Designing, Growing, and Evaluating Biomaterials with AI

A systems-level workshop on decision-making across the biomaterials lifecycle

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A Biomaterials Journey

Scale up/out

Commercialization

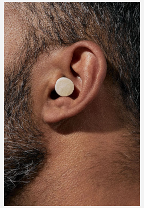
Execution

Research/IP

Innovation

Mycelium-based food scale-up
sold over +2000 stores (500 Wholefoods)

Mycelium textiles R&D for luxury and
consumer electronics




Mycelium foam R&D

Led Data Systems &
Intelligence at Ecovative

Co-founder, CTO of Biorealize
Portable Bioreactor for R&D

UPenn - Faculty
Biodesign (2011-2021)

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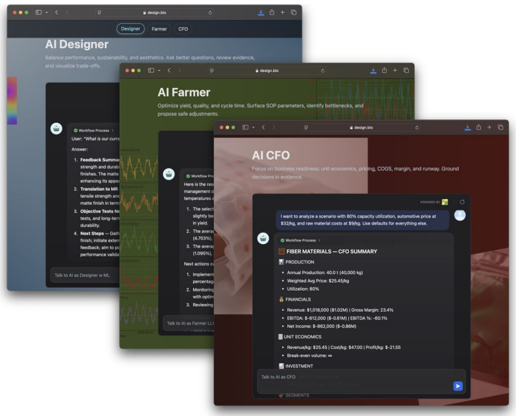
Session Structure

0. Designing or Engineering Biomaterials

1. Designing under uncertainty
2. Operating & Scaling Biomaterials
3. Evaluating Techno-economics
4. Integration & discussion



Test decisions under guided simulations

Learning Outcomes

Systems Reasoning

- Identify where AI can meaningfully support engineering decision-making (in biomaterials)
- Reason about experimental design, process operation, and economics as a coupled system

Trade-off Evaluation

Evaluate trade-offs between technical performance, scalability, and market viability

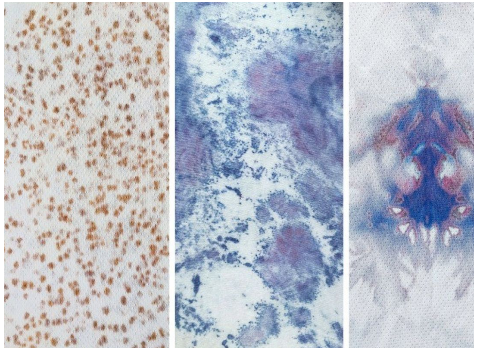
Role of AI

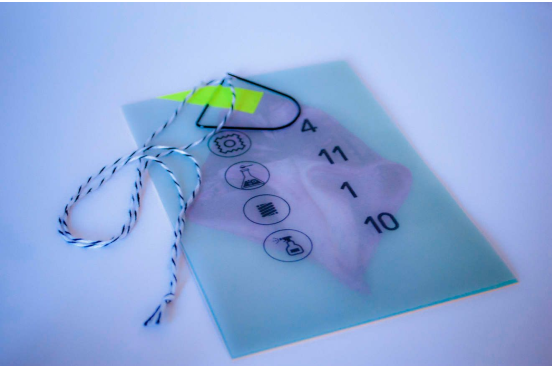
Critically assess the limits of AI in complex biological and manufacturing contexts


CARBON EATERS

MOTHER DIRT
AO+ MIST
RETHINK CLEAN


Bio : p : Cushion

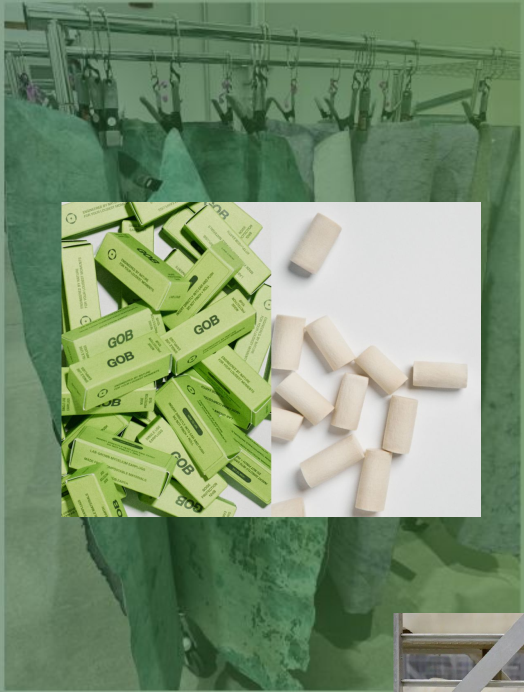

CULTURED COFFEE



4
11
1
10



Vanillin.

ECOVATIVE
DESIGN

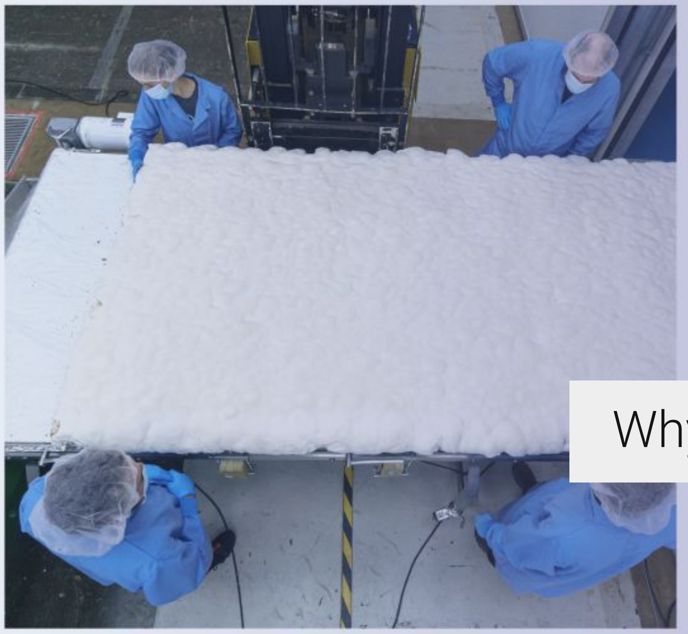


Why This Workshop?

Biomaterials (*and many other innovation*) **often don’t come out of the studio or lab**

— they fail at the boundaries:

- Experiment ↔ Scale
- Process ↔ Economics
- Technical success ≠ Market success



PIVOT-
ABILITY

CAPEX

Investment
readiness

DESTINY
CONTROL

Why things fail?

SCALE-READINESS

RATE of
LEARNING

AI_CFO

uncertainty

Why Biomaterials & AI

- **Using AI for decision-support** across the full biomaterials design lifecycle—from early material innovation, to production and scale-up, to techno-economic evaluation.

- Broadening access, allowing other fields to contribute their expertise.

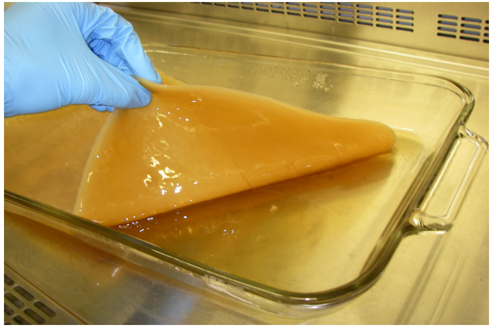
- AI can support three interconnected roles:
  - **Designing** materials under performance and sustainability constraints;
  - **Operating** biological production processes under uncertainty; and
  - **Evaluating** unit economics and market viability.



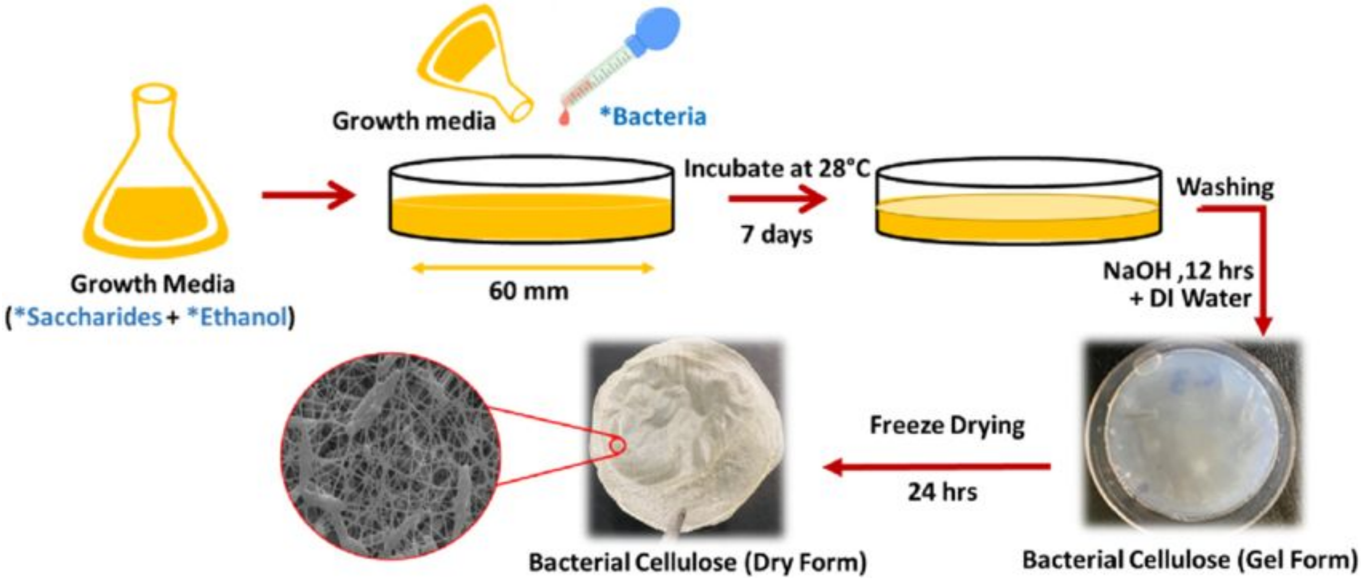




Can we grow a wallet?

How to grow BC pellets at the lab?

