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TECHNOLOGY  
Institute for Energy  
and Materials Processes

# Interface Engineering of Anode Layers for Alkaline Water Electrolysis

Doctoral candidate: Adarsh Jain

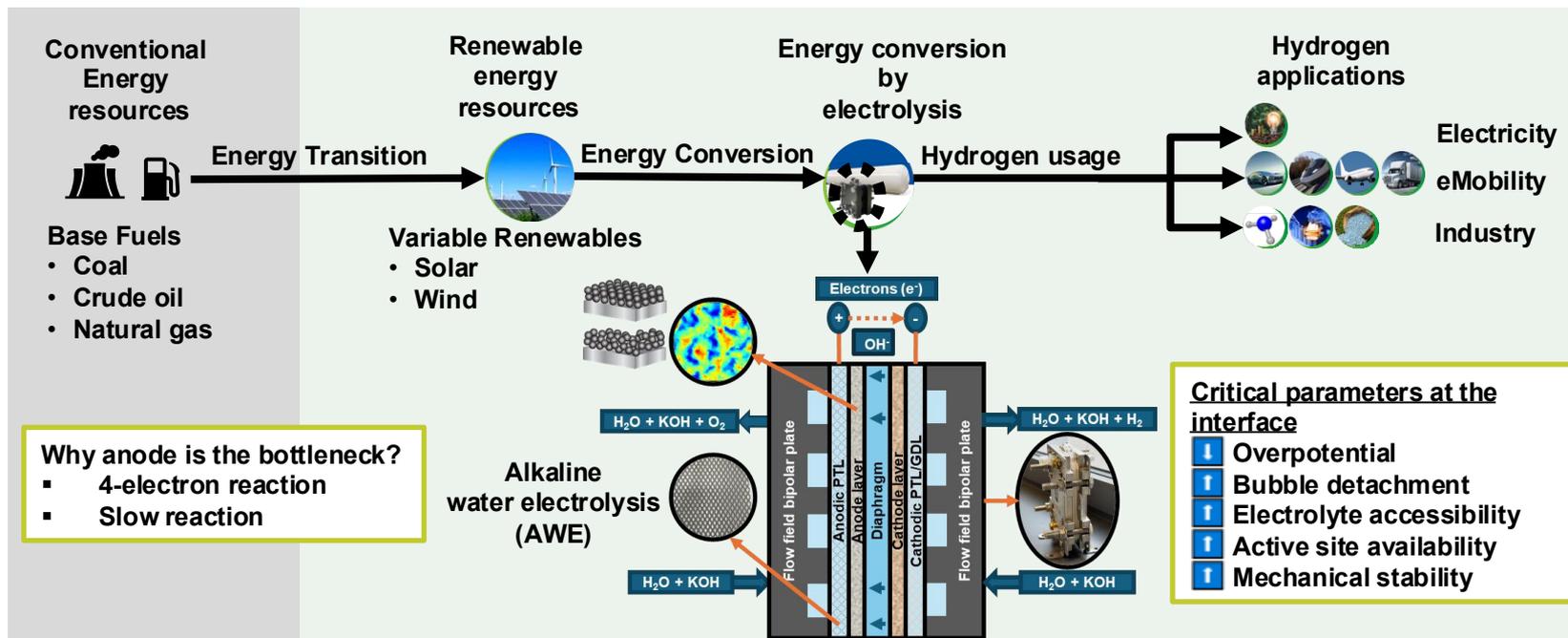
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19.02.2026, Duisburg

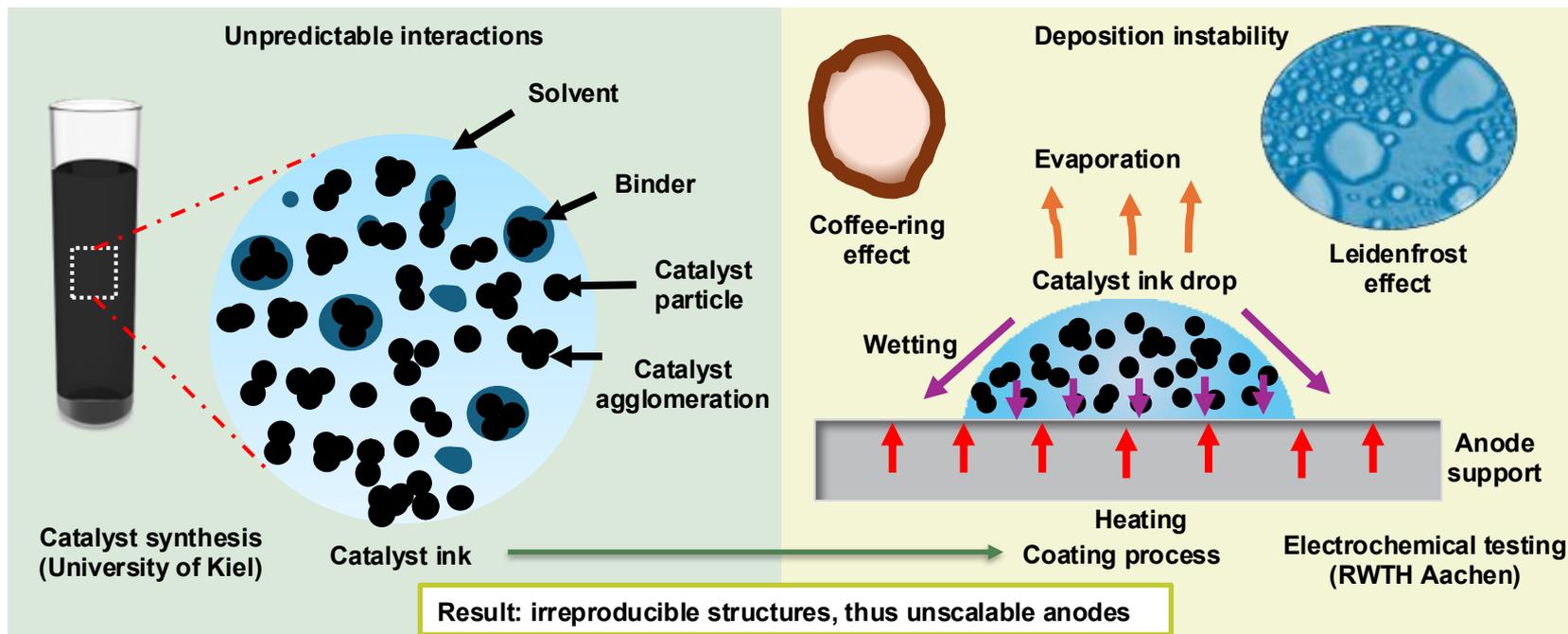
# Green hydrogen: Important link in the energy transition

Overarching challenge: Converting fluctuating electrons into usable molecular energy



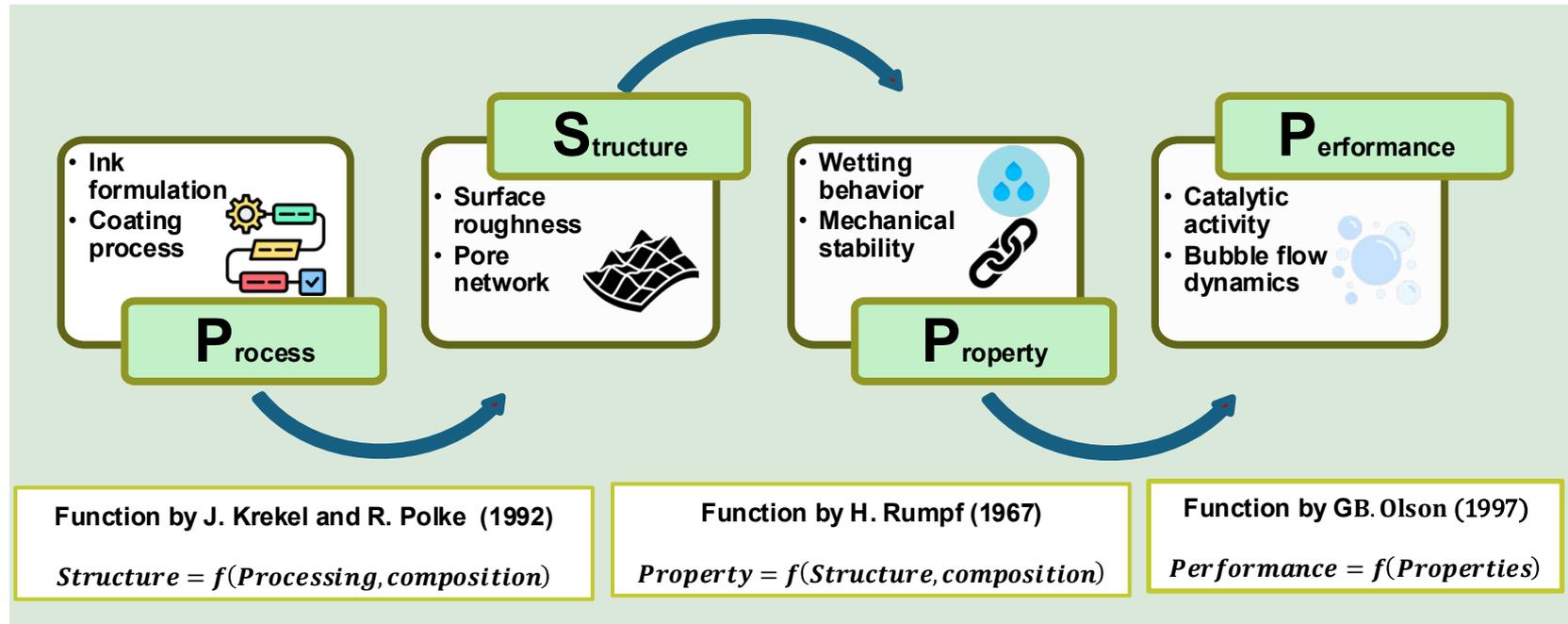
# Fabrication: Black box mystery

Moving beyond empirical trial-and-error approach to knowledge-based understanding



# Solution: Process-structure-property-performance framework

A rational design approach for knowledge-based anode fabrication



# Research objectives

## Three systematic approaches to understand anode design principles

### 1. Enable systematic and representative surface analysis

Development of a statistical framework that allows the extraction of machine-readable surface features



### 2. Establish a systematic relationship between macroscopic anode layer properties and electrochemical performance

Development and characterization of anodes with different structures but similar chemical compositions



### 3. Elucidate the influence of different wetting states on the oxygen-electrolyte-anode interface during OER

Design and fabrication of anodes with varied wetting characteristics via tuning the binder chemistry and coating parameters



# Research objective 1

## Three systematic approaches to understand anode design principles

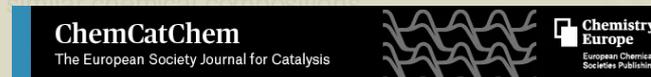
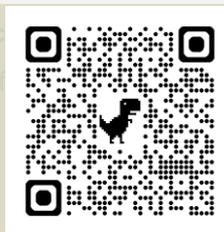
### 1. Enable systematic and representative surface analysis

Development of a statistical framework that allows the extraction of machine-readable surface features



### 2. Establish a systematic relationship between macroscopic anode layer properties and electrochemical performance

Development and characterization of anodes with different wetting characteristics



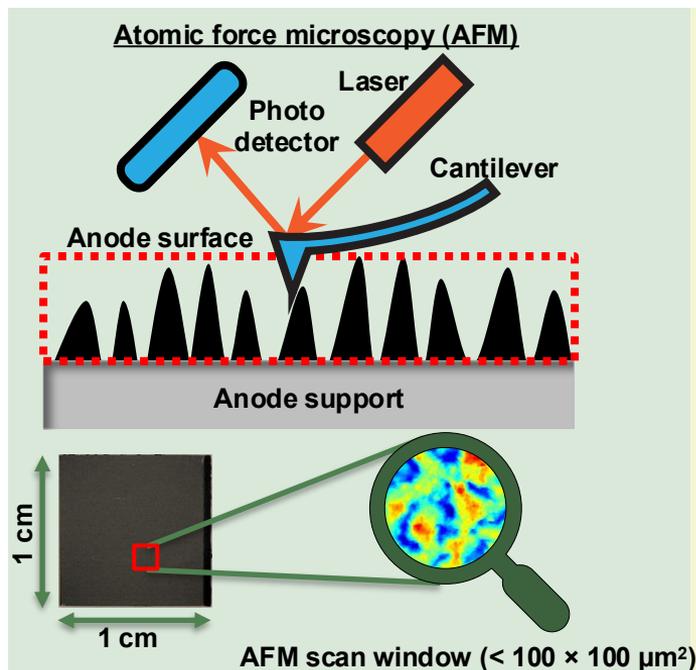
### 3. Elucidate the influence of different wetting characteristics on electrochemical performance

Design and fabrication of anodes with varied wetting characteristics via tuning the binder chemistry and coating parameters

A. Jain, D. Segets et al, *ChemCatChem*, 2024, <https://doi.org/10.1002/cctc.202301461>

# Measurement dilemma: From microscale to macroscale

Scale mismatch: How do we know if an atomic scale microscopic scan is representative of the whole electrode?



- High-resolution 3D surface imaging via AFM
- Non-destructive analysis of sample surface



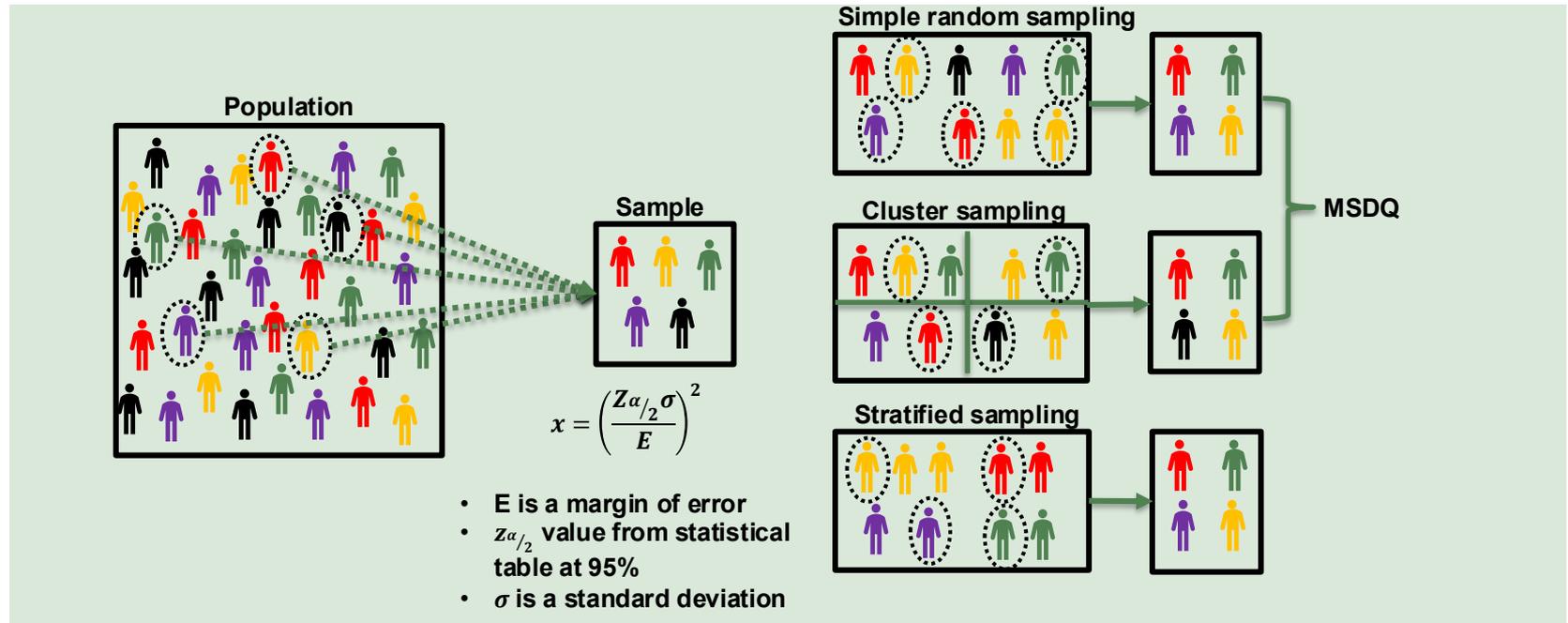
- Can't measure larger surfaces in AFM (e.g.  $> 100 \times 100 \mu\text{m}^2$ )
- Time consuming for suitable features extraction



