

The analysis follows a strict image-first pipeline in which bubble segmentation is followed by extraction of bubble count, size statistics, distribution entropy, and spatial packing metrics based on nearest-neighbor distances. Tracking these features over time enables direct quantification of bubble persistence, coarsening dynamics, size heterogeneity, and spatial organization without incorporating any chemical parameters.

---

4. Bubble Persistence and Population Dynamics

Bubble count dynamics reveal clear differences in foam persistence. The baseline foam exhibits the fastest bubble loss, indicating rapid film rupture and collapse, while the GO-stabilized foam maintains the highest bubble population across nearly all frames. The NGO-stabilized foam shows intermediate behavior, retaining bubbles longer than the baseline but experiencing more pronounced late-stage loss than GO. Early-stage bubble loss rates are −59 bubbles per frame for the baseline, −47 for GO, and −10 for NGO, demonstrating that nanoparticle additives significantly slow bubble rupture, with GO providing the strongest stabilization.

5. Bubble Coarsening Behavior

Bubble coarsening behavior, quantified by the evolution of mean bubble area, further differentiates the formulations. GO-stabilized foam exhibits the slowest coarsening, preserving smaller bubbles for longer durations, while the baseline foam shows rapid early growth. NGO-stabilized foam again displays intermediate behavior. Early-stage coarsening rates are −9.42 area units per frame for GO, −9.54 for the baseline, and −10.17 for NGO, indicating that GO most effectively suppresses bubble growth.

---

6. Size Distribution Heterogeneity and Spatial Organization

Size distribution entropy extracted directly from segmented images reveals sustained heterogeneity in the GO-stabilized foam, whereas the baseline foam rapidly collapses to a low-entropy state dominated by fewer large bubbles. NGO-stabilized foam shows moderate entropy decay. Log-scale size distributions confirm that GO suppresses the formation of very large bubbles, slowing Ostwald ripening and maintaining a diverse bubble population. Spatial analysis based on nearest-neighbor distances shows that GO-stabilized foam preserves dense and stable packing, while the baseline rapidly loses spatial order and NGO provides partial stabilization.

---

7. Image-Derived Foam Stability Ranking

An image-derived foam stability proxy was defined as the time-integrated normalized bubble count. This metric yields a stability value of 20,992 for GO-stabilized foam, compared to 2,478 for NGO-stabilized foam and 1,406 for the baseline, corresponding to approximately an eightfold improvement over NGO and a fifteenfold improvement over the baseline. This ranking is derived entirely from image data without chemical inputs.

---

8. Explainable Machine Learning Analysis

To assess predictability, an explainable ridge regression model was trained using only image-derived features. The model identifies early-stage coarsening rate as the dominant predictor of long-term foam stability, followed by spatial packing dynamics, entropy decay, and bubble loss rate. Leave-one-experiment-out validation confirms that early microscopic dynamics contain sufficient information to infer macroscopic foam stability before collapse occurs.

---

9. Conclusions and Broader Impact

In conclusion, this work demonstrates that microscopy images alone contain sufficient information to explain, compare, and predict foam stability across nanoparticle formulations. Graphene oxide provides superior stabilization by slowing coarsening, preserving size heterogeneity, and sustaining bubble populations more effectively than nano-sized particles or surfactant-only systems. The proposed workflow is fully image-driven, chemistry-agnostic, and explainable, and is readily transferable to other cellular and porous materials where early prediction of stability and failure is critical.