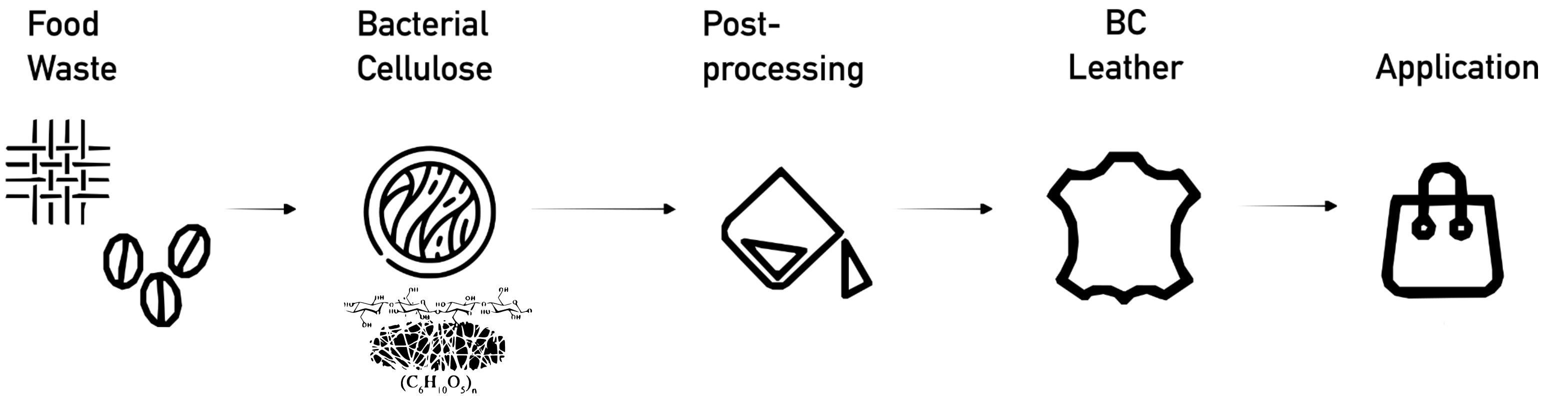


By Francisco X Nascimento

Komagataeibacter xylinus
Nano-scale fibers (~20-100 nm diameter) but forms a macro-scale mat
Pure culture (not SCOBY)

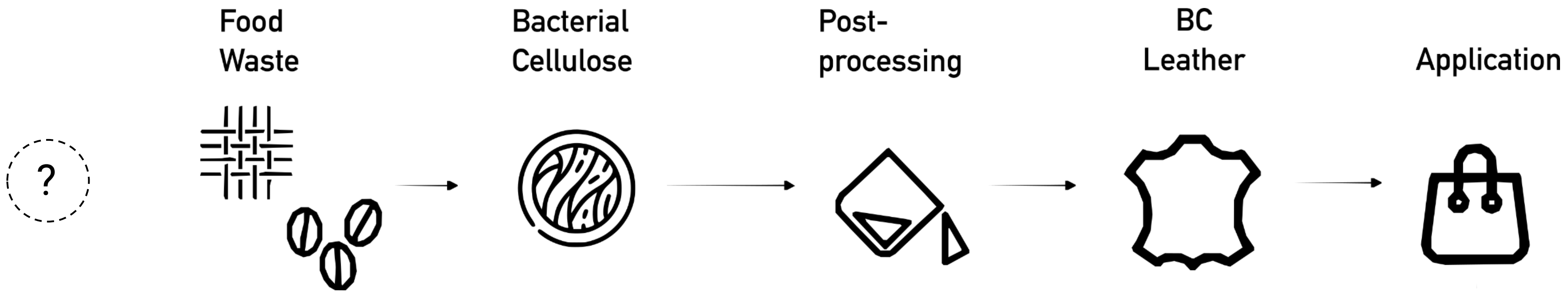
Where do wallets grow?

Scale up Pipeline



Source: **Annah sangosanya** (/textile-academy.org)

Pipeline (of uncertainties)



- Is this a good idea?
- Will it sell?
- Can I make profit?

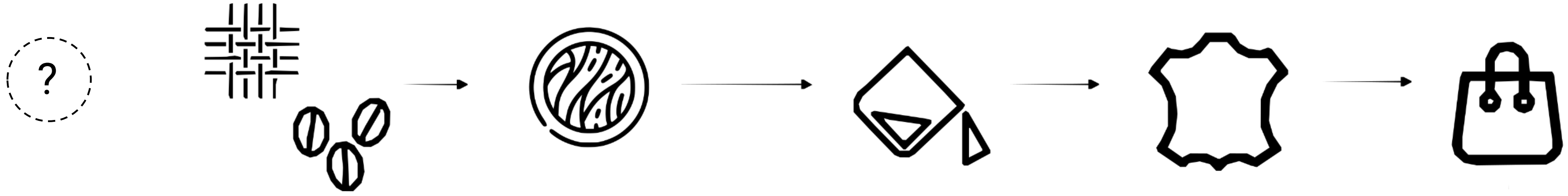
- What are the ingredients?
- Labor costs
- Energy?

- Which organism?
- Which Recipe?

Source: **Annah sangosanya** (/textile-academy.org)

Pipeline (of uncertainties)

Food Waste → Bacterial Cellulose → Post-processing → BC Leather → Application



- Is this a good idea?
- Will it sell?
- Can I make profit?

Food Waste

- What are the ingredients?
- Labor costs
- Energy?

Bacterial Cellulose

- Which organism?
- Which Recipe?

Post-processing

- Can we make it waterproof
- Which color would look best

BC Leather

- Can we scale it?
- Can we make it gross margin positive?

Application

- Will customers buy it?
- How much will they pay?

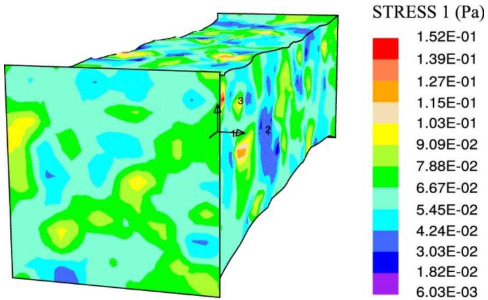
Source: **Annah sangosanya** (/textile-academy.org)

1. Designing Under Uncertainty

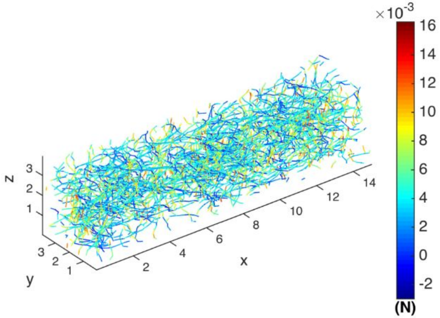
- Translating material performance, sustainability, and aesthetic goals into measurable criteria
- Using AI-assisted analysis to compare formulations, prototypes, and experimental results
- Identifying which uncertainties matter most—and which experiments are worth running next
- Design of Experiments as an economic, not purely statistical, problem

How do we make a reliable material?

How do you use AI for quantitative & quantitative assessment?



(a) Stress σ_{11} (Pa) in the matrix



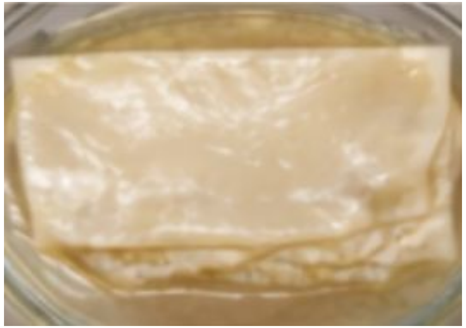
(b) Fiber force f_{fiber} (N) in the network

Jin, T. A computational framework for biomaterials containing three-dimensional random fiber networks based on the affine kinematics. *Biomech Model Mechanobiol* 21, 685–708 (2022). https://doi.org/10.1007/s10237-022-01557-6

Optical Testing

What is uniformity?
(Surface regularity)

What makes a good BC pellicle?



- Growing is expensive
- Testing is expensive
- How do we decide which parameters matters more

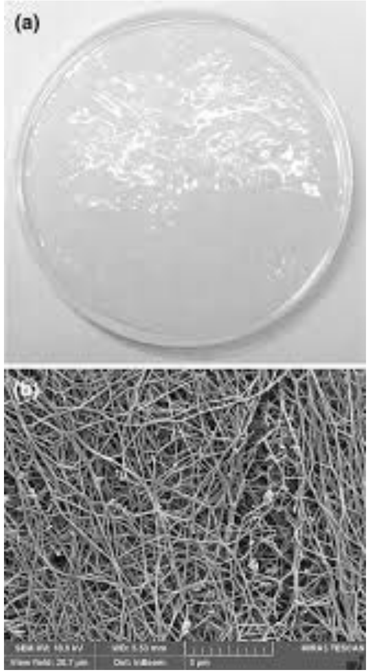
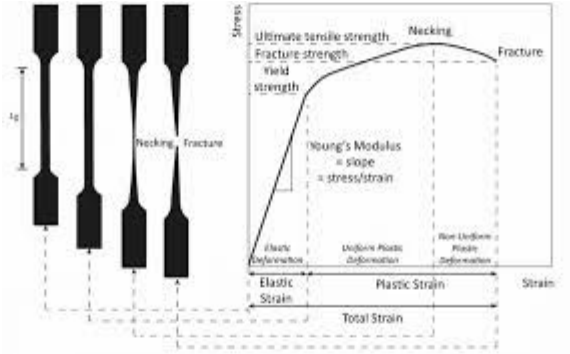
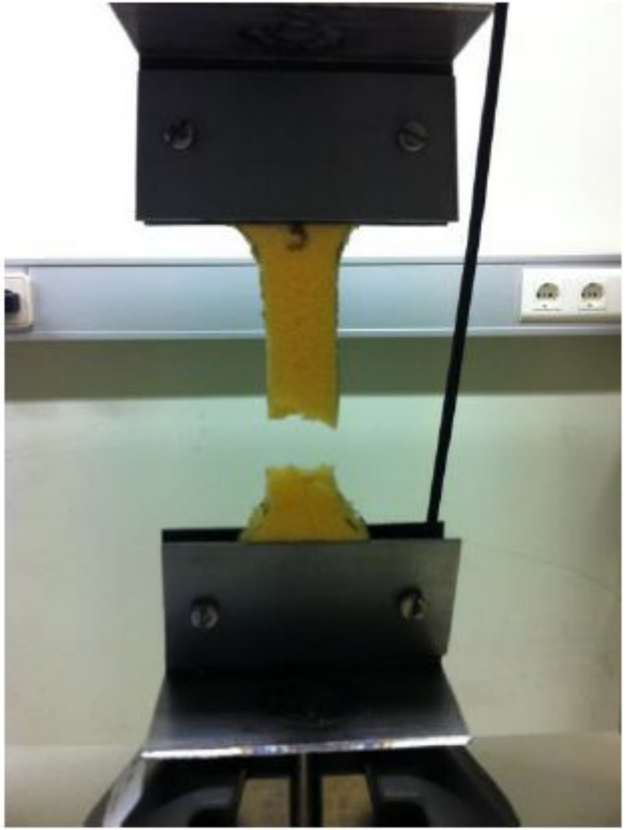
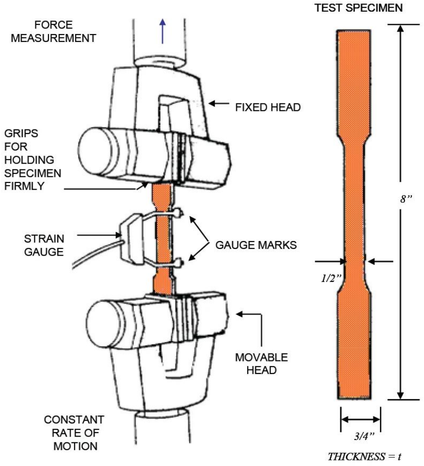


Image → QC
Mechanical Properties

Quality category







Mechanical Testing

What is the tensile strength?

What is elongation at break?

Stiffness?

Which one will the client like?

How do you use AI for qualitative experience?

Preferences

What is the user feedback on the textured finish?
How about color?