- Multi-stage data quantification (MSDQ)
- Matrix-based image analysis

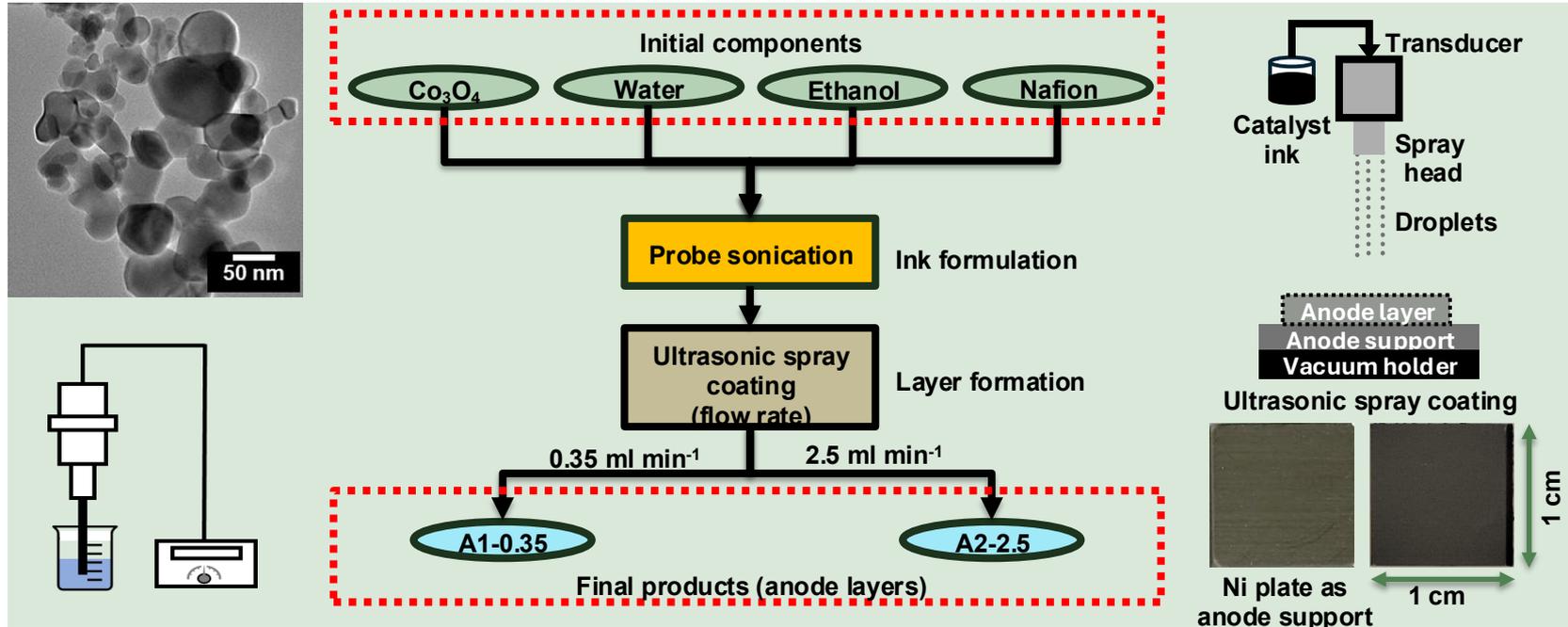
# Background and inspiration for MSDQ

Census approach to extrapolate small-area observations to the full anode with confidence



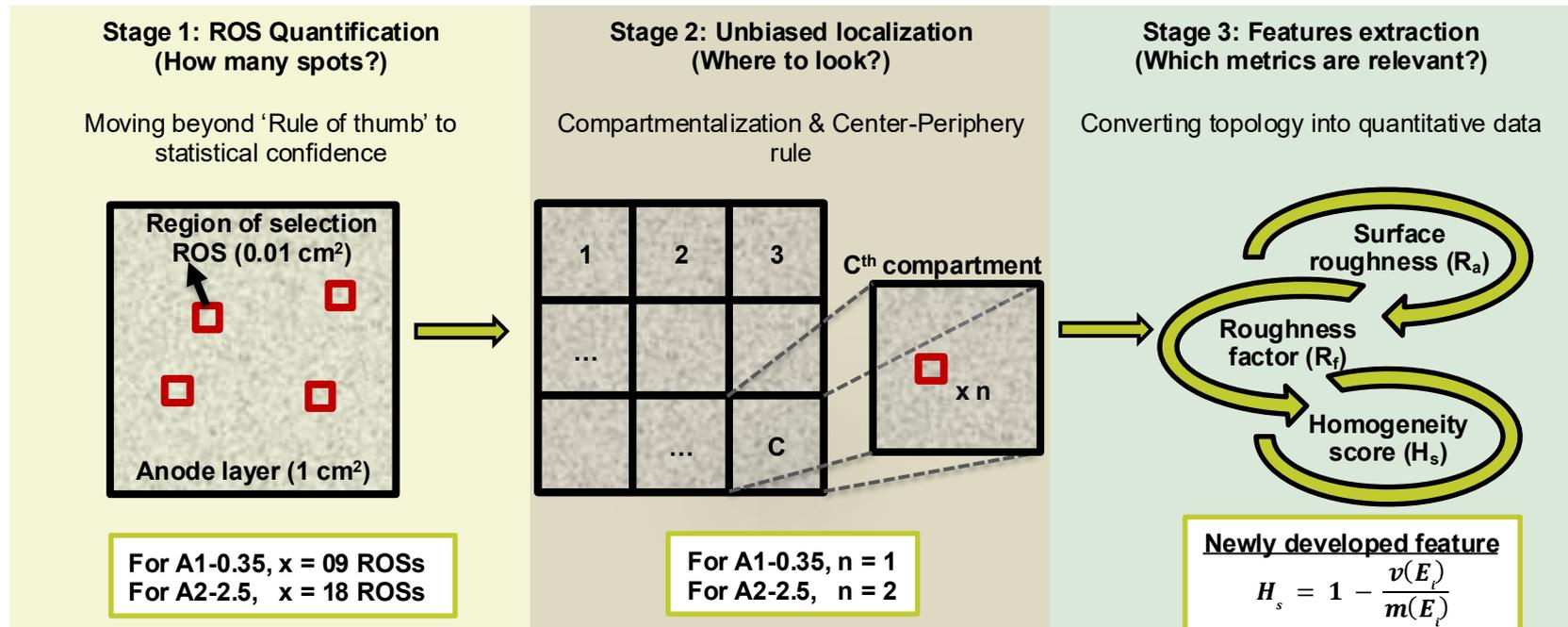
# Tuning structures

Developing anode layers with varying structures and their features



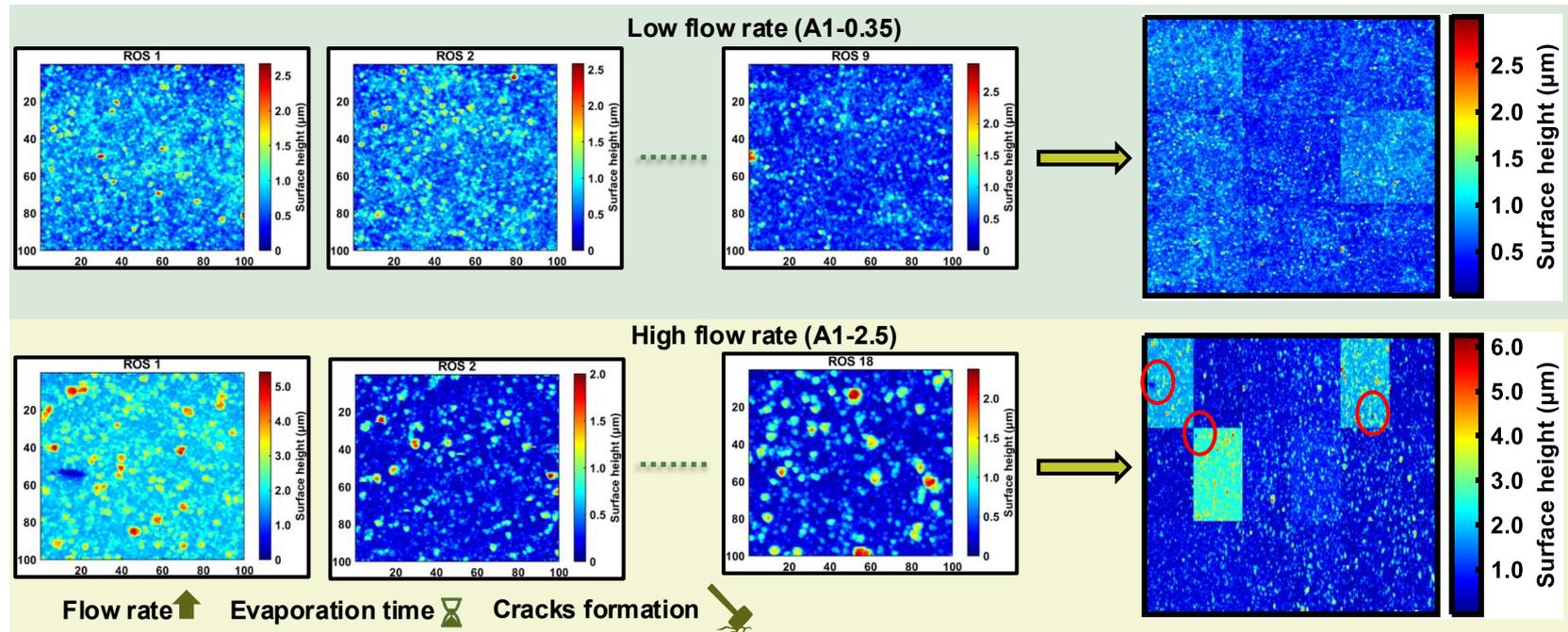
# MSDQ: Calculating the ‘Truth’ of a surface

A statistical framework to turn visual inspection into representative machine-readable data



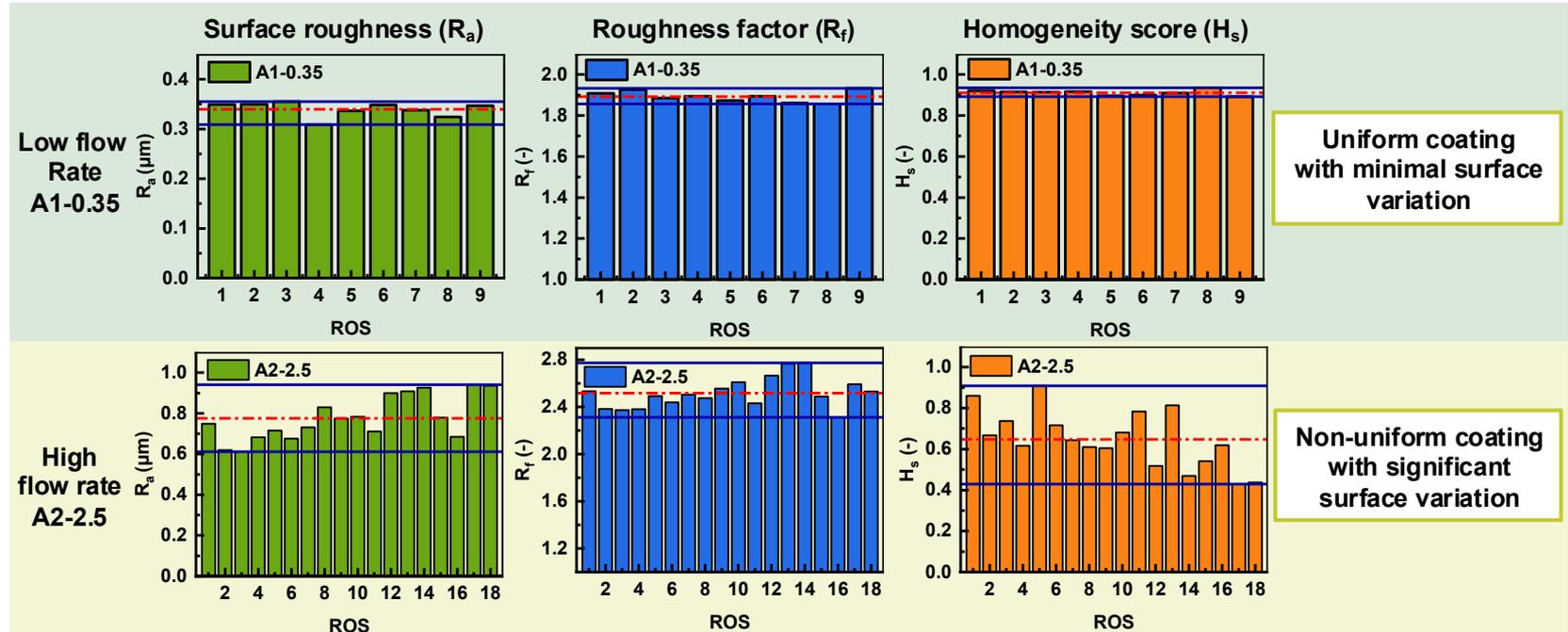
# Visualizing structure: MSDQ-based topological heatmaps

A statistical framework to turn visual inspection into representative machine-readable data



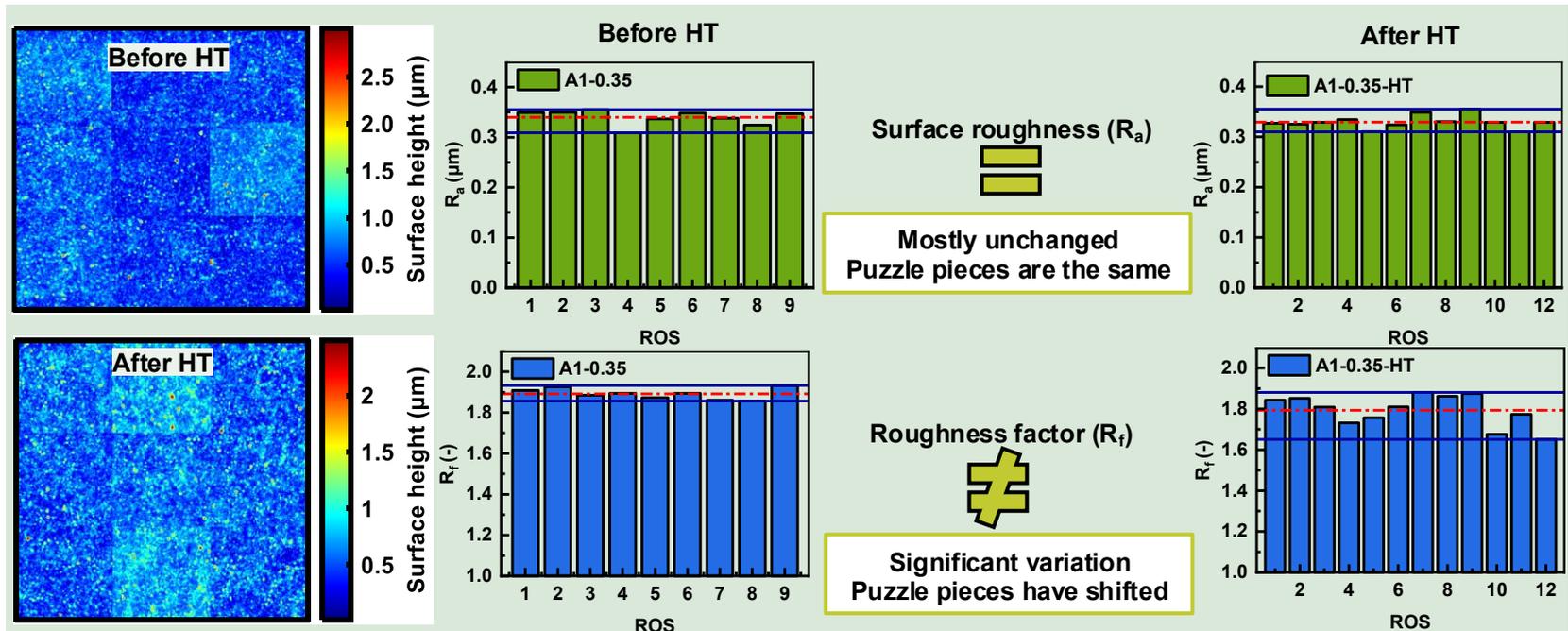
# Quantifying structure: From images to data

Converting topographical data into quantitative distributions



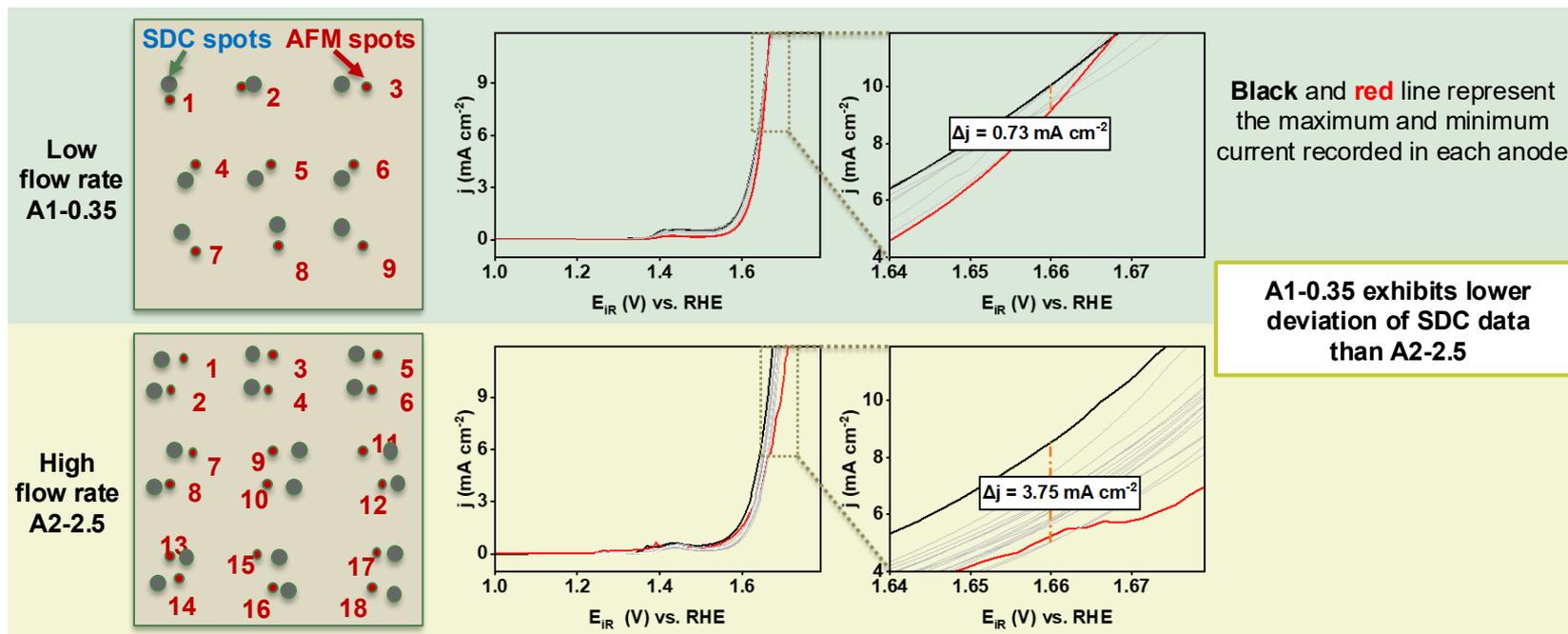
# Plausibility analysis: Heat treatment (HT)

Can MSDQ framework detect subtle changes? Anode A1-0.35 was heat-treated at 600 °C



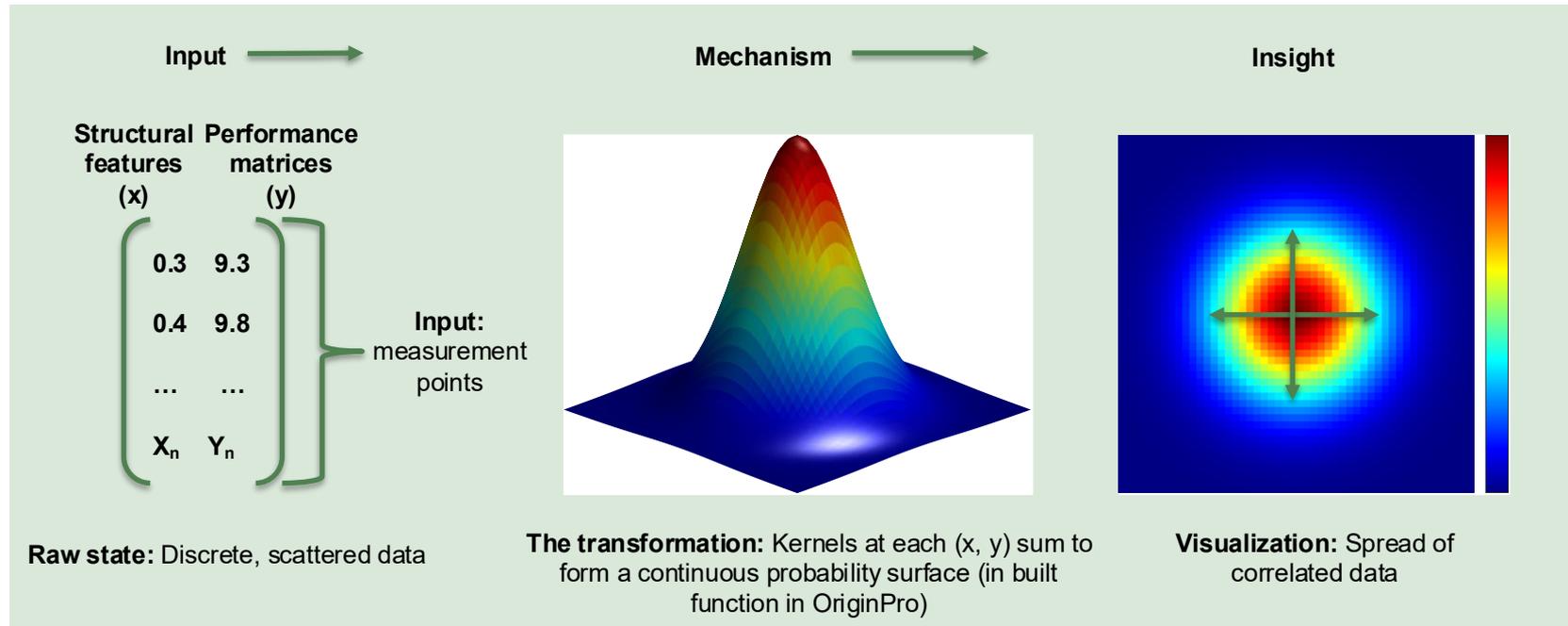
# Electrochemical analysis: Scanning droplet cell (SDC)

Utilizing local-scale electrochemical analytics to measure the performance data



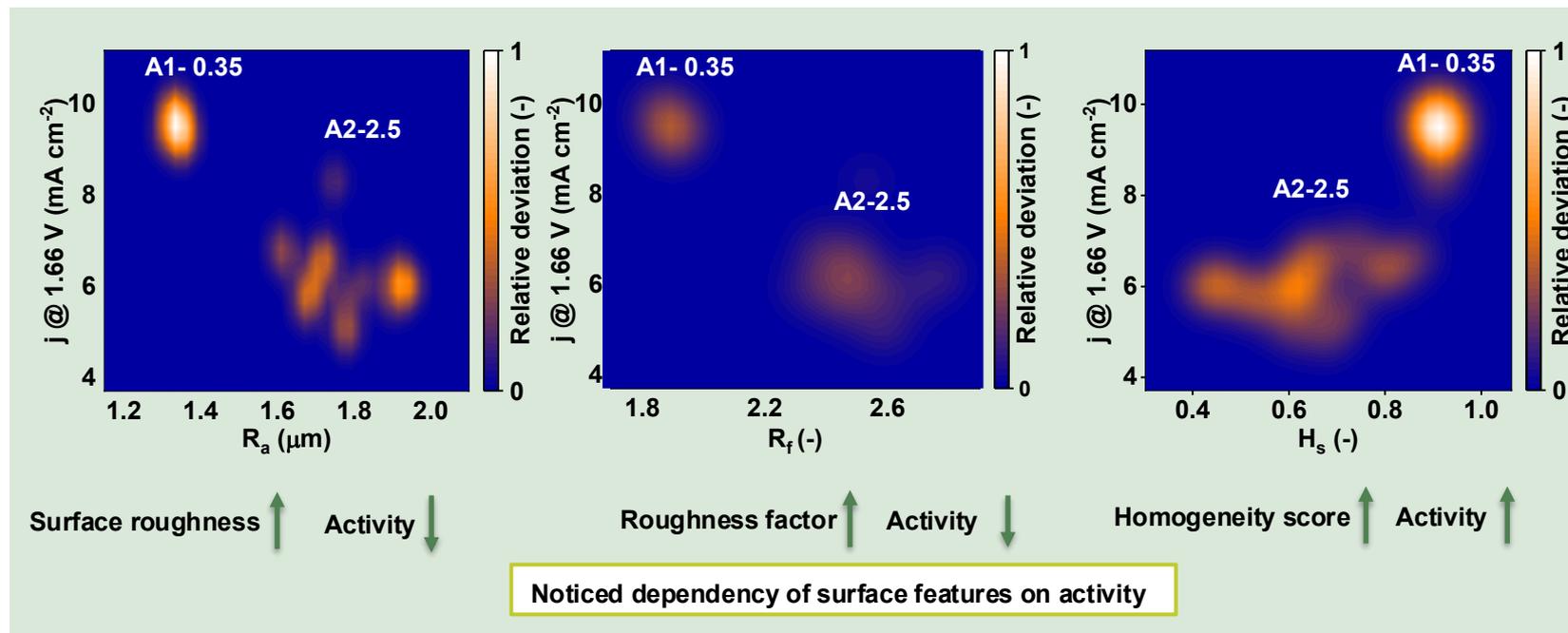
# Mapping correlations: 2D Kernel plot

Can we visualize a correlation in an easy and understandable way?



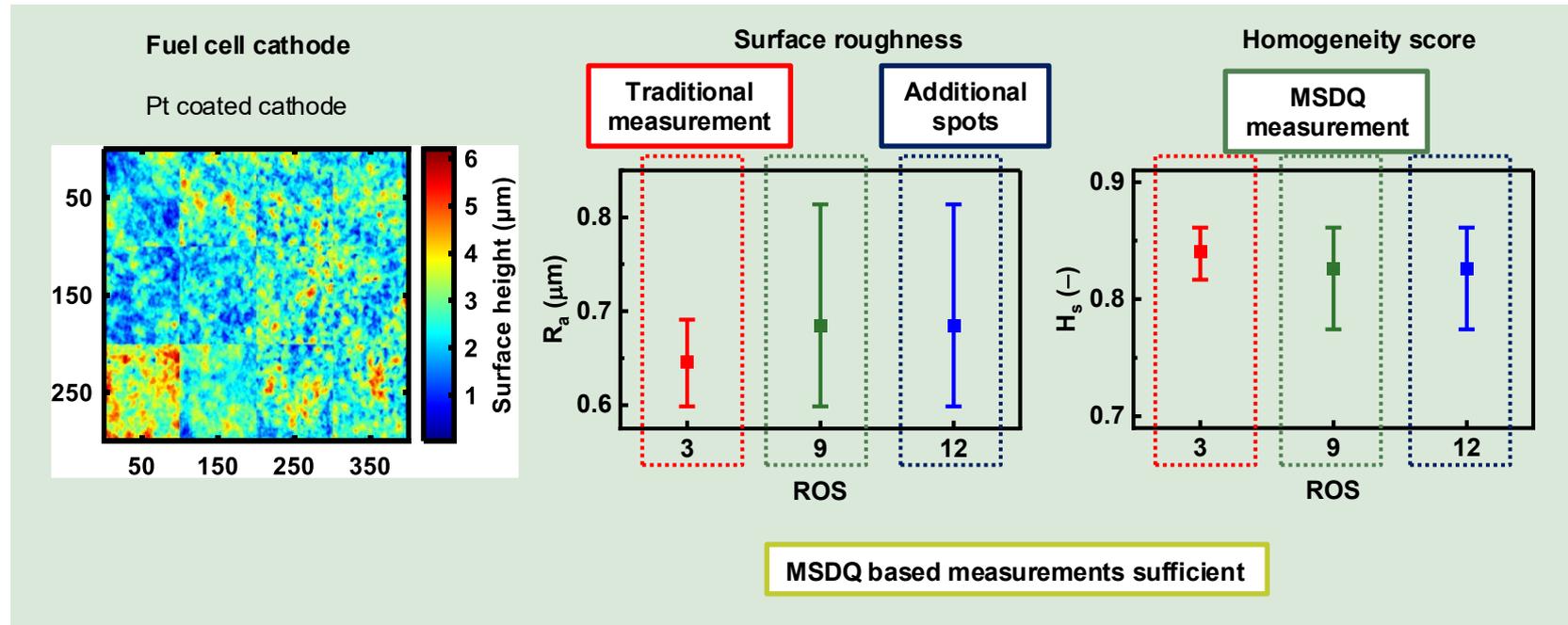
# Structure-activity correlation

Does structure have an influence on activity?



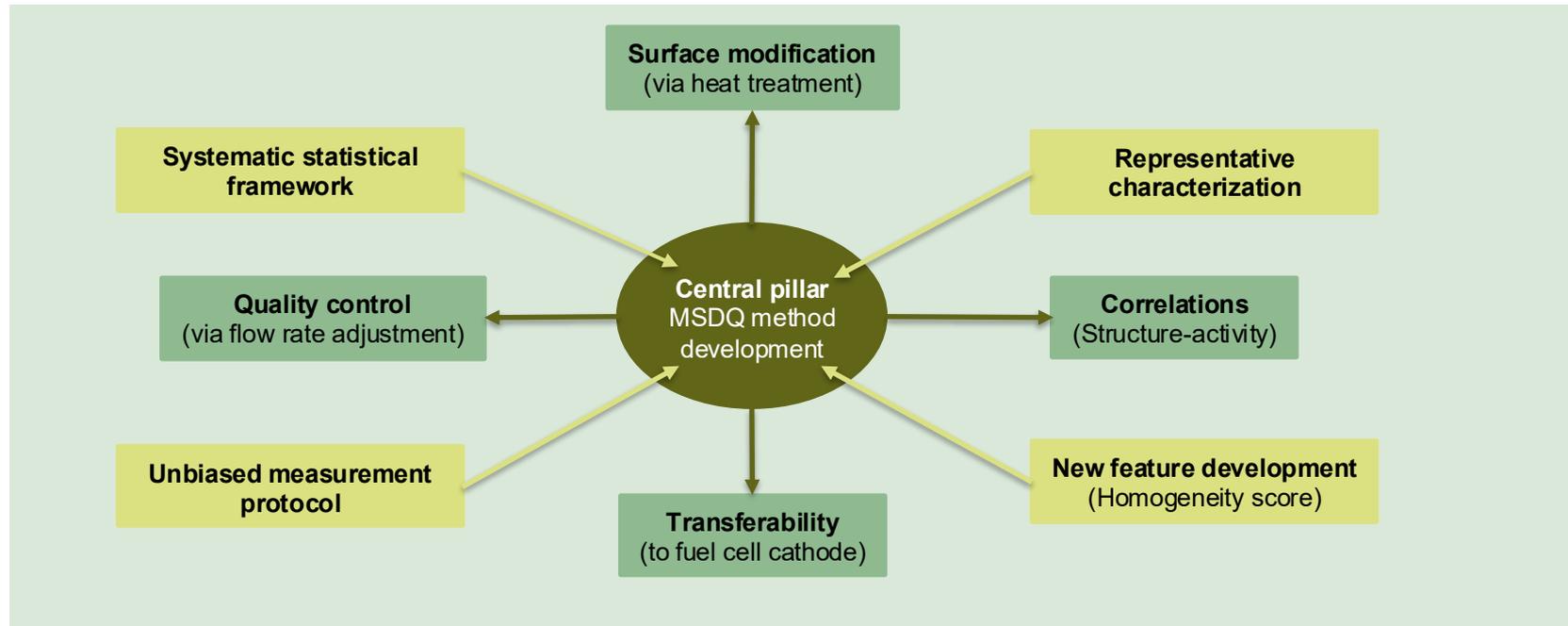
# Applications and comparisons

Is the method transferable to other systems, and are MSDQ-based measurement points sufficient?