AI-ASSISTED DECISION MAKING

Designer/Engineer/Scientist

- Formulation (Recipe) Experiments
- Mechanical Testing
- Product Prototypes
- User feedback forms
- Historical data
- Experience data

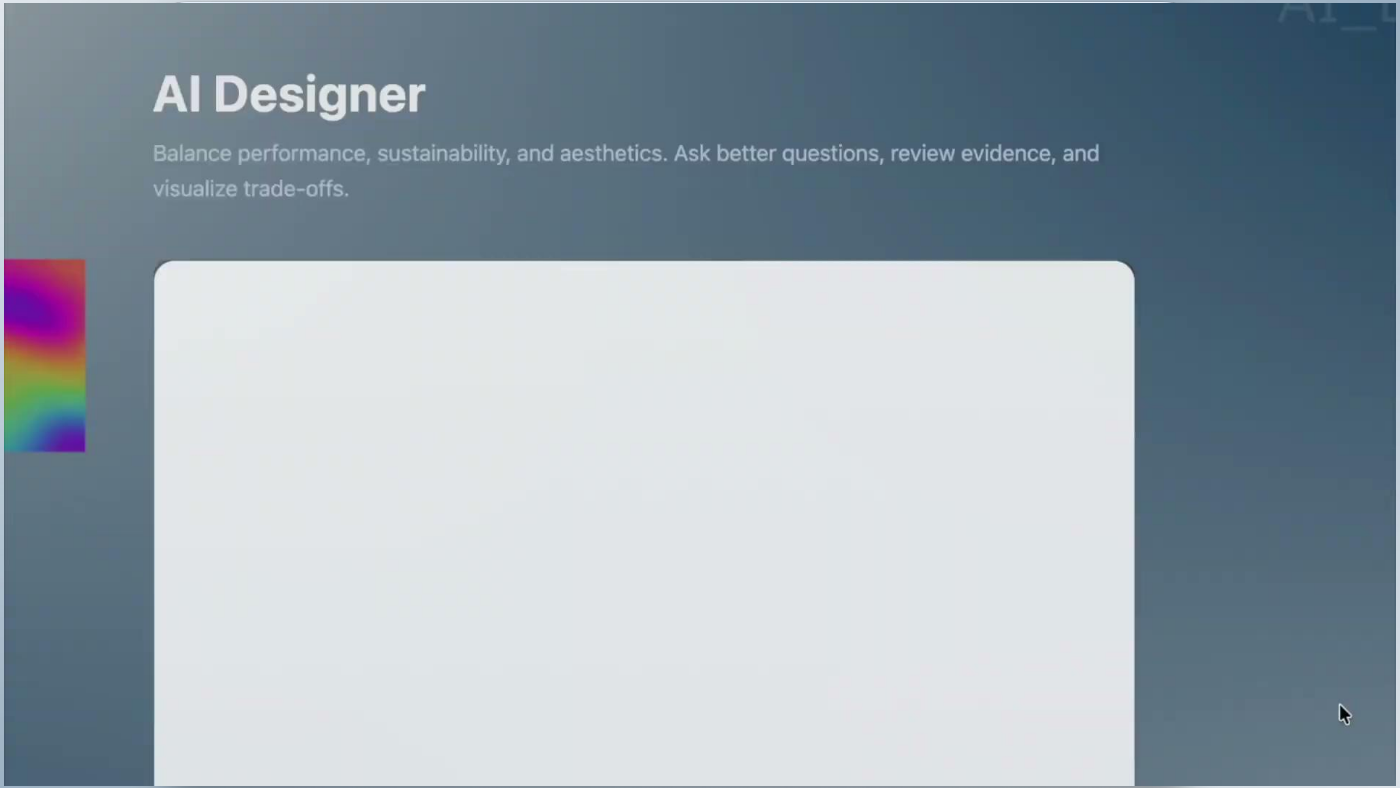
Spreadsheets, recipe databases, forms, ML

AI as DATA MANAGER
AI as KPI TRACKER

AI as ASSUMPTION VALIDATOR
AI as ANALYST

AI as REPORT MAKER
AI as PREDICTOR

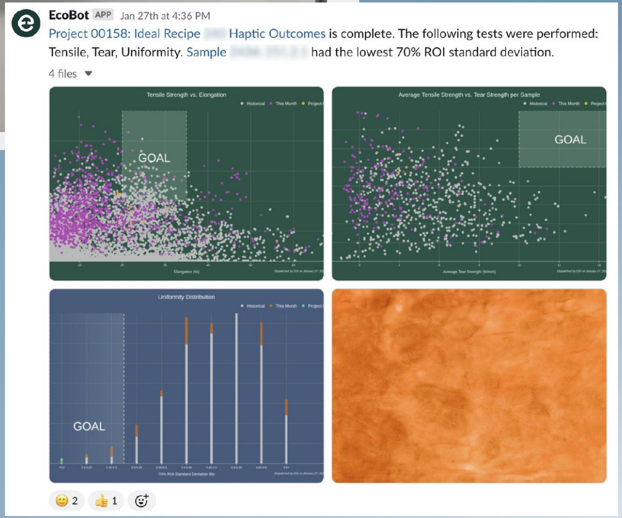
One platform



design.bio/**workshop**

AI as Designer

How does AI support material readiness by helping you navigate the trade-offs between performance, sustainability, and aesthetics?



The material looks good visually, but I’m worried about brittleness. What would be the best next experiment to improve it without losing the surface quality?

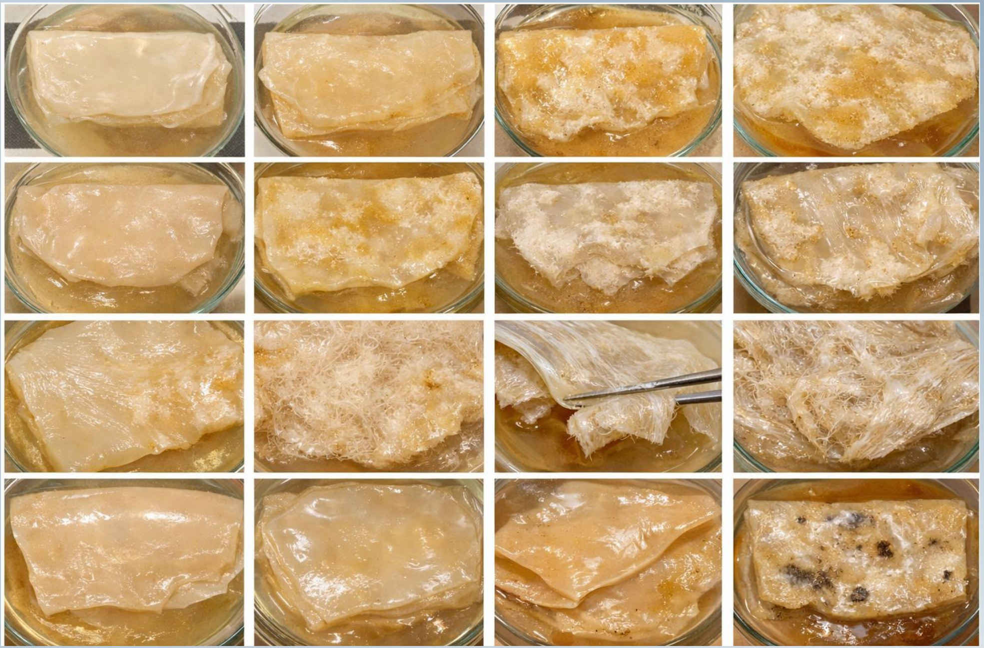
Predicted class: uniform

Top probabilities:

{'contaminated': 0.2413543462753296, 'fiber_texture': 0.0203 05141806602478, 'non_uniform': 0.23074842989444733, 'uniform': 0.5075921416282654}

Classifier Model

Uniform | Non-uniform | Fiber-texture | Contaminated



Regressor Model

- Tensile Strenghth (0-50 MPa)
- Elongation (0-100%)
- Stiffness (0-1)
- Uniformity (0-1)


Uniform
uniform_07.jpg
uniform_07.json
uniform_09.jpg
uniform_08.json
uniform_09.jpg
uniform_19.json
uniform_10.jpg
uniform_10.json
unifcrm_11.jpg
uniform_10.json
unifcrm_12.jpg
uniform_13.json
uniform_14.jpg
uniform_15.json
unifcrm_15.jpg
uniform_16.json
Non-Uniform
non_unifcrm_07.jpg
non_uniform_07.json
non_uniform_07.jpg
non_uniform_08.json
non_uniform_05.jpg
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non_uniform_07.jpg
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Fiber Texture
fiber_texture_01.jpg
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Contaminated
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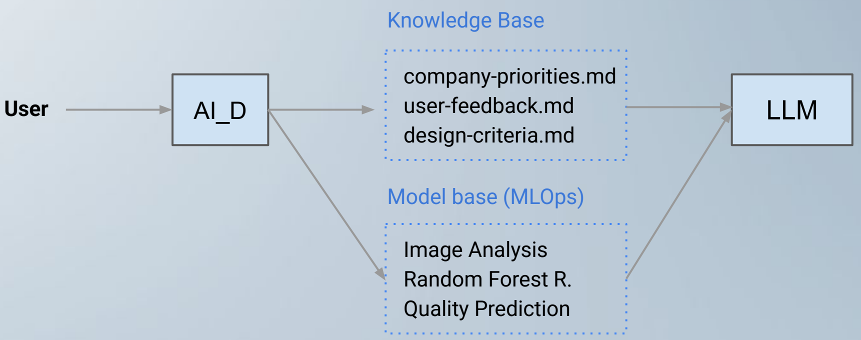
AI Designer



Designer

You are in charge of material readiness, but need to know if you meet performance, sustainability criteria.

You are worried about aesthetics. Which interventions will still yield the best aesthetic results

Questions to AI

- ***Material Readiness (MR1-3)***
  Based on this image, is this material ready to be used as a hanging interior panel, or should I treat it as exploratory? What MR level would you place it in?"
- ***Qualitative DoE:***
  The material looks good visually, but I'm worried about brittleness. What would be the best next experiment to improve it without losing the surface quality?"
- ***Trade-off***
  This sample scores lower on tensile strength but has the most compelling surface texture so far. Is it reasonable to move forward with this version, and what risks should I acknowledge?
- ***Use and Framing***
  If I used this material as-is, what kinds of uses would it be appropriate for, and what should I avoid using it for?

2. Operating & Scaling Biomaterials

- Moving research to production
- Understanding variability in biological production systems
- Using AI to interpret sensor data, detect anomalies, and reason about yield and quality
- Balancing algorithmic insight with human operational knowledge
- Recognizing when increased automation improves robustness—and when it introduces fragility

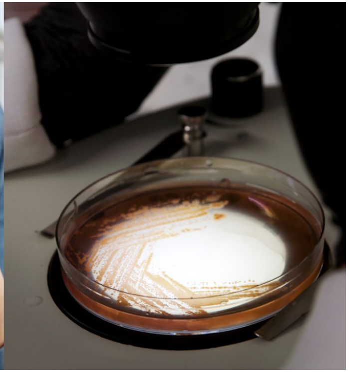
AI as Farmer (Grower)

- How does AI support scale readiness by predicting quality, yield, and production bottlenecks—and by bringing algorithmic insight together with human intuition?

- How do you grow? Move questions from research to operations.