# Summary: MSDQ method development and application

What did we go through so far?



# Research objective 2

## Three systematic approaches to understand anode design principles

### 1. Enable systematic and representative surface analysis

Development of a statistical framework that allows the extraction of machine-readable surface features

### 2. Establish a systematic relationship between macroscopic anode layer properties and electrochemical performance

Development and characterization of anodes with different structures but similar chemical compositions



### 3. Elucidate the influence of different wetting states on the oxygen–electrolyte–anode interface during OER

Design and fabrication of anodes with varied wetting characteristics

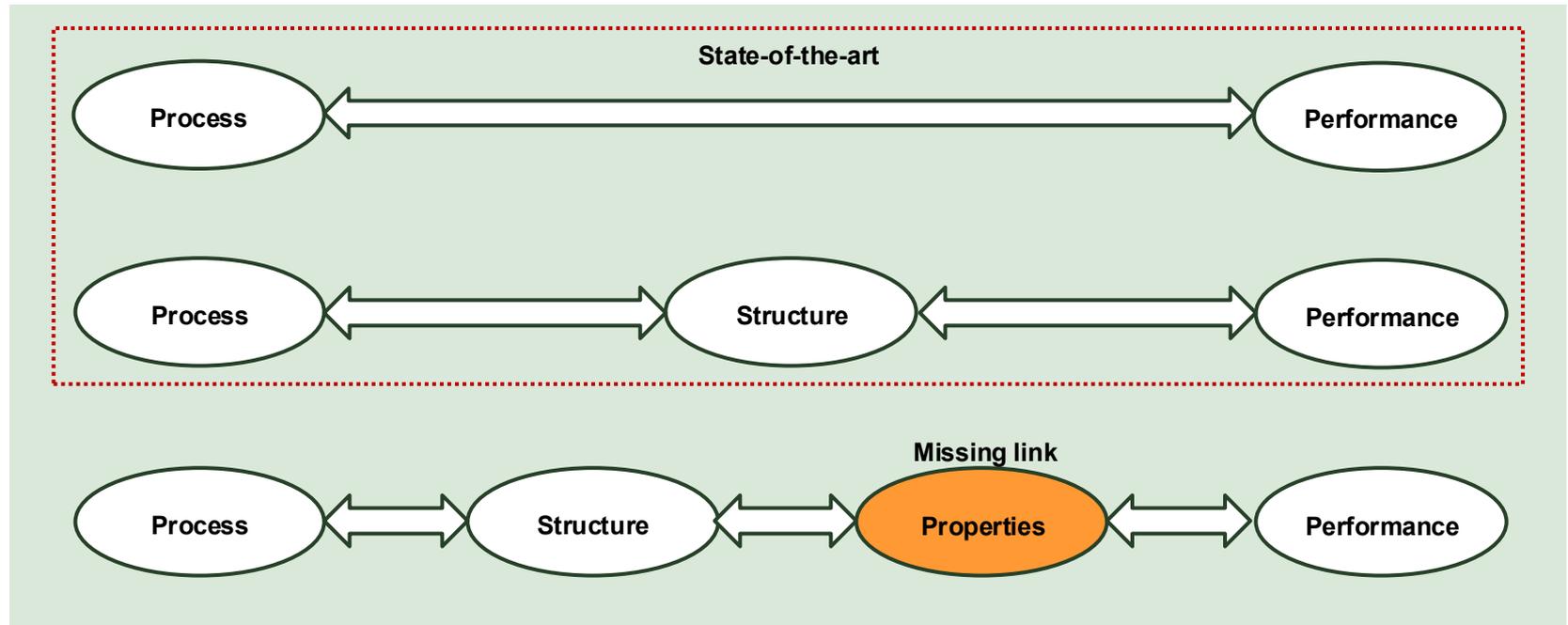


**ADVANCED FUNCTIONAL MATERIALS**

A. Jain, C. Marcks, D. Segets et al, *Advanced Functional Materials*, 2025, <https://doi.org/10.1002/adfm.202421352>

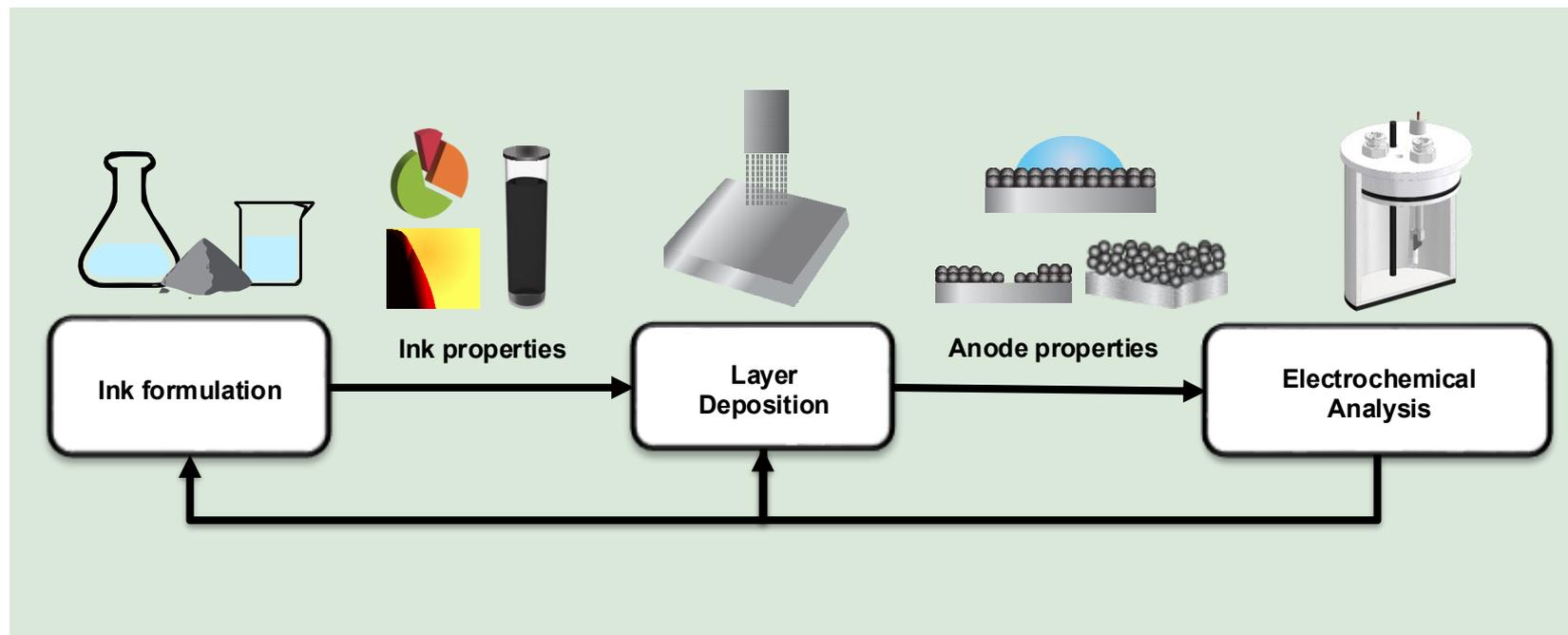
# Missing point: Property

How do structures translate into properties?



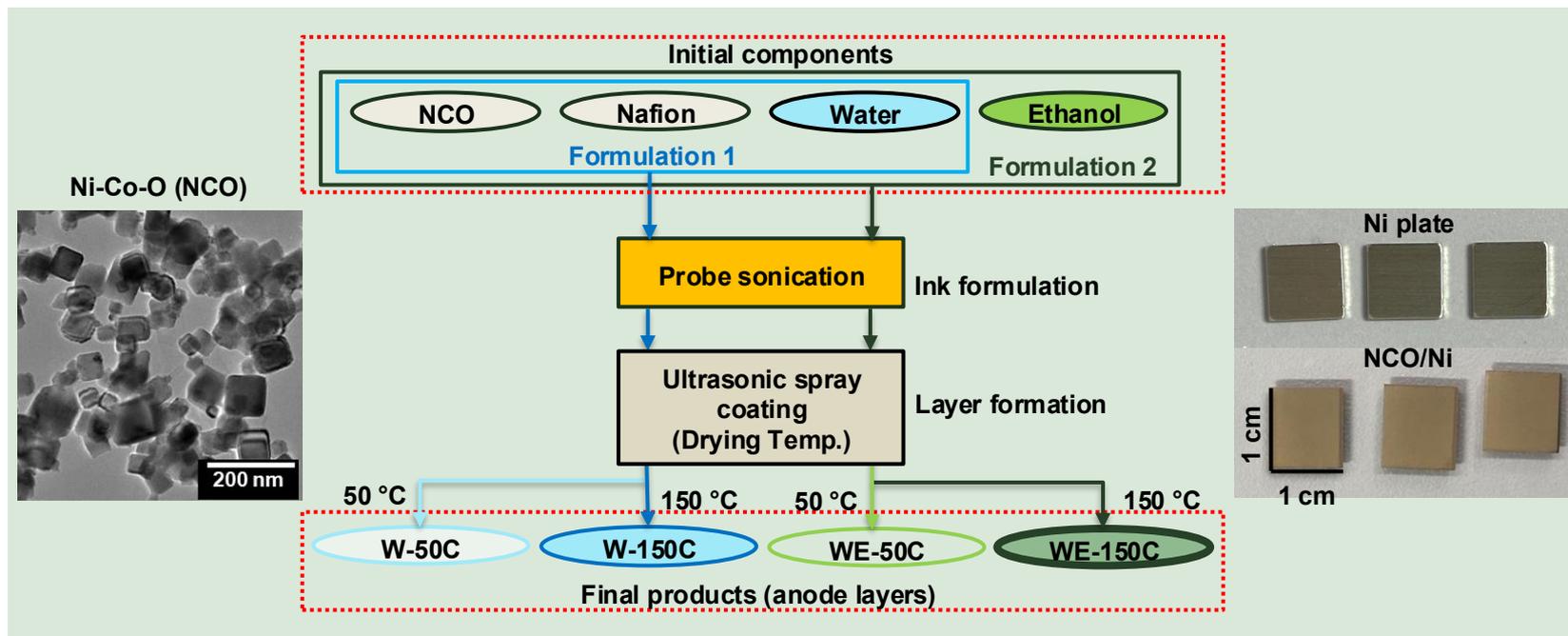
# Strategy for rational design of anode layers

How do layer properties translate into performance metrics?



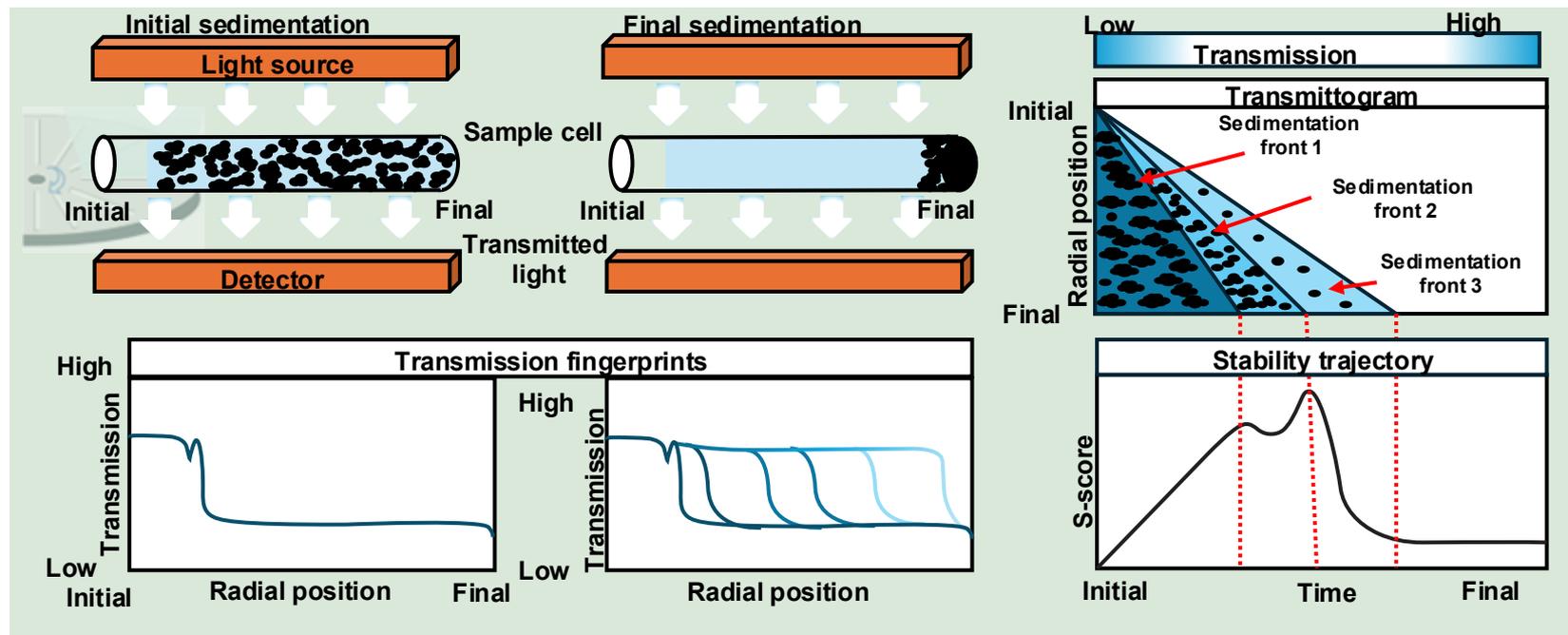
# Developing anodes

Developing anode layers with varying structures and keeping chemical composition and mass loading constant



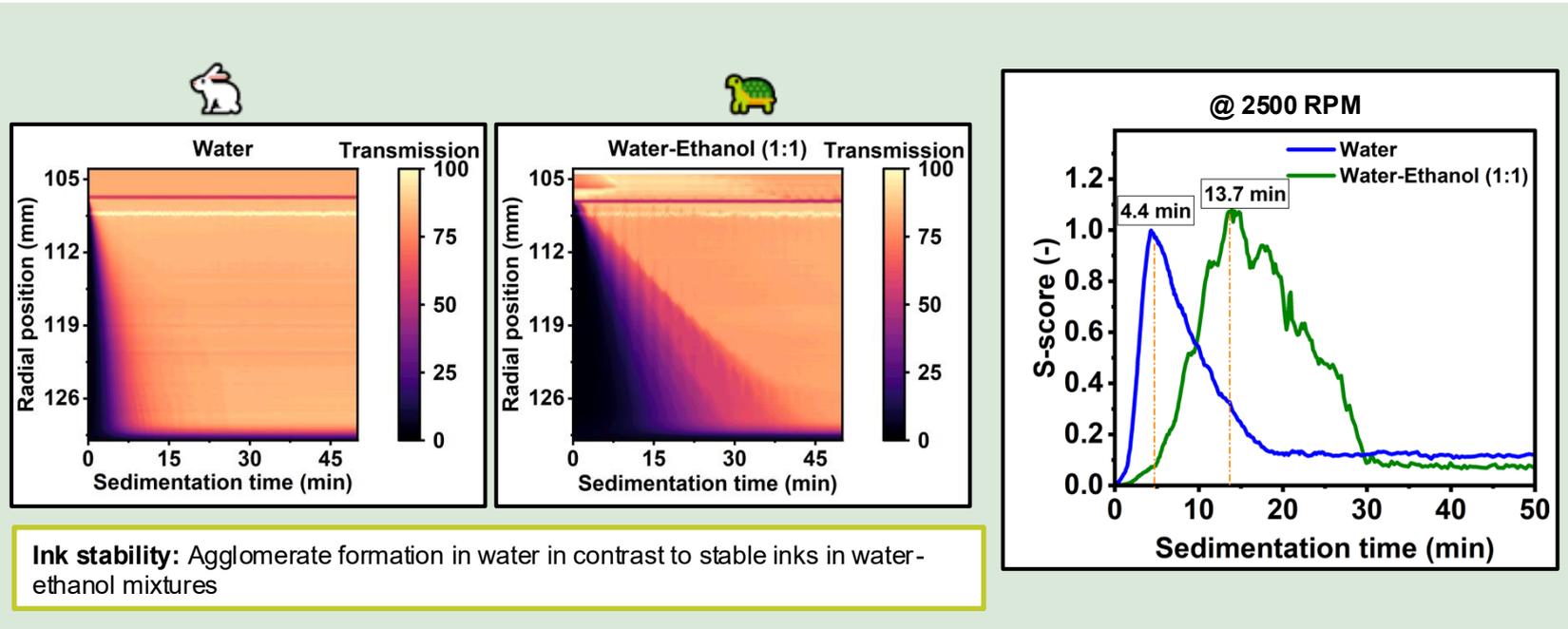
# Ink analysis: Analytical centrifuge (AC)

How can we characterize inks in native state?



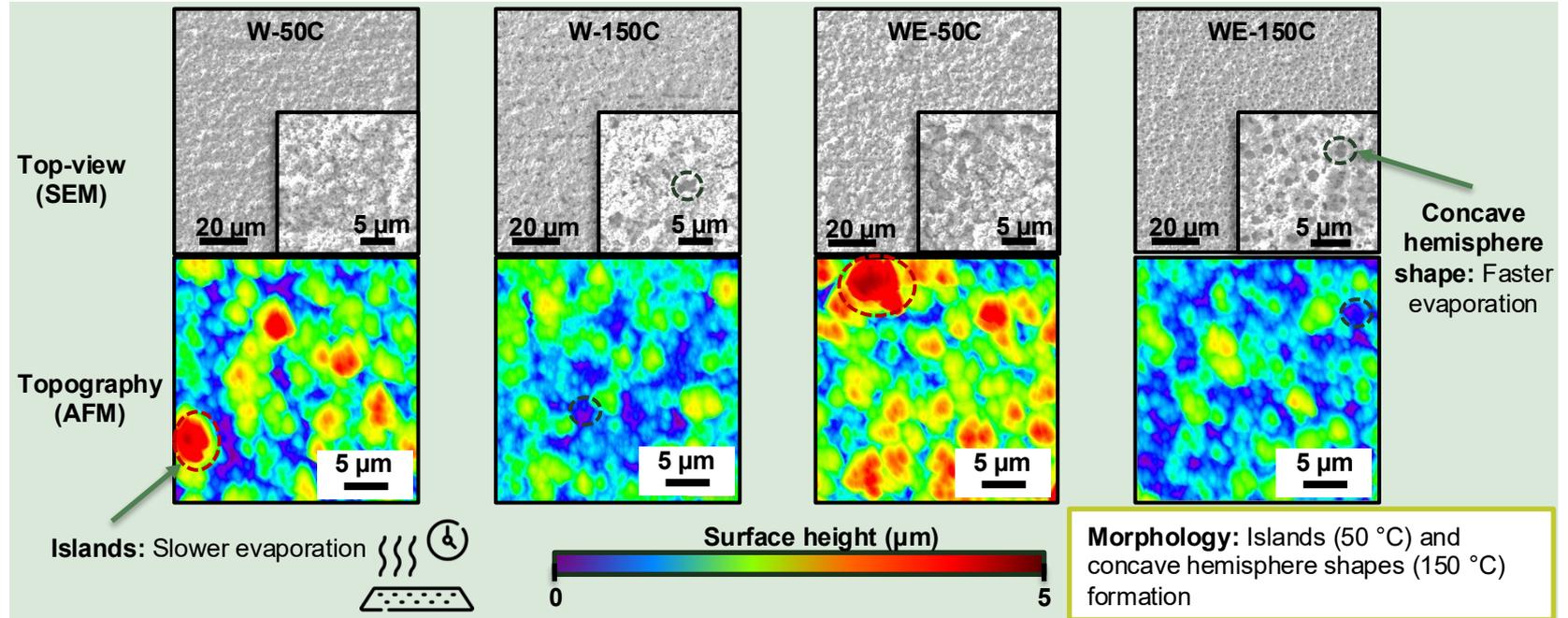
# Ink properties

How water-based ink and water-ethanol-based ink affects ink properties?

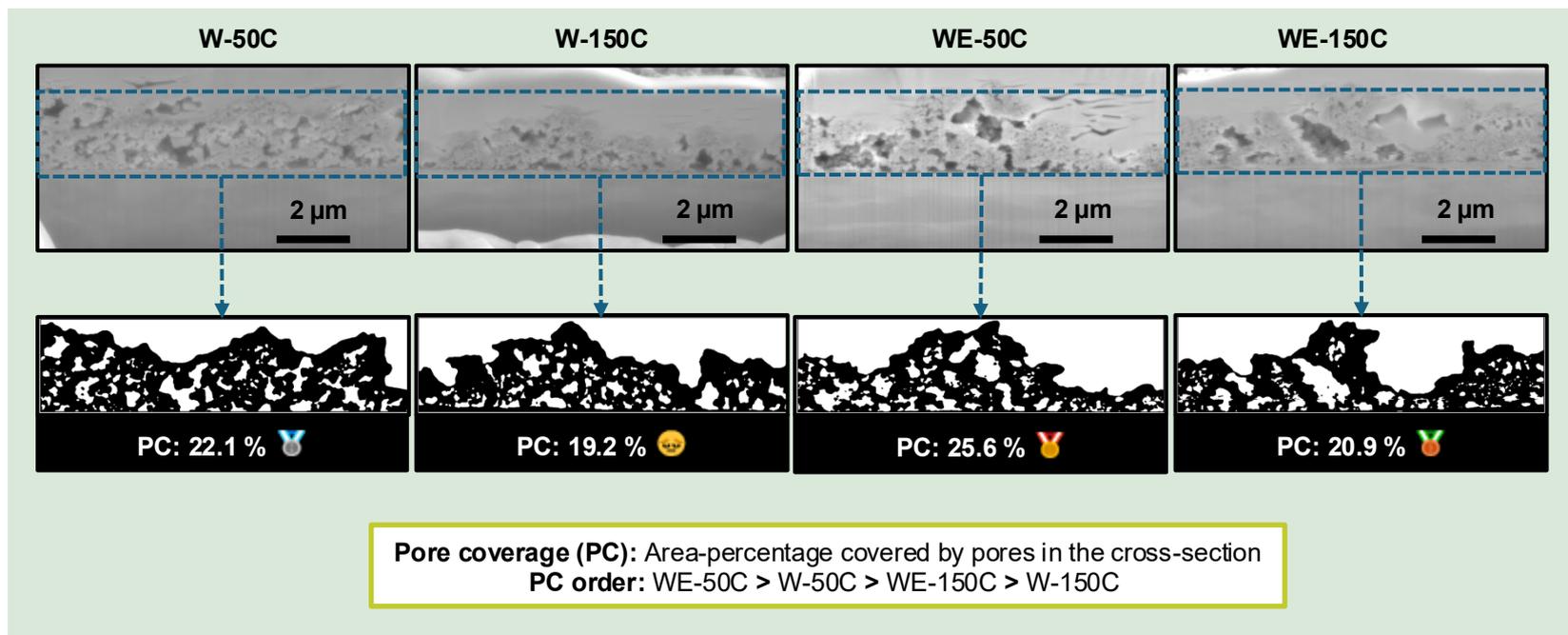


# Morphology of the anode layers

How solvent compositions and drying temperature affects the morphology?

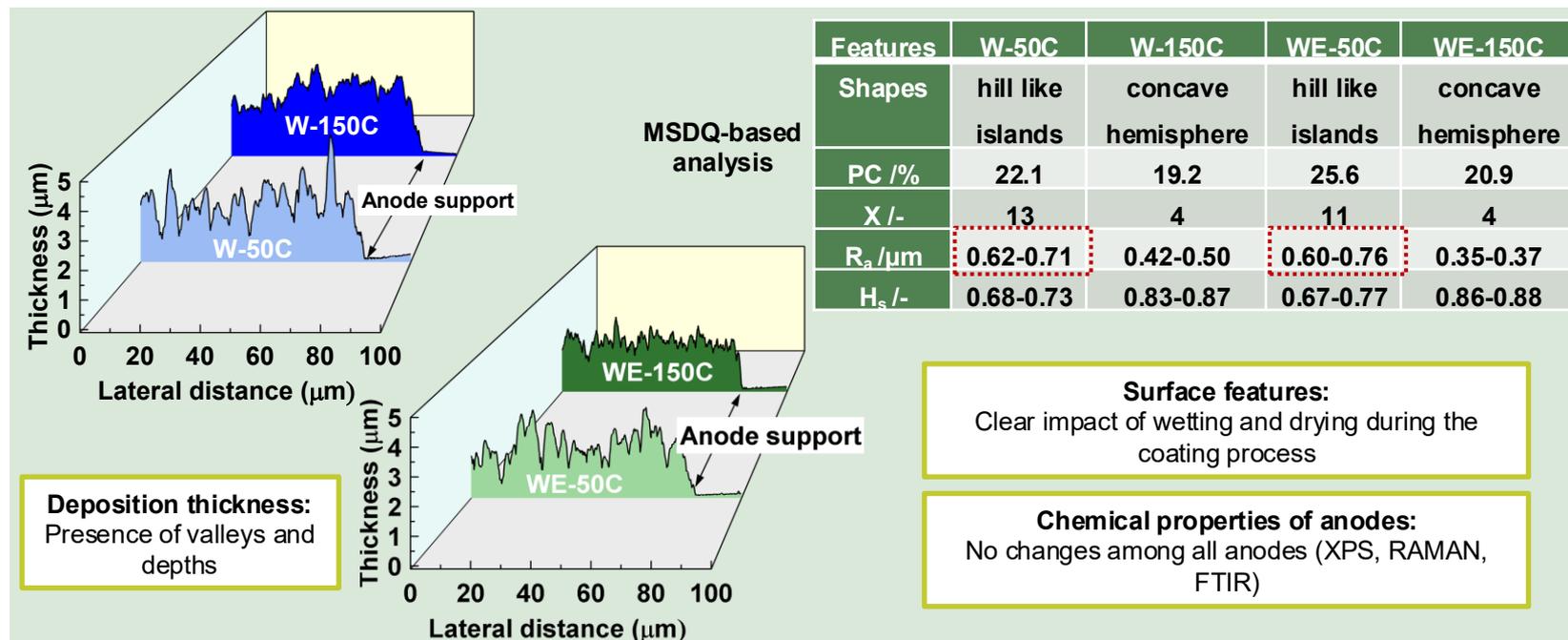


# Cross-section of the anode layers (FIB-SEM) for pore network assessment



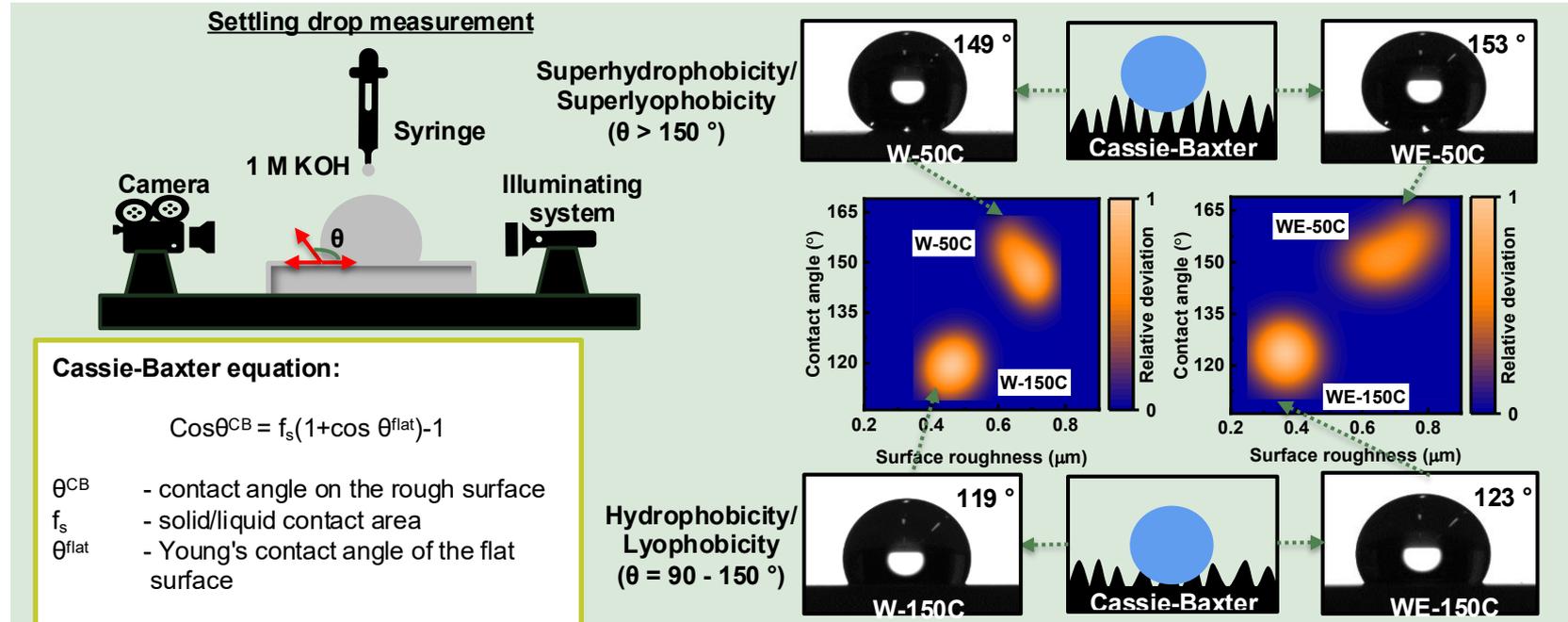
# Surface features of the anode layers

## Quantitative understanding of the structures



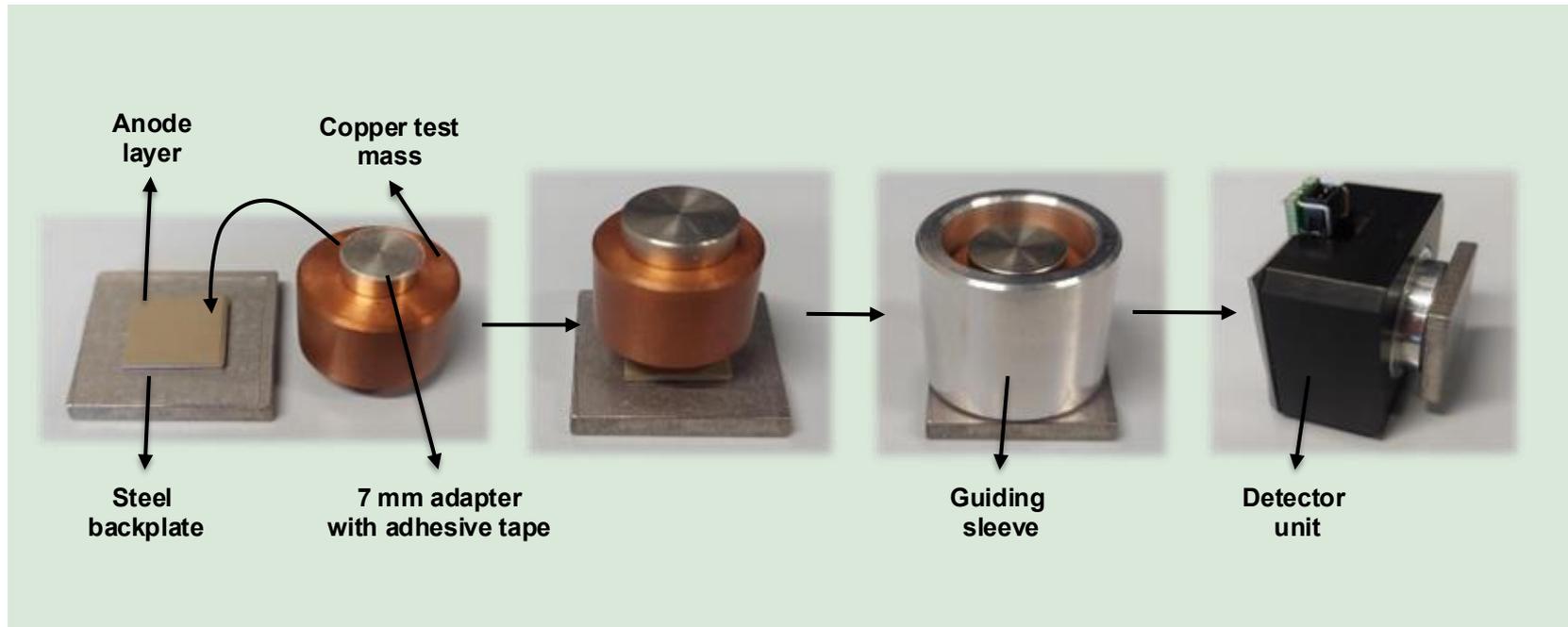
# Wetting analysis: Contact angle measurements

A physics-informed model for wettability understanding and structural effects



# Mechanical strength analysis

## Centrifugal detachment testing for powder-based coatings



# Cohesion and adhesion

Can solvent compositions play an important role on mechanical stability?