POLYBION

foamlab

ModernSynthesis

AI-ASSISTED DECISION MAKING

Farmer (Grower, Fermenter)

- Inventory management
- Grow conditions
- Product Quality
- Environmental and nutrition recipes
- Control Models
- Experience data

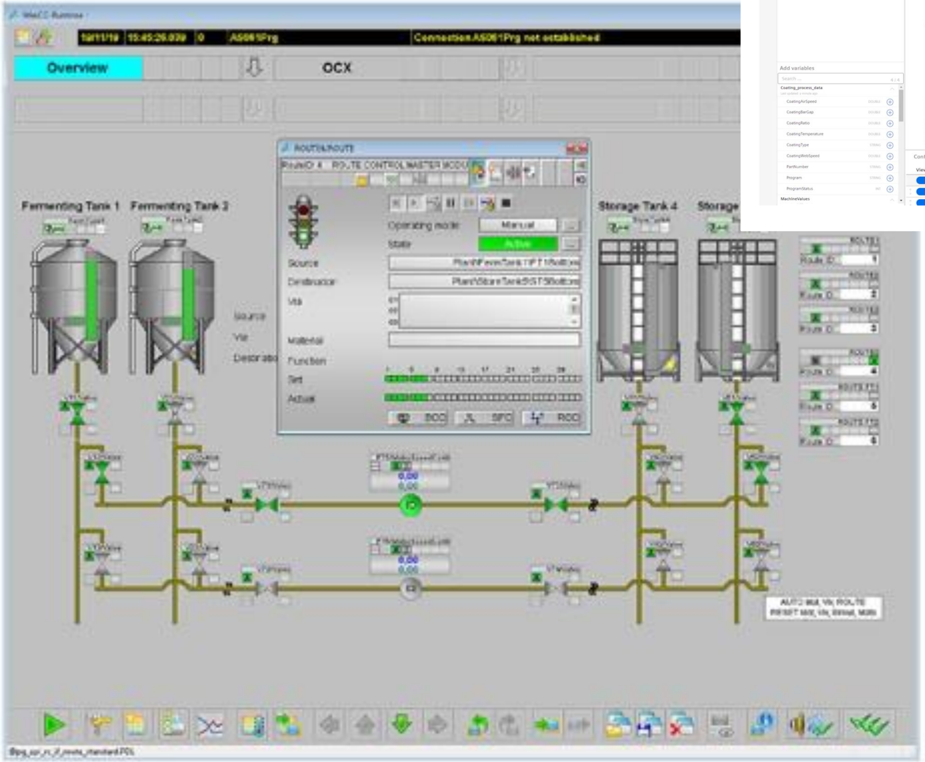
Spreadsheets, Reports, Graphs, Sensor logs

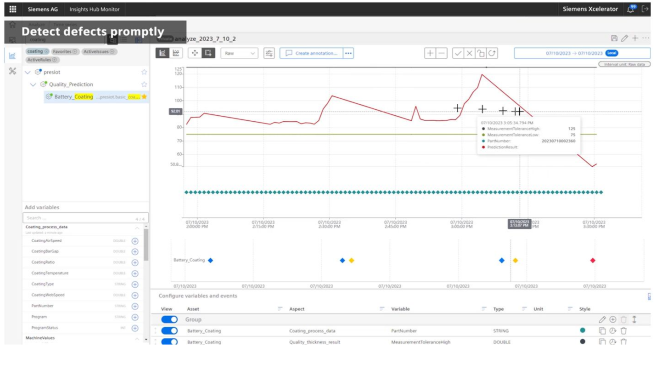
AI as DATA MANAGER
AI as KPI TRACKER

AI as ASSUMPTION VALIDATOR
AI as ANALYST

AI as REPORT MAKER
AI as PREDICTOR

One platform





Environmental monitoring

- **Temperature**: 28-30°C optimal for *Komagataeibacter* (strict control ±1°C)
- **pH**: 4-6 range, typically 5.0 (acetic acid production lowers pH over time)
- **Dissolved oxygen (DO)**: Critical - BC production is aerobic, typically maintain >20% saturation

bc_runs_2024_2025.csv

One row = one fermentation run (static tray batch)

Purpose: operations/anomaly detection, yield benchmarking, run-to-run comparisons.

Identifiers

- run_id *(string, unique)* — e.g., BC_RUN_2024_001
- start_date *(YYYY-MM-DD)*
- end_date *(YYYY-MM-DD)*
- year *(int)*
- recipe *(recipe_1* | *recipe_2* | *recipe_3)*

Process (static tray)

- fermentation_mode *(fixed string: static_tray)*
- fermentation_temp_c *(number)*
- run_period_days *(int)*
- initial_ph *(number)*
- inoculum_pct *(number; v/v %)*

Media

- carbon_source_type *(glucose* | *sucrose* | *glycerol* | *molasses)*
- carbon_concentration_gL *(number)*
- nitrogen_source_type *(yeast_extract* | *peptone* | *mixed* | *none)*
- yeast_extract_gL *(number; allow blank if not used)*
- peptone_gL *(number; allow blank if not used)*

Geometry / scale

- tray_count *(int)*
- tray_area_m2 *(number; total surface area across trays)*
- liquid_depth_cm *(number)*

Run outputs (at harvest)

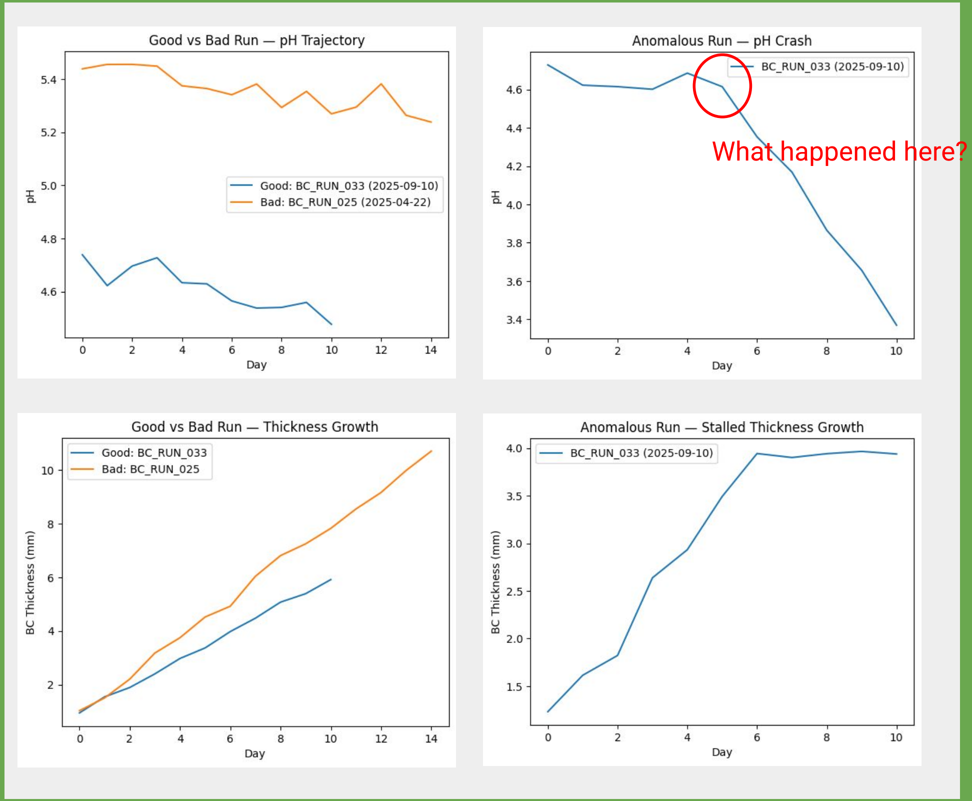
- wet_mass_total_g *(number or blank if not tracked)*
- dry_mass_total_g *(number)*
- yield_per_m2_gm2 *(number; dry_mass_total_g / tray_area_m2)*
- avg_thickness_mm *(number; mean across sampling points)*
- thickness_variation_pct *(number; std/mean*100 across points; optional but very useful)*

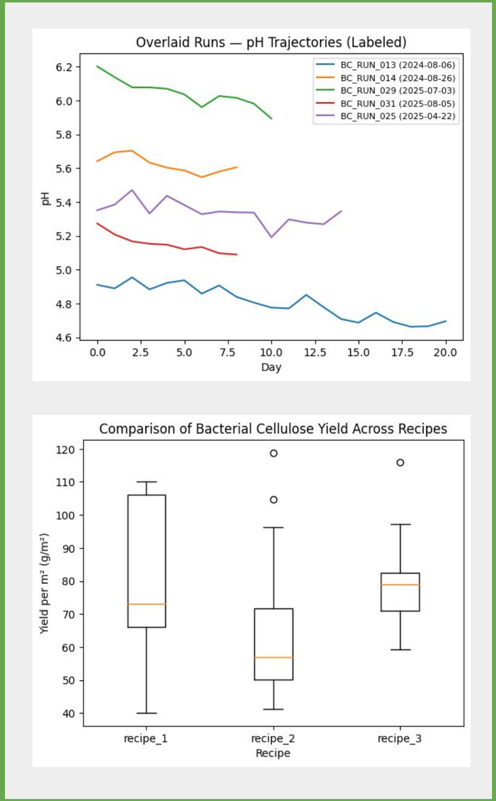
Quality/process flags

- defects_pct *(number; your operational QC score)*
- contamination_flag *(0/1)*
- avg_process_deviation_pct *(number; aggregate deviation metric you already like)*

Notes

- notes *(string; optional)*

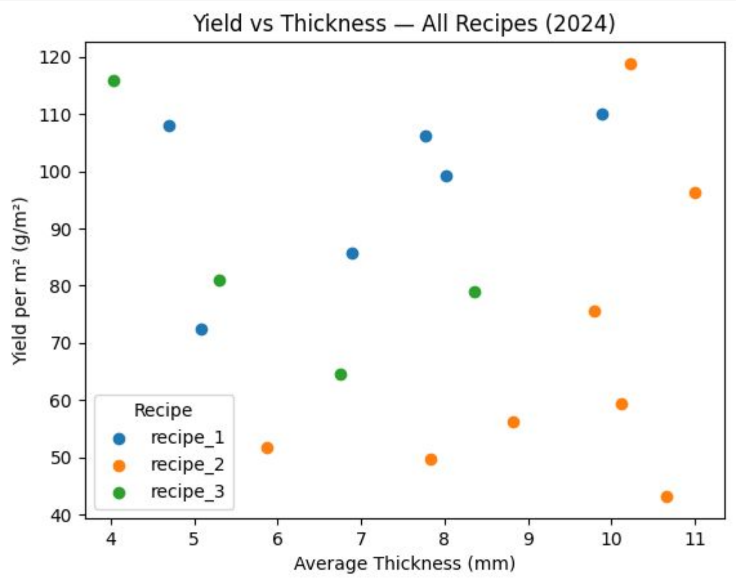


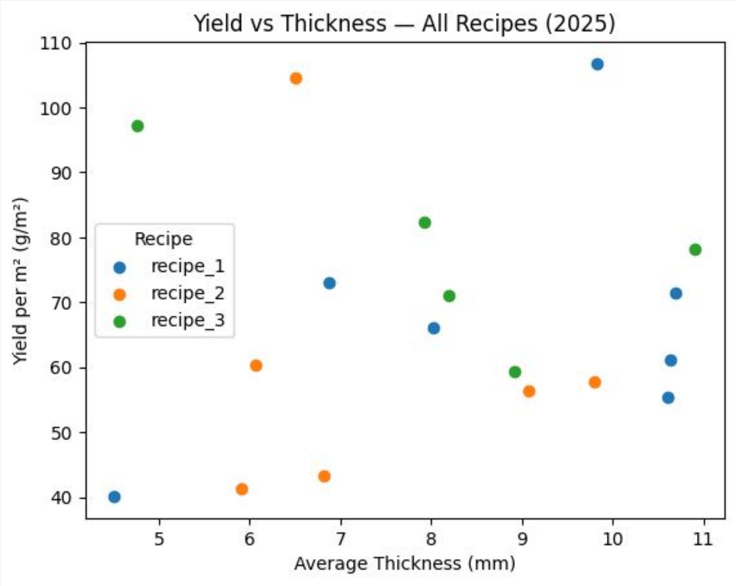


Common issues

Finding causes for deviations

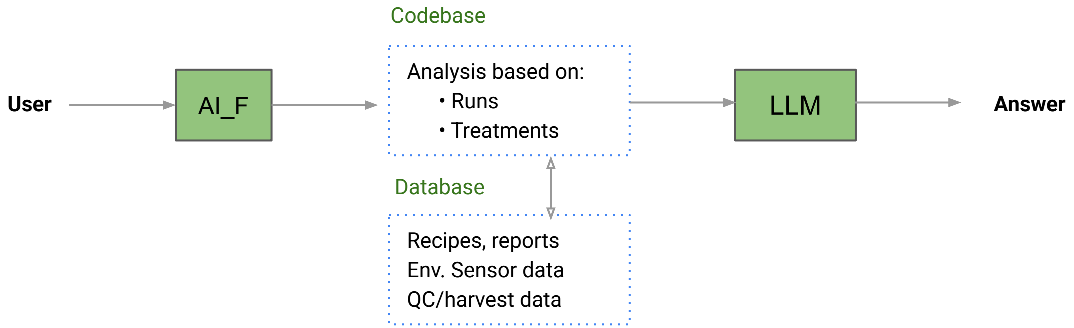
SCALE-UP





Recipe & treatment optimization

AI Farmer



Farmer

Moving from data to insights

What are the insights we can get from our production and treatment runs from 2024-2025?