**Cohesive failure: Weaker particle-particle connectivity**

<p style="text-align: center;">W-50C</p> <p style="text-align: center;">0.5 μm</p>	<p style="text-align: center;">W-150C</p> <p style="text-align: center;">0.5 μm</p>
<p style="text-align: center;">WE-50C</p> <p style="text-align: center;">0.5 μm</p>	<p style="text-align: center;">WE-150C</p> <p style="text-align: center;">0.5 μm</p>

**No failure: Stronger particle-particle connectivity**

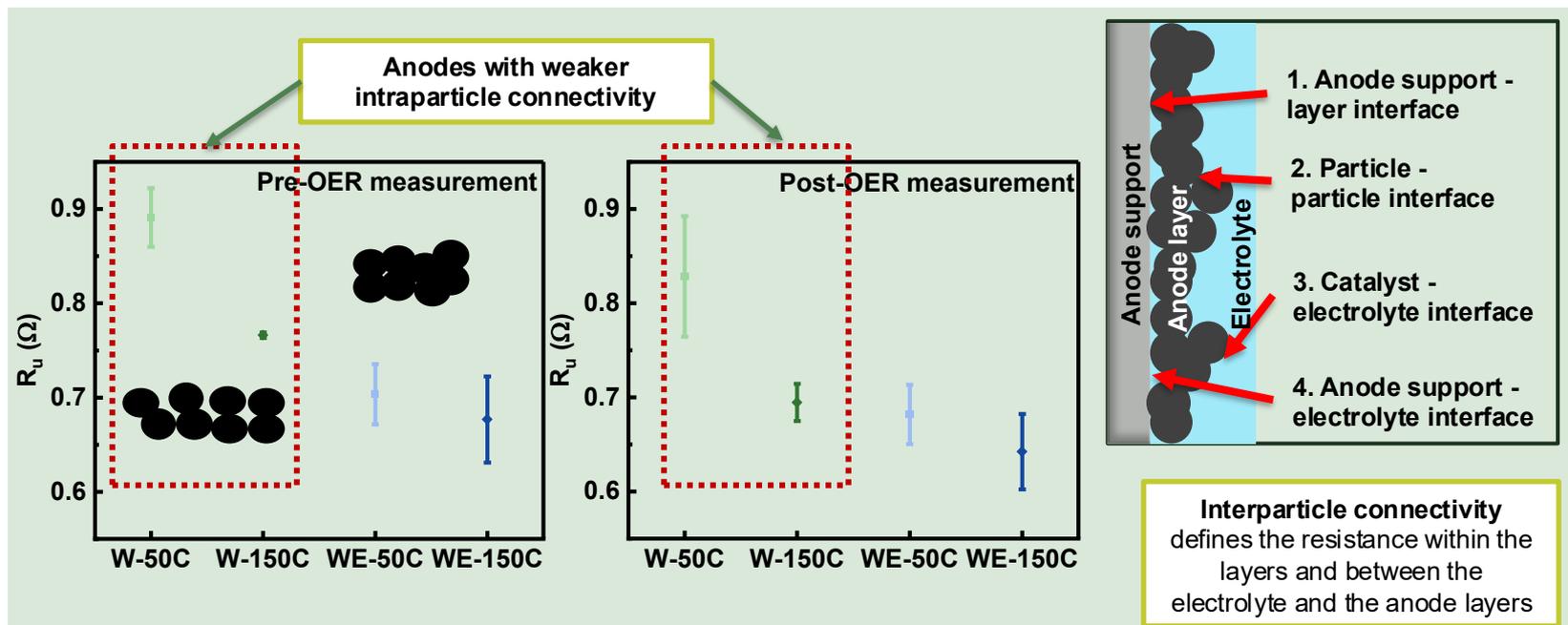
Anode support

**But why?**

- Stable ink (WE)
- Nafion swelling (WE)
- Lyophobicity of the surface (W)

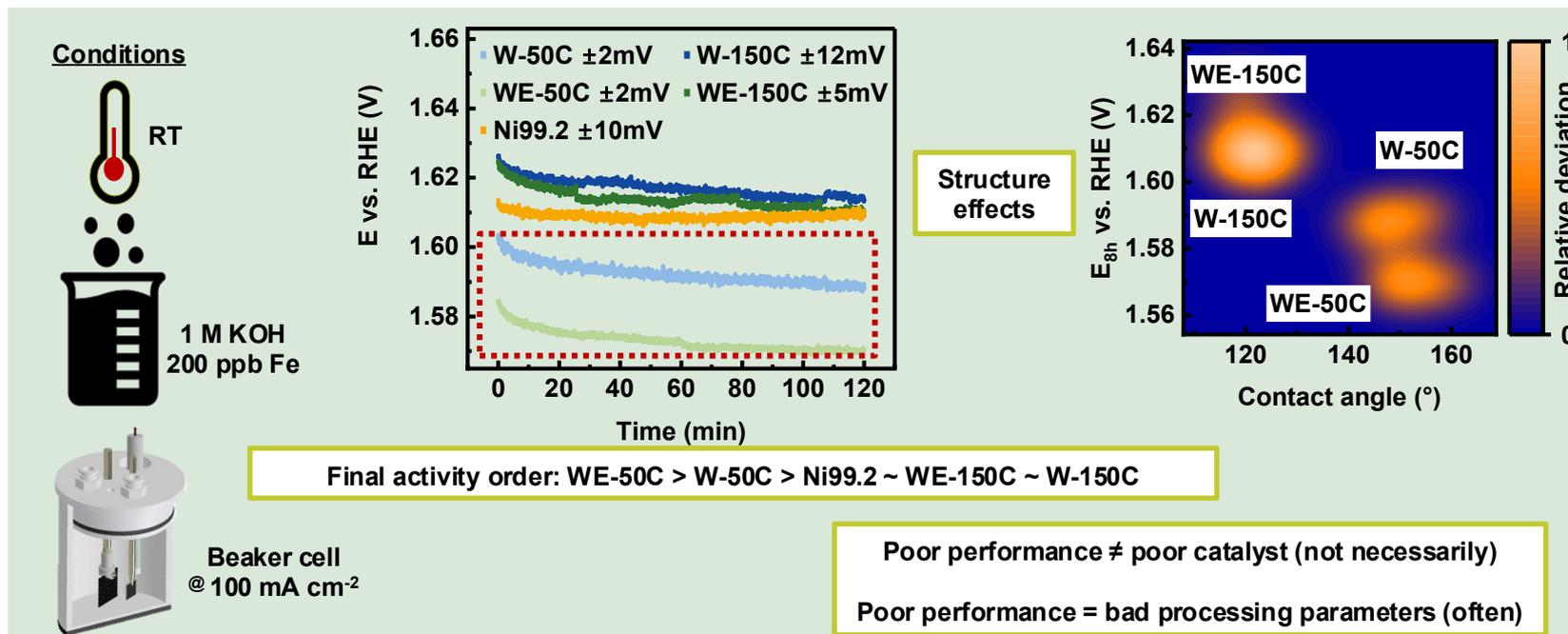
# Static contact resistance within beaker cell (uncompensated)

Does mechanical cohesion affect the uncompensated resistance?



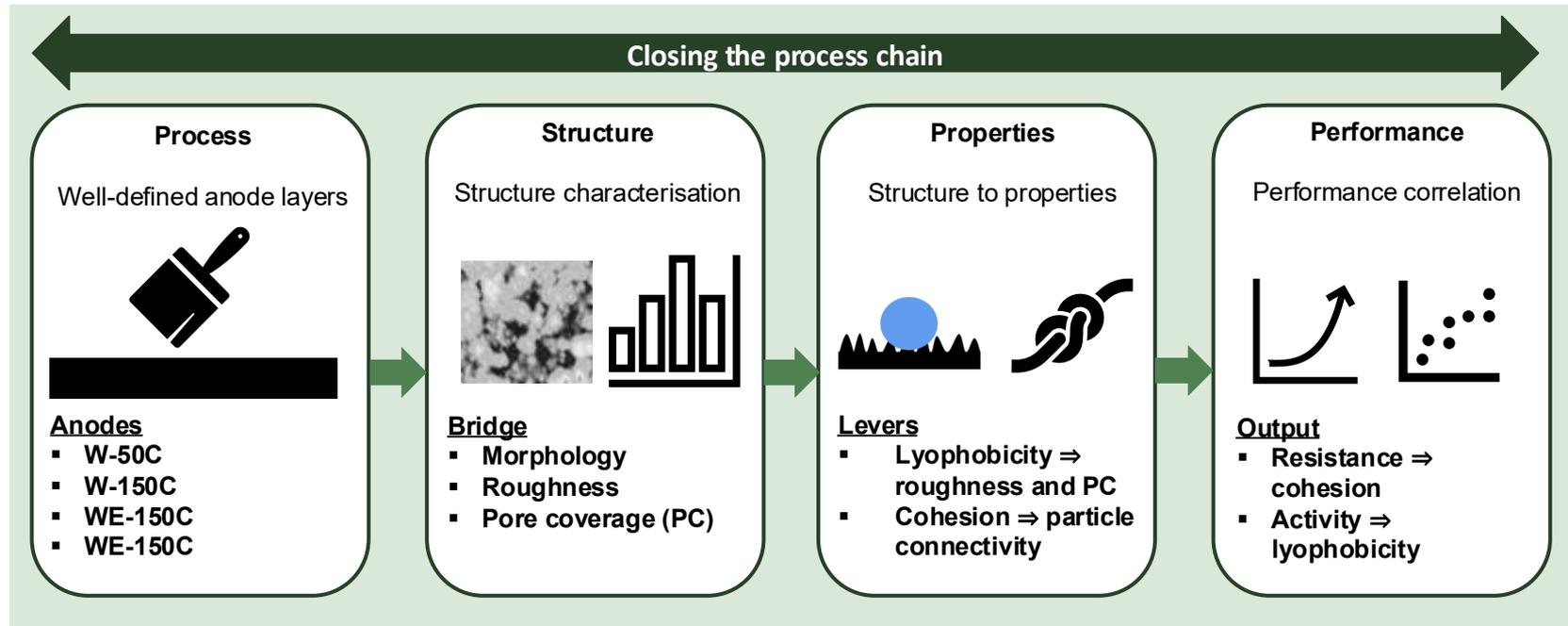
# Electrochemical testing: Stability and activity

What is the role of contact angles on activity?



# Summary

A proof-of-principle demonstration of PSCP relationships



# Research objective 3

## Three systematic approaches to understand anode design principles

### 1. Enable systematic and representative surface analysis

Development of a statistical framework that allows the extraction of machine-readable surface features



### 2. Establish a systematic relationship between macroscopic anode morphology and electrochemical performance

Development and characterization of anodes with different surface morphologies and similar chemical compositions

A. Jain, C. Marcks, D. Segets et al., *ACS Applied Materials and Interfaces*, 2025, <https://doi.org/10.31224/4749>

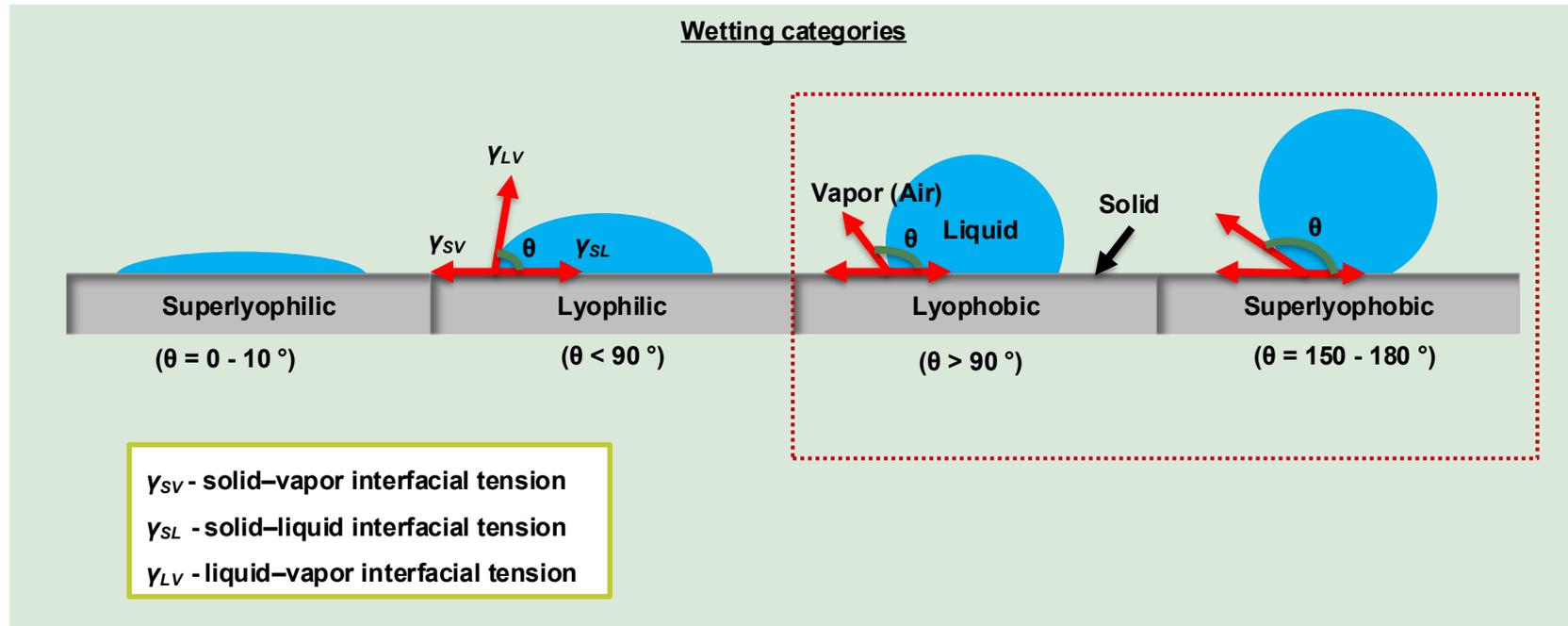
### 3. Elucidate the influence of different wetting states on the oxygen–electrolyte–anode interface during OER

Design and fabrication of anodes with varied wetting characteristics via tuning the binder chemistry and coating parameters