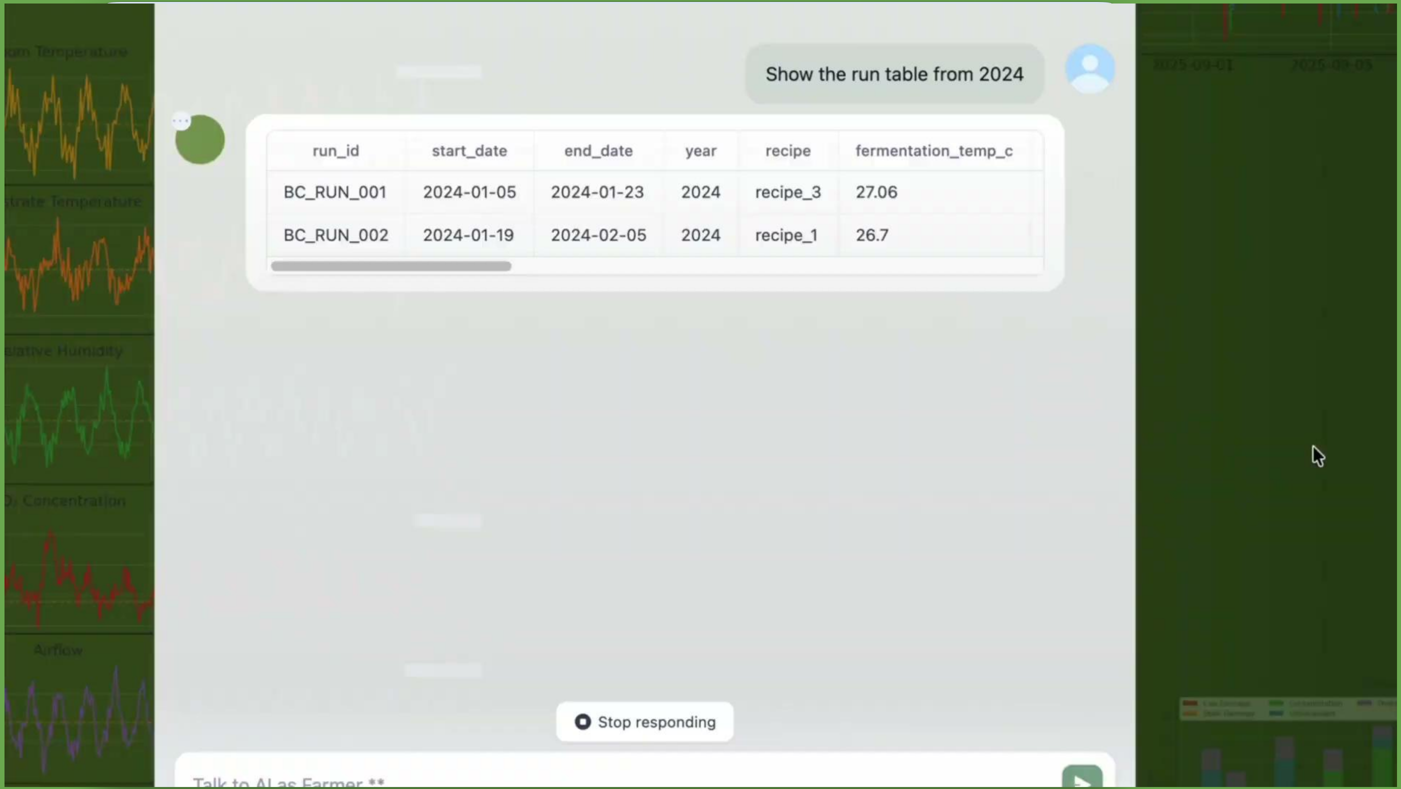
How do you interpret anomalies?

What is unique to a farmer?

Questions to AI Farmer

- ***Production and Yield***
  What was our best recipe for yield in 2024?
  How did total dry mass production change from 2024 to 2025?
- ***Process Inputs → Outputs***
  Which variables explain variation in yield the best?
  Which process parameter most strongly correlates with defects?
- ***Anomaly Detection and Q&C***
  Which runs were flagged as anomalous in 2024 and why?
- ***Recipes and Process Comparison***
  What was our best recipe for yield in 2024?
  Did recipe performance change between 2024 and 2025?

Show yield by recipe as a table



Let’s chat with AI Farmer

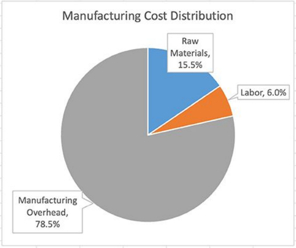
3. Evaluating Techno-economics

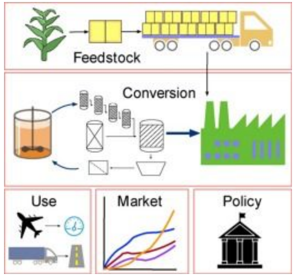
- Moving beyond spreadsheets to link process performance to unit economics
- Exploring how changes in yield, throughput, and recovery affect unit economics, pricing, and total addressable market (TAM)
- Scenario-based evaluation: scale, pivot, or stop
- Treating techno-economic models as living design constraints rather than post-hoc justification

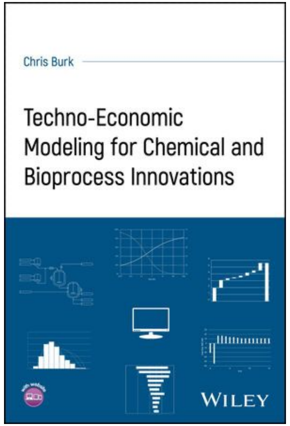
What is TEM?

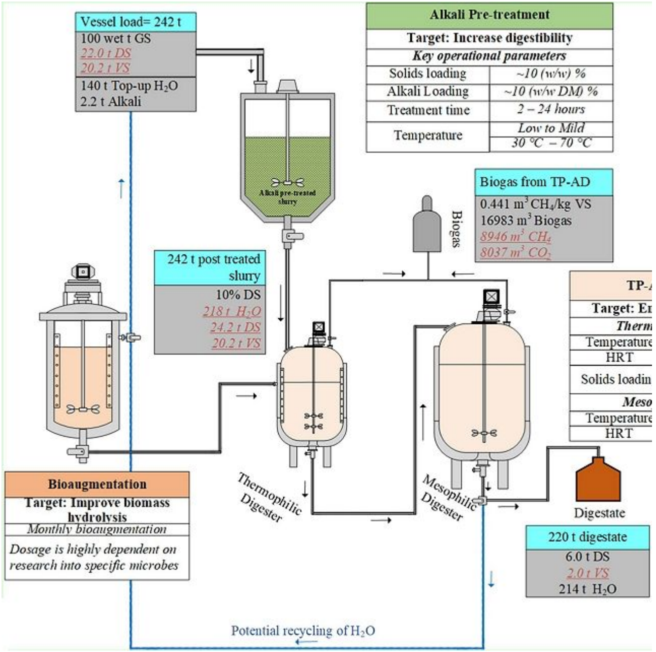
Process Costs	$/GJ	$/year	% of Total
Raw Materials	$ 8	$ 4,180,394	15.5%
Carbon dioxide	$ 8	$ 4,114,924	15.2%
Water	$ 0	$ 20,214	0.1%
Catalyst (annual need)	$ 0	$ 45,257	0.2%
Labor	$ 3	$ 1,620,787	6.0%
Direct labor	$ 1	$ 760,933	2.8%
Indirect labor	$ 1	$ 380,466	1.4%
Fringe	$ 1	$ 479,388	1.8%
Manufacturing Overhead	$ 39	$ 21,209,419	78.5%
Factory floor space	$ 0	$ 6,502	0.0%
Capital equipment	$ 3	$ 1,846,189	6.8%
Maintenance	$ 1	$ 656,204	2.4%
Insurance	$ 0	$ 164,051	0.6%
Utilities - electricity	$ 34	$ 18,536,474	68.6%
Total Manufacturing Cost	$ 50	$ 27,010,600	100.0%

Energy Consumption	Value	Unit	Notes
Process energy per GJ methane produced	1.77	GJ/GJ	energy used by this process to produce one gigajoule of methane



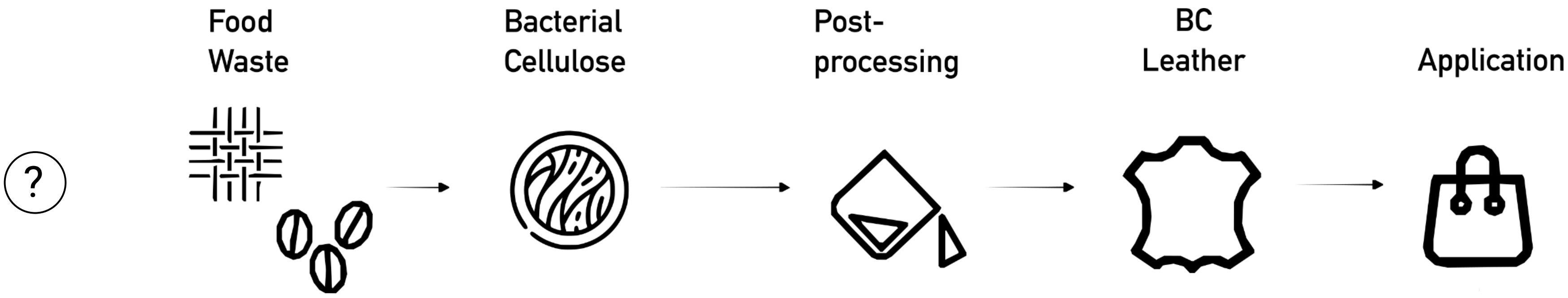






- **Combines technical + financial data**: Links process parameters (yields, energy use, throughput) with costs (CAPEX, OPEX, materials) to assess commercial viability
- **Calculates key metrics**: Produces cost per unit, payback period, ROI, and break-even points for a technology or process
- **Identifies cost drivers**: Shows which technical or operational factors most impact economics, guiding R&D priorities
- **Guides scale-up decisions**: Evaluates whether lab/pilot innovations can compete economically at commercial scale

Evaluation Techno-economics



Should I build this platform, buy it, partner with a company?