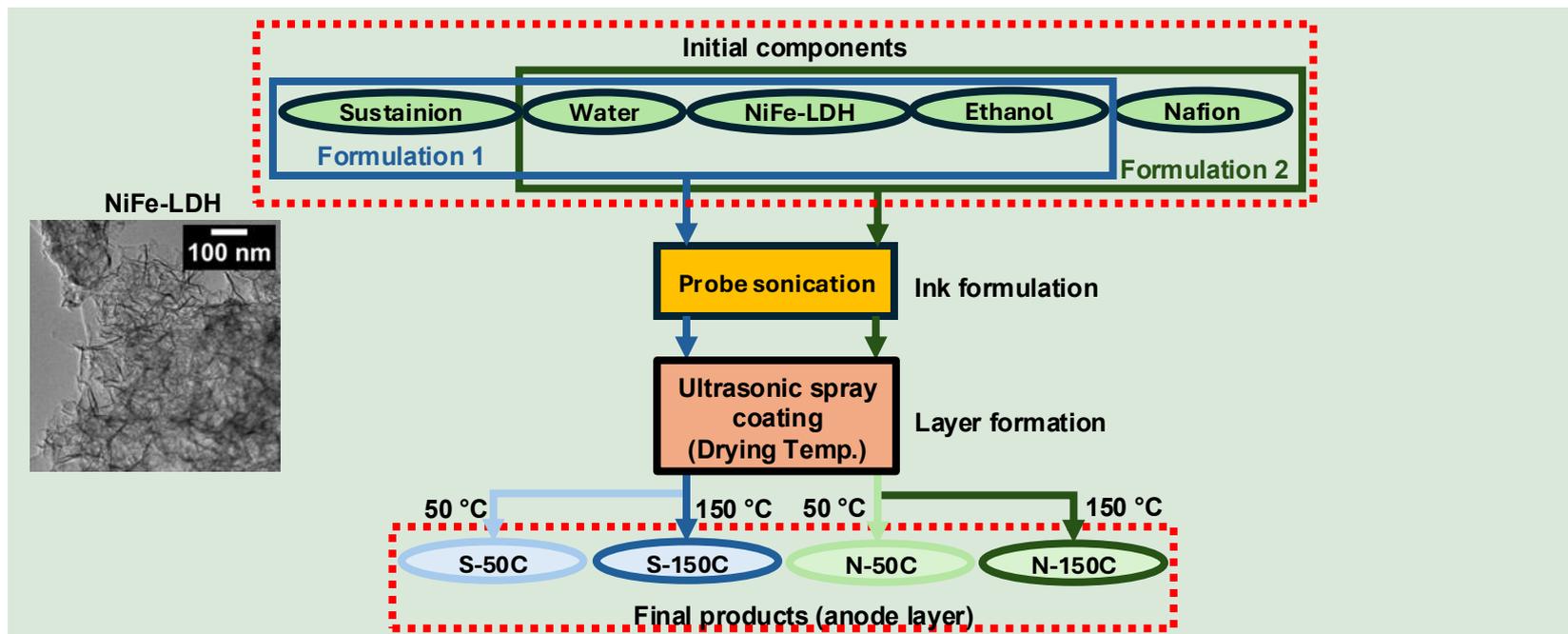
# Wettability spectrum and transferability

A systematic comparison between superlyophilic and superlyophobic anodes



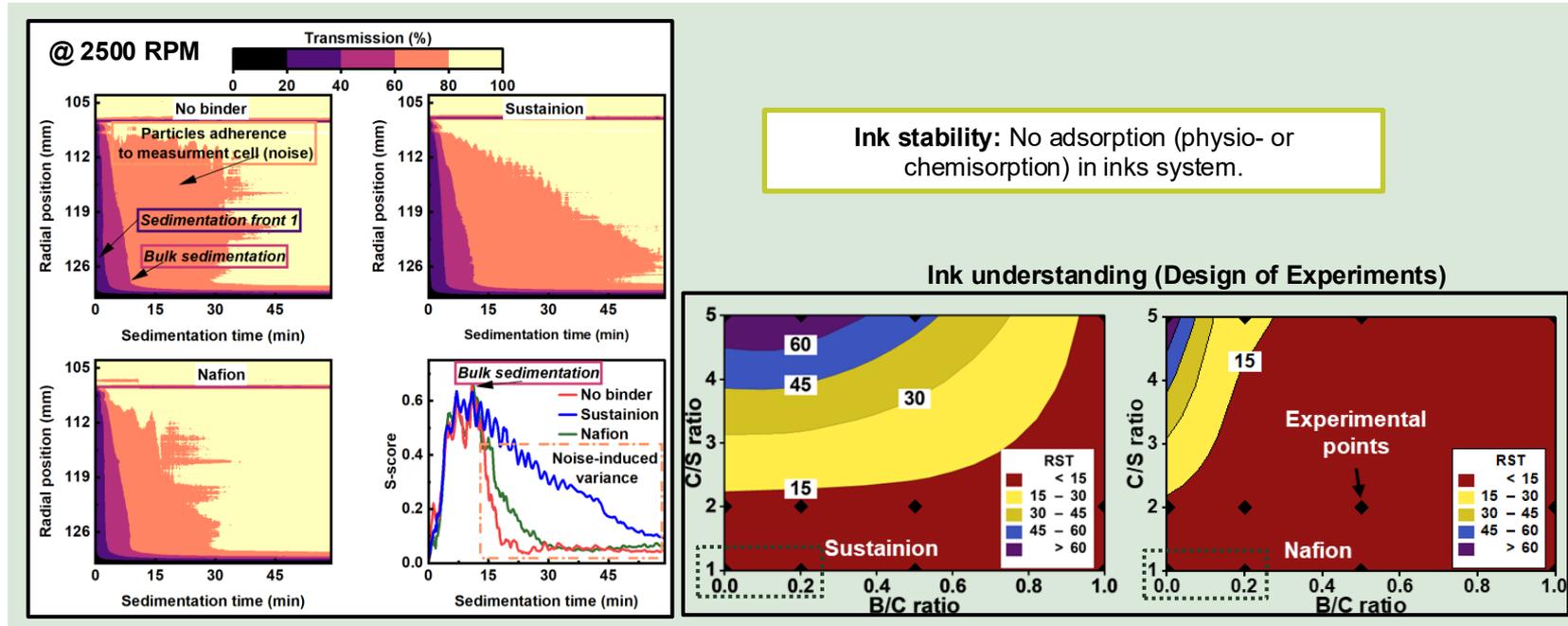
# Developing anode layers

Developing anode layers with varying wetting characteristics



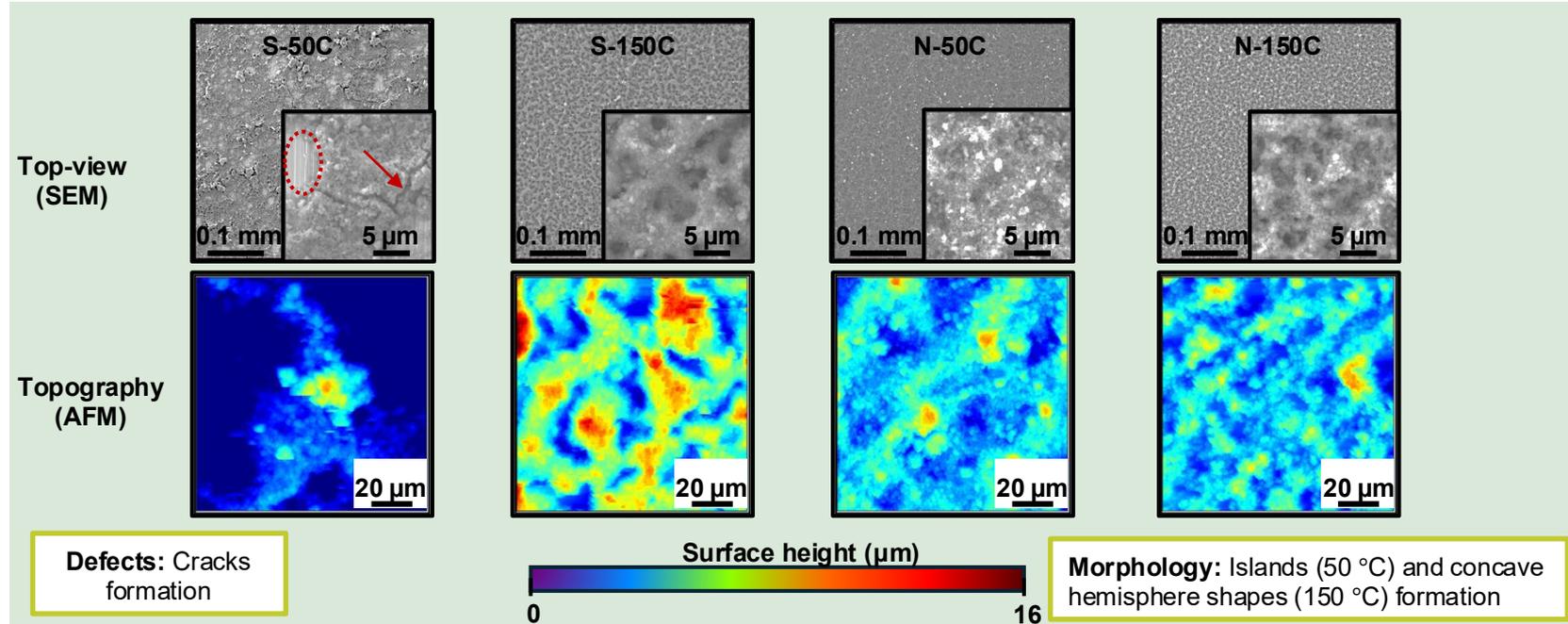
# Ink properties

How binders impact the ink properties?



# Morphology of the anode layers

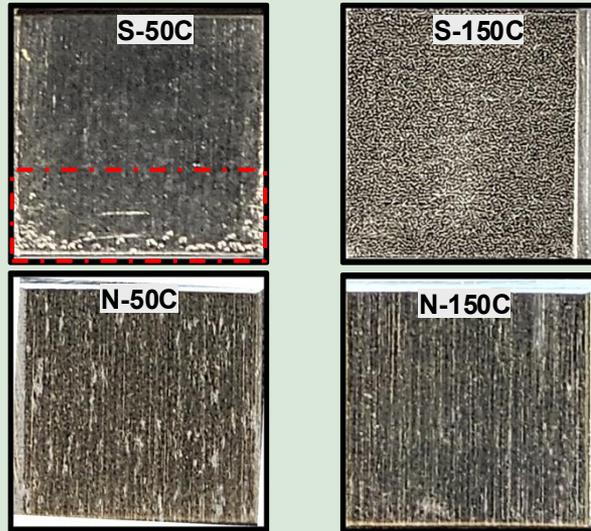
Can we see similar morphology formation as NCO?



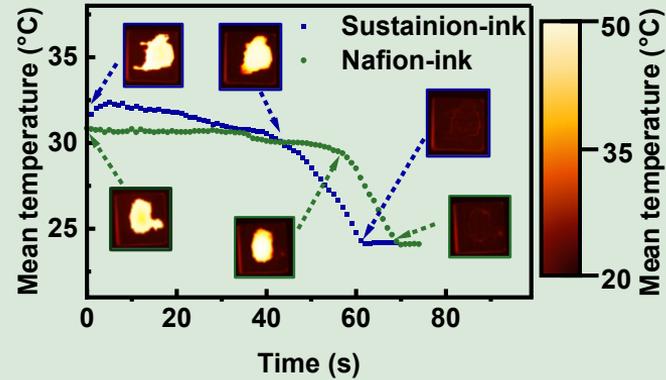
# Possible interactions

## Mobility of catalysts and binder molecules on Ni support during coating

### Catalyst-free coatings (binders + solvents)



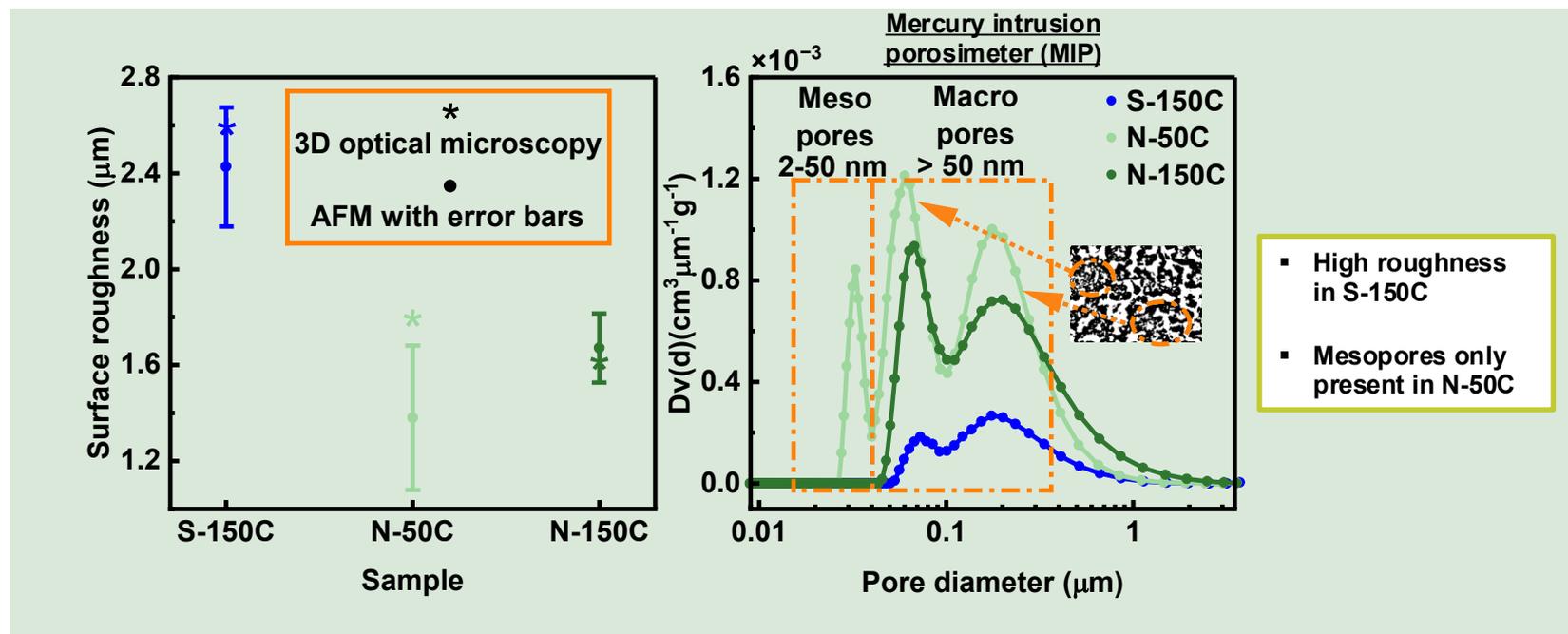
### Drying kinetics of inks (Infrared camera)



- Binder agglomerations
- Irregular distribution of an Sustainion ink
- Faster evaporation

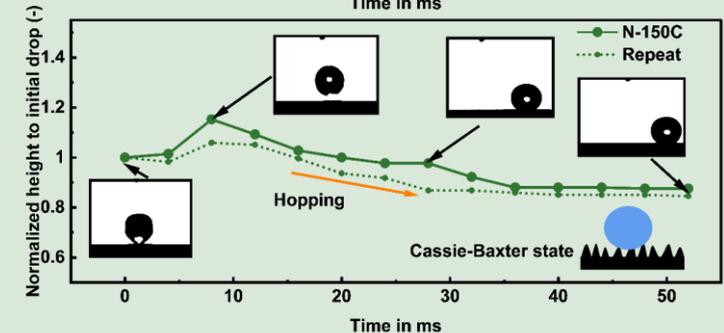
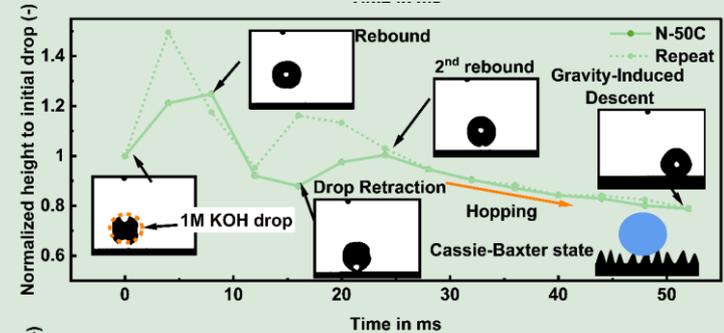
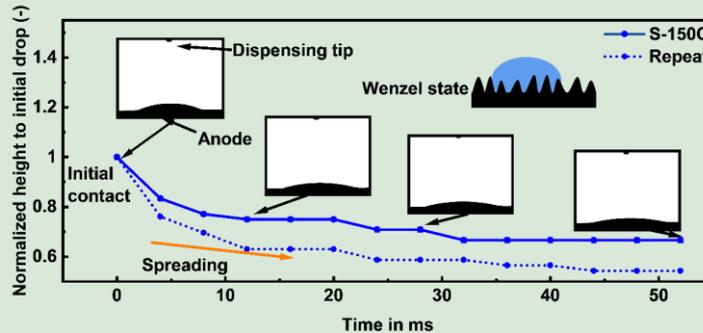
# Surface features

## Surface roughness and pore networks



# New approach to quantify the contact angles

How can we understand highly mobile droplets?