Unit cost is too high, should I still make more?

We are not getting the contracts? How do I de-risk?

Source: **Annah sangosanya** (/textile-academy.org)

AI as CFO

- How does this product turn into a business?
  - How does AI support business readiness by going beyond spreadsheets to model unit economics and market realities?

- Tracking econometrics KPIs

- Baking techno-economic model into the everyday of the business

- Why do I need to know about EBITDA

AI_CFO

AI-ASSISTED DECISION MAKING

Finance Officer (CFO)

- Techno-economic models (ML)
- Capital expenditure (CAPEX), Operational expenditure (OPEX)
- Cash, loans, grants
- Term sheets

Spreadsheets, Quickbooks, Finance models

AI as DATA MANAGER	AI as ASSUMPTION VALIDATOR	AI as REPORT MAKER
AI as KPI TRACKER	AI as ANALYST	AI as PREDICTOR

One platform

🏭 Bacterial Cellulose Techno Economic Evaluation

I will help you analyze the techno-aesthetic-economic (TAE) performance of your **bacterial cellulose** system. You can use the **default values** as a starting point and override only what you want to change.

📊 PRODUCTION PARAMETERS

- **Production Capacity**: What's your annual production capacity? *(default: 60 tonnes)*
- **Capacity Utilization**: What percentage of capacity are you currently using? *(default: 75%)*

💰 PRICING BY SEGMENT (per kg)

- **Fashion Segment**: Current selling price *(default: $20.00/kg)*
- **Automotive Segment**: Current selling price *(default: $30.00/kg)*
- **Upholstery Segment**: Current selling price *(default: $25.00/kg)*

🎯 MARKET MIX (percentages should total 100%)

- **Fashion Mix**: What % of production goes to fashion? *(default: 40%)*
- **Automotive Mix**: What % goes to automotive? *(default: 35%)*
- **Upholstery Mix**: What % goes to upholstery? *(default: 25%)*

🧪 YIELD & QUALITY (TAE core)

- **Fashion Contamination Loss:** % lost to failed runs *(default: **8%**)*
- **Drying/Finishing Loss:** % lost during drying/trimming *(default: **10%**)*
- **Design-Grade Pass Rate:** % meeting aesthetic/quality criteria *(default: **70%**)*

🔧 VARIABLE COSTS (per kg)

- **Raw Materials**: Cost per kg *(default: $8.00)*
- **Energy**: Cost per kg *(default: $3.50)*
- **Labor**: Cost per kg *(default: $2.50)*
- **Maintenance**: Cost per kg *(default: $1.50)*
- **Quality Control**: Cost per kg *(default: $1.00)*
- **Packaging & Logistics**: Cost per kg *(default: $2.00)*

🔧 🧪 PROCESS / TREATMENT (farm-app fields)

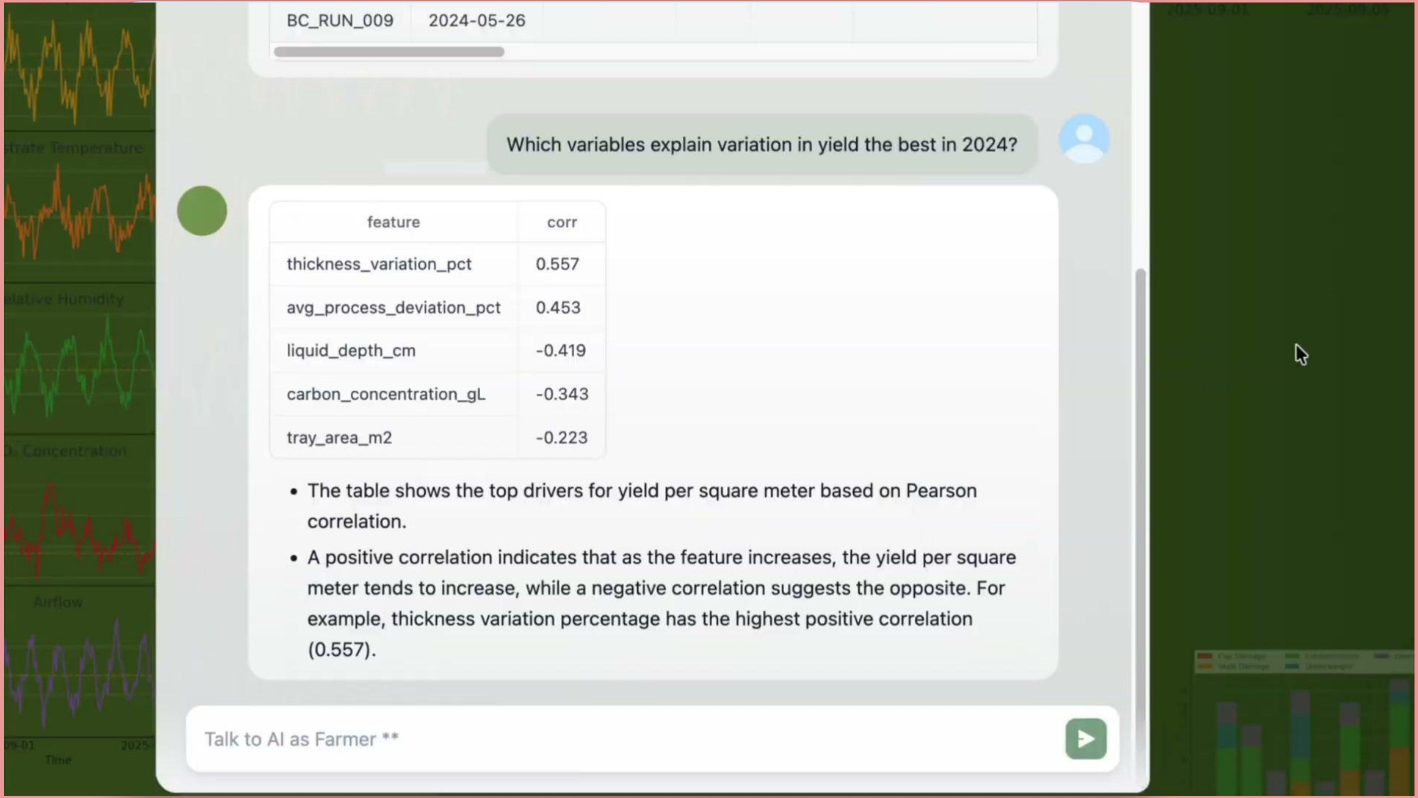
- **Drying Method:** *(default: air_dry)*
- **Pressing Level:** *(default: none)*
- **Conditioning RH:** *(default: 50% RH)*
- **Conditioning Temp:** *(default: 23°C)*
- **Final Moisture:** *(default: 10%)*
- **Plasticizer Type:** *(default: none)*
- **Plasticizer %:** *(default: 0%)*

🏢 FIXED COSTS & INVESTMENT (in millions)

- **Initial CAPEX**: Total capital investment *(default: $2.5M)*
- **Annual Fixed Costs**: Facilities, insurance, etc. *(default: $0.4M)*
- **R&D Investment**: Annual R&D spending *(default: $0.15M)*
- **Marketing & Sales**: Annual budget *(default: $0.1M)*
- **Corporate Overhead**: Annual overhead *(default: $0.2M)*

📈 FINANCIAL ASSUMPTIONS

- **Depreciation Period**: Equipment life in years *(default: 10 years)*
- **Discount Rate**: Cost of capital *(default: 12%)*
- **Tax Rate**: Corporate tax rate *(default: 25%)*



Let’s chat with AI CFO

- Guardrails
- Validation
- Intention discovery

Good **Ideas** vs Good **Businesses**

Scenario-driven Evaluation

Everything looks great, but why doesn't scale up?

What are my options?

Risk Assessment

What is in my blindspot?

The product quality is not improving, where else can I focus

Basic Economics

What are these terms?

- EBITDA:
- CAPEX
- Gross Margin+

TL;DR:

1. **Sellable yield** (biology + process)
2. **Unit margin** (price − variable cost)
3. **Scale** (spreading fixed costs)

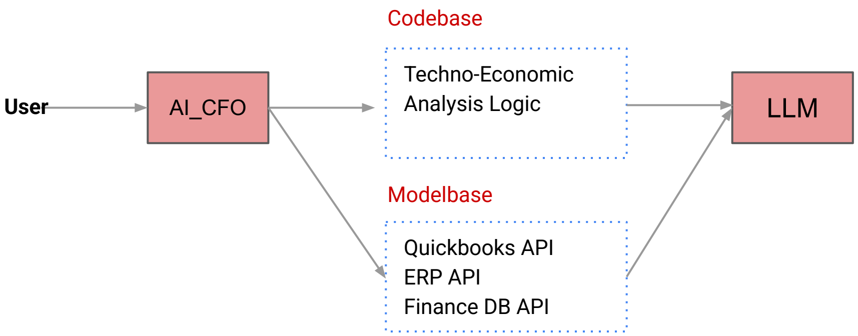
REVENUE: Total money the business earns
EBITDA: Earnings before Interest, Taxes, Depreciation, Amortization
EBITDA: What's left after subtracting operating costs from revenue (but before interest, taxes, depreciation, and amortization)
How well the business runs day-to-day, excluding financial decisions.

AI_CFO

You don't really need to remember calculations

```
# --- Calculations ---
  util = capacity_utilization_percent / 100.0
  mix_f, mix_a, mix_u = fashion_mix_percent/100.0, automotive_mix_percent/100.0,
upholstery_mix_percent/100.0
  dr, tax_rate = discount_rate_percent/100.0, tax_rate_percent/100.0

  prod_t = production_capacity_tonnes * util
  prod_kg = prod_t * 1000.0

  avg_price = fashion_price*mix_f + automotive_price*mix_a + upholstery_price*mix_u
  var_cost = raw_material_cost + energy_cost + labor_cost + maintenance_cost +
quality_control_cost + packaging_logistics_cost

  revenue = prod_kg * avg_price
  var = prod_kg * var_cost
  gp = revenue - var
  gm_pct = (gp/revenue*100.0) if revenue > 0 else 0.0

  capex_dollars = initial_capex * 1_000_000.0
  fixed_total = (annual_fixed_costs + rd_investment + marketing_sales + corporate_overhead)
* 1_000_000.0
  dep = capex_dollars / max(depreciation_period_years, 1)

  ebitda = gp - fixed_total
  ebit = ebitda - dep
  ebt = ebit
  taxes = max(0.0, ebt*tax_rate) if ebt > 0 else 0.0
  ni = ebt - taxes

  rev_kg, fixed_kg = avg_price, (fixed_total+dep)/prod_kg if prod_kg > 0 else 0.0
  cost_kg, profit_kg = var_cost + fixed_kg, rev_kg - (var_cost+fixed_kg)

  payback = (capex_dollars/ni) if ni > 0 else float("inf")
  roi_pct = (ni/capex_dollars*100.0) if capex_dollars > 0 else 0.0

  npv = -capex_dollars
  for y in range(1, 6):
    npv += ni/((1.0+dr)**y)

  rev_f, rev_a, rev_u = revenue*mix_f, revenue*mix_a, revenue*mix_u
```

AI CFO



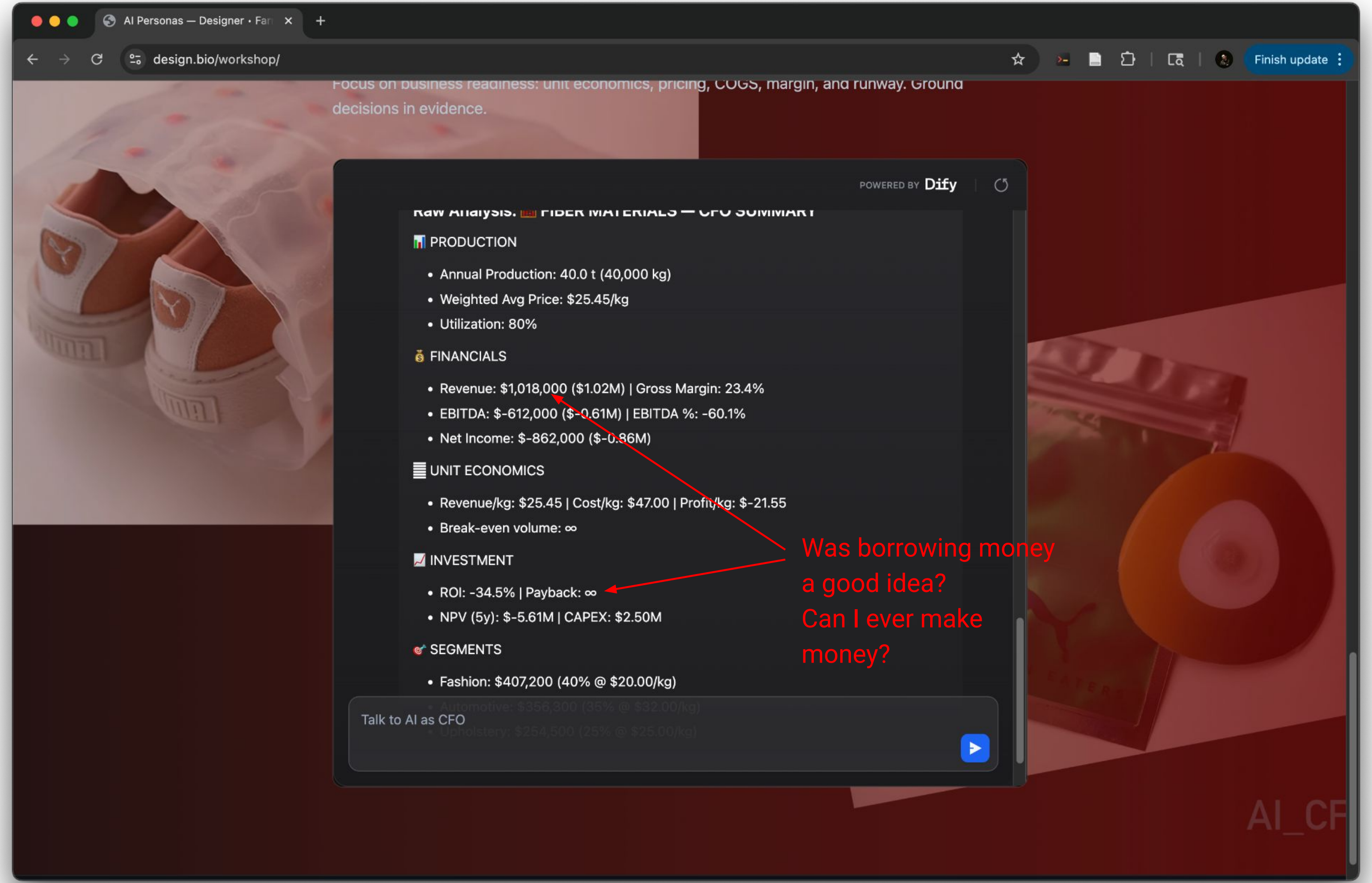
Human CFO

- What is our burn-rate? Where is the money spent?
- Where are our bottlenecks (i.e., supply-side or demand-side)
- What is ROI expectations?
- What are our capacity requirements?

Questions to AI CFO

- Run the baseline scenario using all defaults.
- Why is EBITDA negative?
- Which costs are most damaging at small scale?
- What is driving profit/kg?
- What should I change to improve this?

- Run a scenario at 90% capacity utilization. Use defaults for everything else.
- What happens if capacity utilization drops to 60%?
- Run a scenario with contamination loss reduced to 4%.
- What if all sellable material goes to fashion at $30/kg?


AI Personas — Designer • Far
design.bio/workshop/
Finish update
Focus on business readiness: unit economics, pricing, COGS, margin, and runway. Ground decisions in evidence.
POWERED BY Dify
Raw Analysis: FIBER MATERIALS — CFO SUMMARY
PRODUCTION
• Annual Production: 40.0 t (40,000 kg)
• Weighted Avg Price: $25.45/kg
• Utilization: 80%
FINANCIALS
• Revenue: $1,018,000 ($1.02M) | Gross Margin: 23.4%
• EBITDA: $-612,000 ($-0.61M) | EBITDA %: -60.1%
• Net Income: $-862,000 ($-0.86M)
UNIT ECONOMICS
• Revenue/kg: $25.45 | Cost/kg: $47.00 | Profit/kg: $-21.55
• Break-even volume: ∞
INVESTMENT
• ROI: -34.5% | Payback: ∞
• NPV (5y): $-5.61M | CAPEX: $2.50M
SEGMENTS
• Fashion: $407,200 (40% @ $20.00/kg)
Talk to AI as CFO
Was borrowing money a good idea?
Can I ever make money?
AI_CF

Can we ever make money?

Fast Strategy

- Focus on **design-grade quality**
- Sell into **premium segments early**
- Accept higher costs temporarily

Primary levers

- ↑ **Design-grade pass rate** (→ 85–95%)
- ↑ **Grade A mix / price multipliers**
- Target **fashion / specialty interiors**
- Maintain **tight process control**

1. **What happens if the design-grade pass rate increases to 90%, using defaults for everything else?**
2. **Now assume premium pricing: fashion price $30/kg, automotive $40/kg, with the same 90% pass rate.**
3. **What if all sellable material goes to fashion at $30/kg?**

Slow Strategy

- Focus on **biological reliability**
- Drive down **unit costs**
- Scale gradually to amortize fixed costs

Primary levers

- ↓ **Contamination & drying losses**
- ↑ **Capacity utilization** (80–95%)
- ↓ **Raw material / energy / labor costs**
- Expand **sellable volume**

1. **Reduce contamination loss to 2% and drying loss to 5%, using default pricing.**
2. **Increase capacity utilization to 90% and annual capacity to 120 tonnes.**
3. **Reduce raw material cost to $6/kg and energy cost to $2.5/kg at the same scale.**

What are your levers?

Scale & Throughput (Volume Levers)

How much material you can sell.

- **Annual production capacity** (tonnes/year)
  → Bigger plant vs pilot scale
- **Capacity utilization (%)**
  → How hard you run the system
- **Batch cycle time (days)** *(advanced)*
  → Faster cycles = more runs per year

Yield & Quality (Material Levers)

How much of what you grow is sellable.

- **Design-grade pass rate* (%)**
  → Core quality lever
- **Contamination loss (%)**
  → Biological reliability
- **Drying loss (%)**
  → Process damage / shrinkage

Market Position (Price Lever)

What customers are willing to pay

- **Fashion price** ($/kg)
- **Automotive price** ($/kg)
- **Upholstery price** ($/kg)
- **Market mix** (%)
  → How production is allocated across segments
- **Grade price multipliers** (A / B / C)
  → Monetizing quality differences

What are your levers?

Variable Costs (Efficiency - Unit cost)

How much each kg costs to make.

- **Raw material cost** ($/kg)
- **Energy cost** ($/kg)
- **Labor cost** ($/kg)
- **Maintenance cost** ($/kg)
- **Quality control cost** ($/kg)
- **Packaging & logistics** ($/kg sellable)

Process Choices (Treatment Levers)

Affect yield, quality, and cost indirectly.

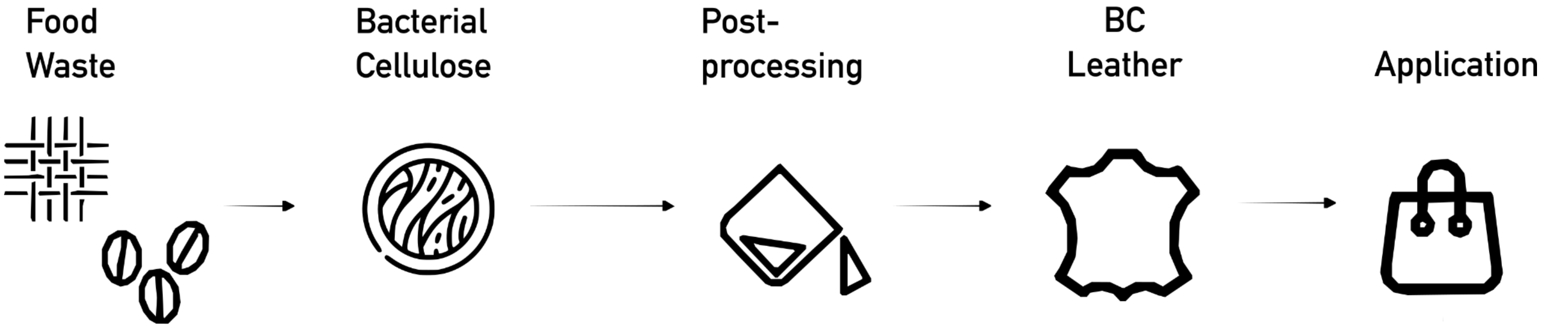
- **Drying method** (air | oven | press)
- **Pressing level** (none | light | heavy)
- **Conditioning** (RH, Temp)
- **Plasticizer** (Type & %)

Fixed Costs (Business Model Decisions)

What customers are willing to pay

- **Initial Capex** ($M)
- **Annual fixed costs** ($M) (facilities, R&D, sales, overhead)

Discussion/Integration



A designer, farmer, and CFO walks into a bar…

biodesignchallenge.org

@Columbia check out:

- Lola Ben-Alon, GSAPP
- Tal Danino, Bioengineering
- Theanne Schiros, Research Scientist

PDL Survey 2026

orkan@design.bio | **Orkan Telhan**, PhD

Appendix

AI-ASSISTED DECISION MAKING

Designer/Engineer/Scientist

- Formulation (Recipe) Experiments
- Mechanical Testing
- Product Prototypes
- User feedback forms
- Historical data
- Experience data

Spreadsheets, recipe databases, forms, ML

Farmer (Grower, Fermenter)

- Inventory management
- Grow conditions
- Product Quality
- Environmental and nutrition recipes
- Control Models
- Experience data

Spreadsheets, Reports, Graphs, Sensor logs

Finance Officer (CFO)

- Techno-economic models (ML)
- Capital expenditure (CAPEX), Operational expenditure (OPEX)
- Cash, loans, grants
- Term sheets

Spreadsheets, Quickbooks, Finance models

AI as DATA MANAGER
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AI as PREDICTOR

One platform

Image Classifier: What type of material does this look like?

- Takes an image and assigns it to one of four visual categories (uniform, non-uniform, fiber-textured, contaminated)
- Uses a pretrained vision model to extract texture features
- Learns only a small decision layer on top
- Output = category + confidence

```
Predictions:
  non_uniform      0.5828
  uniform          0.2454
  contaminated     0.1128
  fiber_texture    0.0590

non_uniform (0.5828)
```

This model names surface conditions it has seen before.

Image Regressor: What properties might this material have?