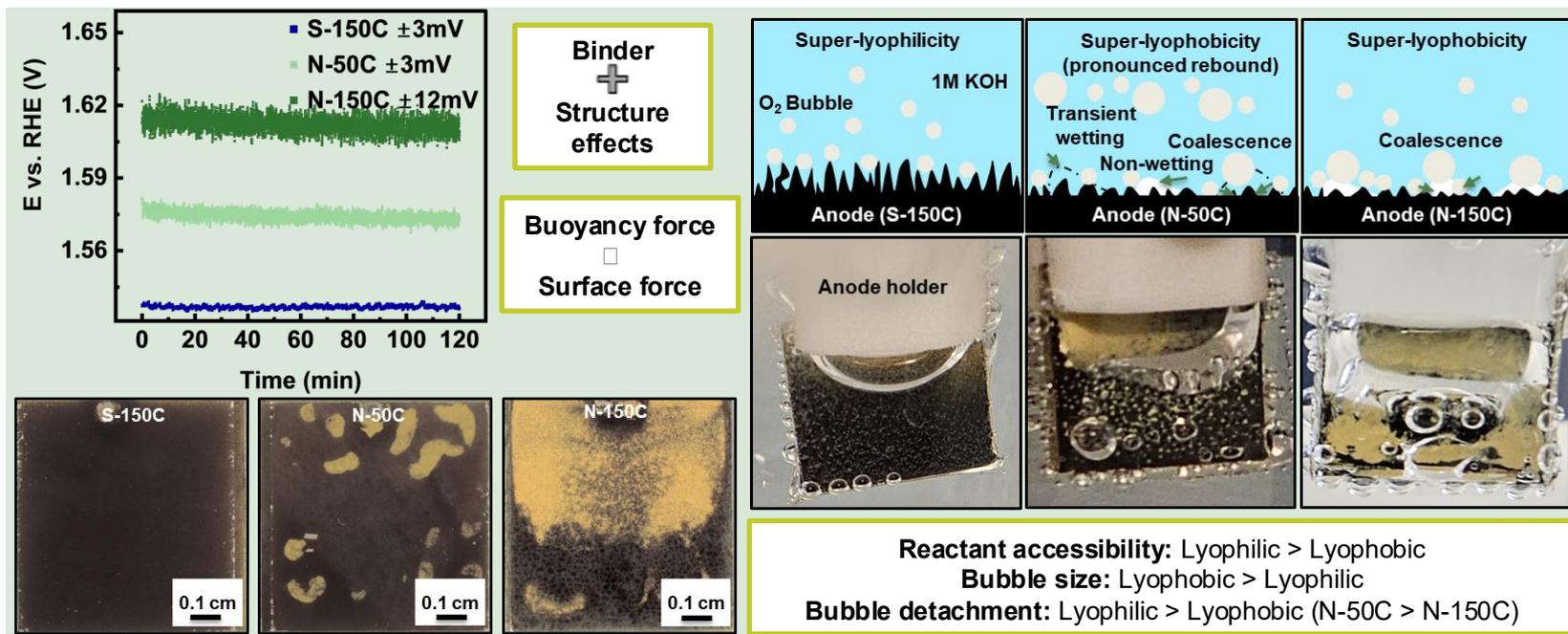
**Mobility:** No hopping in S-150C

**Penetration:** No spreading in N-50C and N-150C

**Wettability regime:** N-50C & N-150C (**Lyophobicity**, 90-180°), S-150C (**Lyophilicity**, 0-90°)

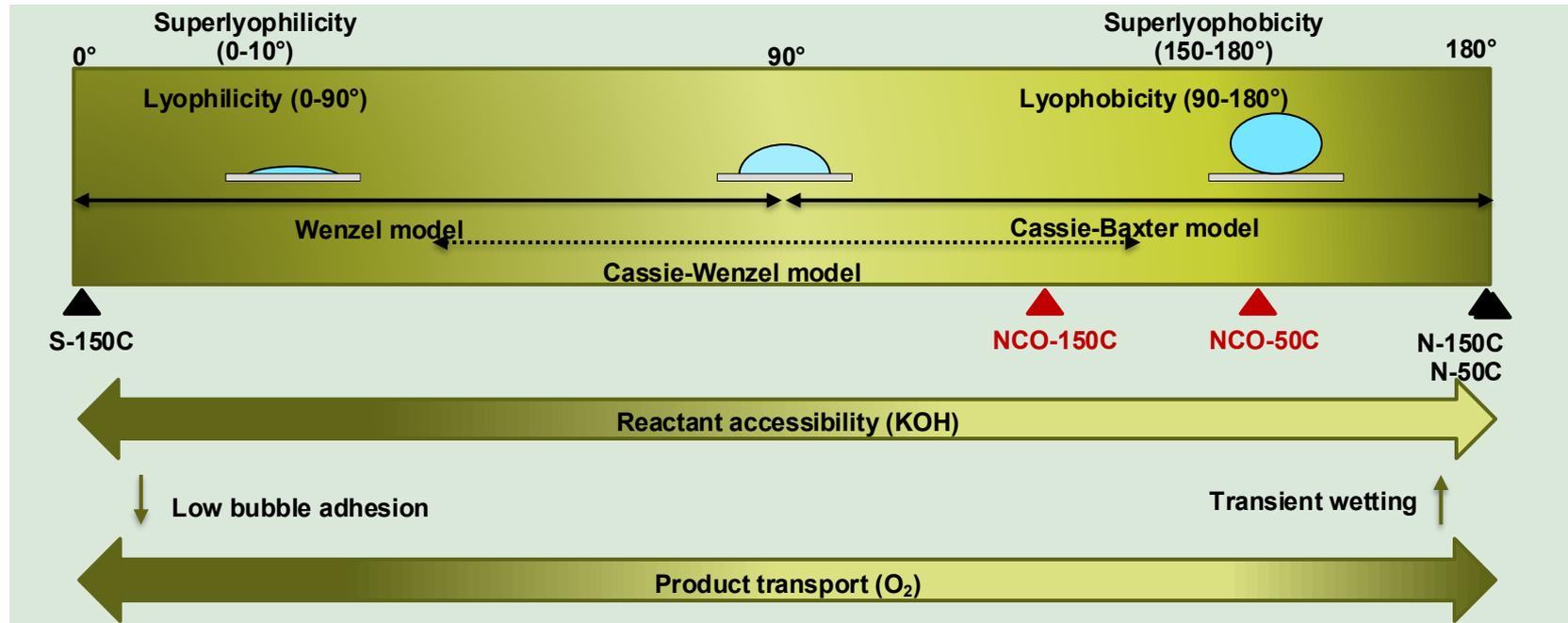
# Single-drop wettability vs. Three-phase contact line

Understanding of fluid dynamics at the interface



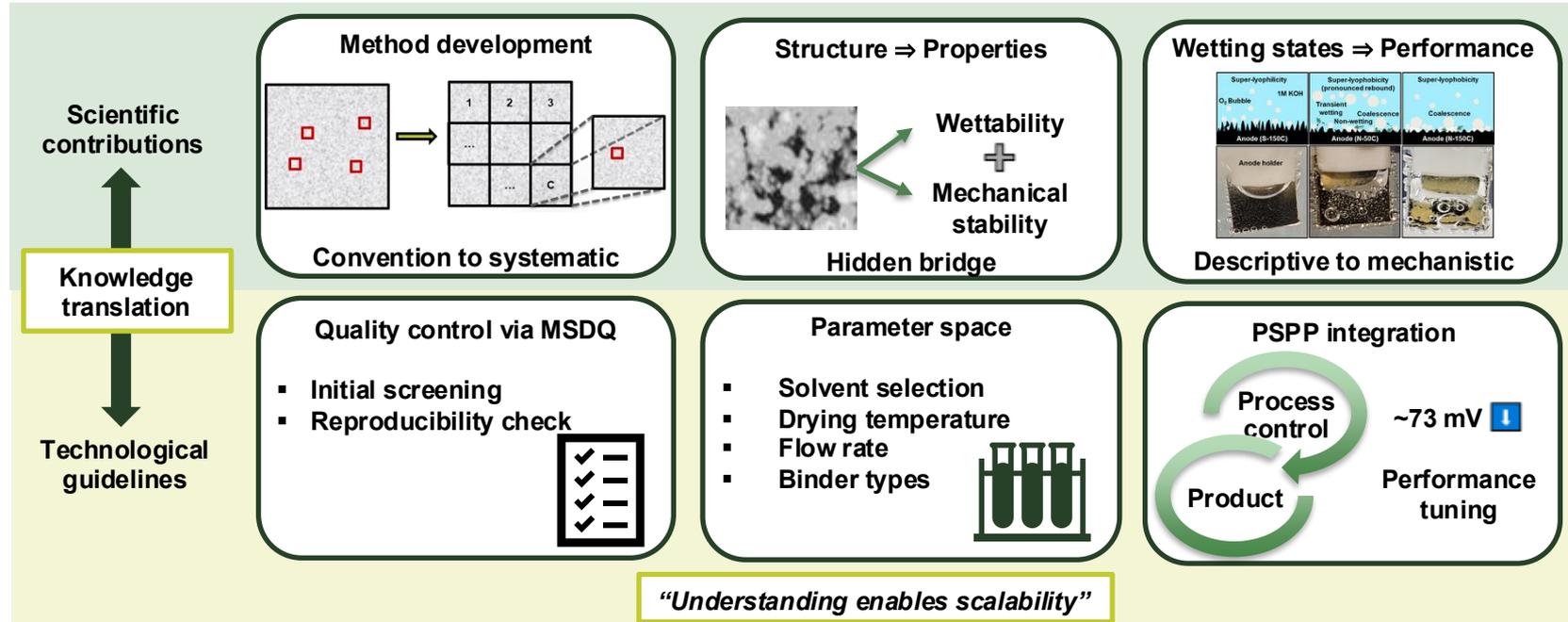
# Summary

## Overview and transferability



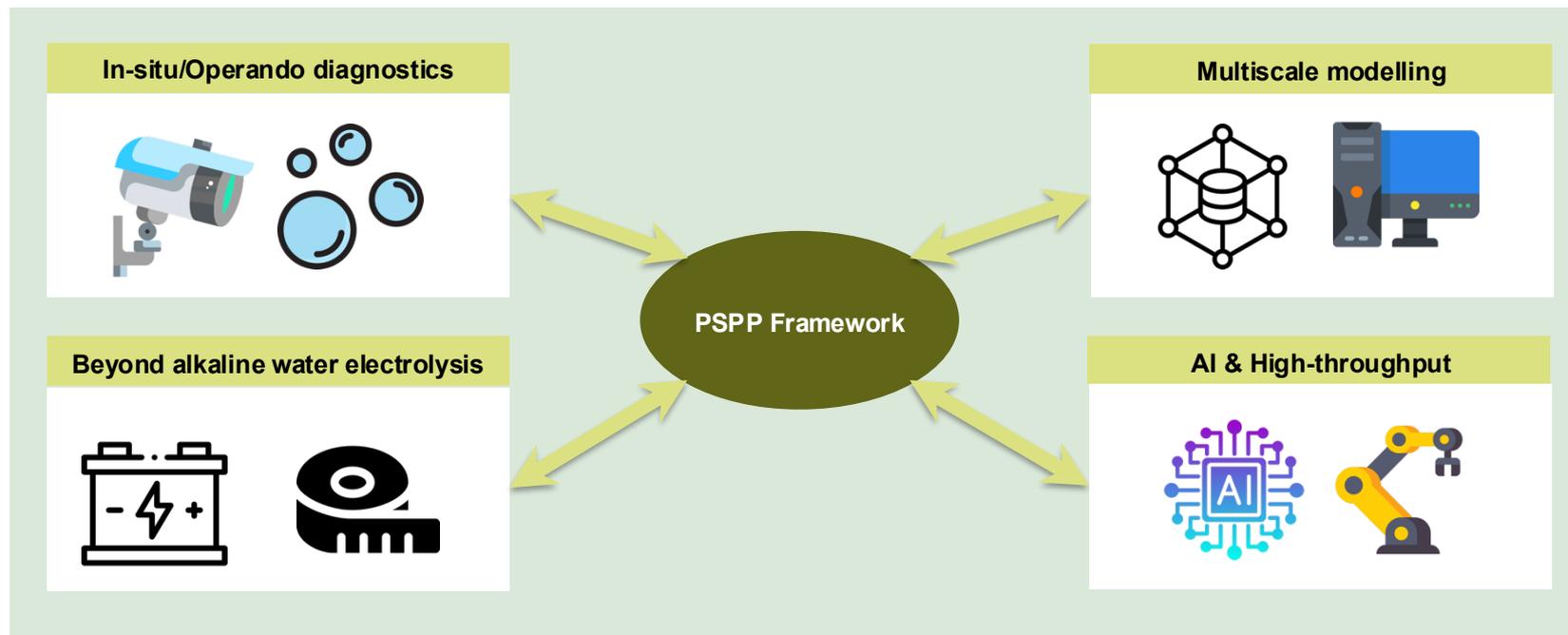
# Concluding remarks

From empirical to rational design of anode layers



# Outlook

## A futuristic view on PSPP relationships



# Scientific contributions

## Publications and conferences (2022 - present)

### Publications

1. A. Jain et al., ACS Appl. Mater. Interfaces, 2025
2. A. Jain et al., Adv. Funct. Mater., 2025,
3. A. Jain et al., ChemCatChem, 2024
4. M. Hammad et al., ACS Appl. Mater. Interfaces, 2025
5. M. Kräenbring et al., Chem. Eng. J., 2025
6. V. Vinayakumar et al., Chem. Eng. J., 2025
7. A. S. Amin et al., Int. J. Hydrogen Energy, 2024
8. A. Olean-Oliveira et al., ACS Catal., 2024
9. M. Hammad et al., J. Water Process Eng., 2024
10. A. Olean-Oliveira et al., Electrochim. Acta, 2025
11. B. Toplak et al., Chem. Eng. J., 2025
12. C. Marcks et al., Electrochim. Acta, 2025
13. J. Hoffmann et al., ACS Appl. Mater. Interfaces, 2025
14. M. Chatwani et al., Int. J. Hydrogen Energy, 2025
15. G. Mahler et al., manuscript submitted, 2026
16. V. Vinayakumar et al., ChemElectroChem, 2025
17. V. Vinayakumar et al., Appl. Surf. Sci., 2026

### Conferences

1. European Coating Symposium 2023, Paris
2. ECCE-ECAB 2023, Berlin
3. ECS PRiME 2024, Honolulu (2 talks)
4. ZBT Hydrogen Energy Symposium 2024, Duisburg
5. ACAMEC 2022, Mülheim
6. EFCF 2023, Lucerne
7. H<sub>2</sub>Giga Status Conference 2024, Berlin
8. GDCh Energy Division 2025, Duisburg
9. NRW Nano Conference 2025, Dortmund

ACS APPLIED MATERIALS  
& INTERFACES



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**Max Planck Institute for Chemical Energy Conversion:** Dr. Jacob Johny, Dr. Marc F. Tesch

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**Research Group:** EMPI-PST team

**Institutional Support:** IMPRS-RECHARGE, ICAN, CENIDE, Prometh<sub>2</sub>eus and H<sub>2</sub>Giga coordination team

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**Examination Committee:** Prof. Dr. Dieter Bathen, Dr. Magnus Liebherr

**Family and friends**



# Thank you for your attention

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