- Takes the same image features
- Predicts continuous values (stiffness, strength, elongation, uniformity)
- Trained on proxy labels, not physical measurements
- Output = estimated numbers with uncertainty

{'uniformity_score':
0.5486684441566467,
'stiffness_index':
0.38718467950820923,
'elongation_pct':
8.714523315429688,
'tensile_strength_mpa':
43.994346618652344}

This model *infers numbers* from visual similarity, not material physics.

bc_runs_2024_2025.csv

One row = one fermentation run (static tray batch)

Purpose: operations/anomaly detection, yield benchmarking, run-to-run comparisons.

Identifiers

- run_id *(string, unique)* — e.g., BC_RUN_2024_001
- start_date *(YYYY-MM-DD)*
- end_date *(YYYY-MM-DD)*
- year *(int)*
- recipe *(recipe_1* | *recipe_2* | *recipe_3)*

Process (static tray)

- fermentation_mode *(fixed string: static_tray)*
- fermentation_temp_c *(number)*
- run_period_days *(int)*
- initial_ph *(number)*
- inoculum_pct *(number; v/v %)*

Media

- carbon_source_type *(glucose* | *sucrose* | *glycerol* | *molasses)*
- carbon_concentration_gL *(number)*
- nitrogen_source_type *(yeast_extract* | *peptone* | *mixed* | *none)*
- yeast_extract_gL *(number; allow blank if not used)*
- peptone_gL *(number; allow blank if not used)*

Geometry / scale

- tray_count *(int)*
- tray_area_m2 *(number; total surface area across trays)*
- liquid_depth_cm *(number)*

Run outputs (at harvest)

- wet_mass_total_g *(number or blank if not tracked)*
- dry_mass_total_g *(number)*
- yield_per_m2_gm2 *(number; dry_mass_total_g / tray_area_m2)*
- avg_thickness_mm *(number; mean across sampling points)*
- thickness_variation_pct *(number; std/mean*100 across points; optional but very useful)*

Quality/process flags

- defects_pct *(number; your operational QC score)*
- contamination_flag *(0/1)*
- avg_process_deviation_pct *(number; aggregate deviation metric you already like)*

Notes

- notes *(string; optional)*

AI_FARMER

bc_runs_2024_2025.csv

bc_runs_2024_2025

run_id	start_date	end_date	year	recipe	fermentation_mode	fermentation_temp_c	run_period_days	initial_ph	inoculum_pct	carbon_source_type	carbon_concentration_gL	nitrogen_source_type	yeast_extract_gL	peptone_gL	tray_count	tray_area_m2	liquid_depth_cm	wet_mass_total_g	dry_mass_total_g	yield_per_m2_gm2	avg_thickness_mm	thickness_variation_pct	defects_pct	contamination_flag	avg_process_deviation_pct	notes
BC_RUN_001	2024-01-05	2024-01-23	2024	recipe_3	static_tray	27.06	18	4.65	9.35	sucrose	25.72	mixed	4.58	5.61	7	4.85	2.27	7307.41	313.51	64.64	6.75	13.44	12.76	0	1.15	
BC_RUN_002	2024-01-19	2024-02-05	2024	recipe_1	static_tray	26.7	17	5.84	13.5	glucose	45.2	mixed	4.15	4.07	9	5.63	1.93	13349.2	608.62	108.1	4.7	10.76	11.82	1	1.16	
BC_RUN_003	2024-02-07	2024-02-19	2024	recipe_1	static_tray	27.1	12	5.27	8.82	glucose	54.58	mixed	4.11	4.38	4	2.52	2.03	5880.27	216.24	85.81	6.89	16.69	4.89	0	1.28	
BC_RUN_004	2024-02-26	2024-03-08	2024	recipe_1	static_tray	28.67	11	5.25	12.25	glucose	55.81	mixed	5.21	4.47	9	5.37	1.94	11487.19	388.87	72.42	5.08	13.09	10.92	0	0.83	
BC_RUN_005	2024-03-15	2024-03-31	2024	recipe_2	static_tray	26.38	16	5.86	9.22	glucose	55.71	mixed	4.51	4.19	7	4.56	2.41	5484.16	196.86	43.17	10.66	7.61	10.32	0	1.33	
BC_RUN_006	2024-03-31	2024-04-11	2024	recipe_1	static_tray	27.07	11	4.9	8.98	sucrose	42.37	mixed	3.7	3.53	7	3.85	1.84	10165.59	423.83	110.09	9.89	15.01	12.25	0	1.36	
BC_RUN_007	2024-04-21	2024-05-12	2024	recipe_3	static_tray	26.71	21	5.17	13.52	sucrose	34.58	mixed	5.44	4.21	4	1.65	2.79	3460.26	133.77	81.07	5.3	15.37	11.29	0	1.88	
BC_RUN_008	2024-05-10	2024-05-30	2024	recipe_3	static_tray	26.88	20	5.44	10.18	glucose	46.94	mixed	3.79	4.58	9	3.65	2.66	8610.78	288.52	79.05	8.36	12.81	16.56	1	1.54	
BC_RUN_009	2024-05-26	2024-06-08	2024	recipe_2	static_tray	27.85	13	5.16	10.23	sucrose	61.98	mixed	4.92	5.59	6	4.1	2.08	10421.53	395.26	96.4	11.0	11.25	7.24	0	1.51	
BC_RUN_010	2024-06-11	2024-06-29	2024	recipe_2	static_tray	26.04	18	5.91	13.41	sucrose	45.64	mixed	5.31	5.6	7	4.78	3.19	7400.61	283.59	59.33	10.11	4.33	6.35	0	0.79	
BC_RUN_011	2024-07-02	2024-07-18	2024	recipe_1	static_tray	26.73	16	5.68	10.21	glucose	33.93	mixed	4.95	4.53	5	2.32	2.05	6188.01	230.12	99.19	8.01	14.78	8.29	1	2.16	
BC_RUN_012	2024-07-17	2024-07-31	2024	recipe_1	static_tray	26.95	14	6.1	12.57	glucose	27.33	mixed	3.01	3.53	6	3.82	1.72	10294.08	405.53	106.16	7.77	11.16	5.87	0	1.79	
BC_RUN_013	2024-08-06	2024-08-27	2024	recipe_2	static_tray	26.15	21	4.96	8.1	sucrose	52.42	mixed	3.44	3.62	4	2.06	1.51	2900.34	106.58	51.74	5.87	6.59	14.97	0	0.81	
BC_RUN_014	2024-08-26	2024-09-04	2024	recipe_2	static_tray	26.42	9	5.66	12.54	glucose	53.33	mixed	3.73	5.36	8	5.35	2.29	8676.7	404.38	75.59	9.79	12.13	6.63	0	1.61	
BC_RUN_015	2024-09-12	2024-10-02	2024	recipe_2	static_tray	26.37	20	5.58	8.25	glucose	37.21	mixed	5.67	3.61	5	2.56	2.66	2918.87	127.4	49.77	7.83	14.03	10.29	0	0.69	
BC_RUN_016	2024-10-01	2024-10-19	2024	recipe_2	static_tray	26.46	18	4.59	11.86	glucose	41.69	mixed	4.08	5.63	4	2.32	2.07	6415.42	275.66	118.82	10.22	13.02	7.26	0	0.99	
BC_RUN_017	2024-10-17	2024-11-01	2024	recipe_2	static_tray	29.71	15	5.92	9.31	glucose	66.9	mixed	3.88	5.02	8	4.64	1.88	7086.62	260.8	56.21	8.82	7.71	16.11	0	1.04	
BC_RUN_018	2024-11-02	2024-11-21	2024	recipe_3	static_tray	26.37	19	5.36	6.95	sucrose	34.67	mixed	5.29	5.81	4	1.66	1.58	4750.49	192.35	115.87	4.04	17.99	2.76	0	1.46	
BC_RUN_019	2025-01-05	2025-01-23	2025	recipe_1	static_tray	29.48	18	5.98	11.74	sucrose	29.4	mixed	3.9	4.46	7	4.08	2.18	10911.26	435.57	106.76	9.83	7.33	12.63	0	1.84	
BC_RUN_020	2025-01-19	2025-02-02	2025	recipe_3	static_tray	28.74	14	4.69	11.16	sucrose	33.36	mixed	5.72	5.25	8	4.21	2.13	8394.05	347.06	82.44	7.93	13.05	14.41	0	1.32	
BC_RUN_021	2025-02-08	2025-02-22	2025	recipe_2	static_tray	29.64	14	5.77	12.74	glucose	64.26	mixed	4.53	4.4	7	4.36	2.64	7629.01	263.16	60.36	6.07	12.55	9.07	0	2.13	
BC_RUN_022	2025-02-24	2025-03-17	2025	recipe_2	static_tray	28.8	21	6.14	8.05	sucrose	35.61	mixed	3.44	4.62	5	2.24	2.75	5623.83	234.38	104.63	6.5	10.44	6.39	0	1.35	
BC_RUN_023	2025-03-17	2025-03-29	2025	recipe_3	static_tray	27.06	12	6.2	6.51	sucrose	51.19	mixed	5.89	5.82	8	4.16	1.51	6822.94	325.27	78.19	10.91	17.83	9.71	0	1.77	
BC_RUN_024	2025-04-04	2025-04-18	2025	recipe_1	static_tray	28.1	14	4.54	8.37	glucose	26.31	mixed	5.96	3.26	6	3.0	2.81	3155.0	120.39	40.13	4.51	9.61	10.06	0	1.49	
BC_RUN_025	2025-04-22	2025-05-07	2025	recipe_1	static_tray	27.95	15	5.45	11.25	glucose	29.84	mixed	4.94	5.76	8	5.58	1.98	9010.01	309.07	55.39	10.61	16.91	17.37	0	2.07	
BC_RUN_026	2025-05-07	2025-05-22	2025	recipe_2	static_tray	29.01	15	4.87	8.95	sucrose	59.75	mixed	3.7	3.97	9	4.85	2.26	5790.95	279.7	57.67	9.8	10.99	11.9	0	1.7	
BC_RUN_027	2025-05-28	2025-06-10	2025	recipe_1	static_tray	28.58	13	5.16	8.01	sucrose	40.51	mixed	3.61	5.59	6	2.58	1.85	5081.35	188.39	73.02	6.88	13.81	10.32	0	1.19	
BC_RUN_028	2025-06-14	2025-06-27	2025	recipe_1	static_tray	27.2	13	5.56	10.92	sucrose	42.64	mixed	3.44	4.15	9	4.1	2.77	6267.55	270.7	66.02	8.03	13.81	17.05	0	1.84	
BC_RUN_029	2025-07-03	2025-07-14	2025	recipe_2	static_tray	27.02	11	6.13	10.56	glucose	41.58	mixed	4.4	3.82	8	5.5	3.02	8005.73	309.87	56.34	9.08	11.22	15.13	0	1.57	
BC_RUN_030	2025-07-19	2025-08-05	2025	recipe_3	static_tray	29.66	17	6.17	6.54	glucose	28.34	mixed	4.67	3.75	5	2.55	1.69	5307.32	181.09	71.02	8.19	12.73	8.77	0	0.83	
BC_RUN_031	2025-08-05	2025-08-14	2025	recipe_2	static_tray	28.98	9	5.22	8.42	glucose	25.0	mixed	3.39	3.16	9	5.79	2.59	6539.34	250.95	43.34	6.82	8.7	10.45	0	1.35	
BC_RUN_032	2025-08-24	2025-09-14	2025	recipe_3	static_tray	28.09	21	4.89	6.24	glucose	41.58	mixed	5.25	3.83	9	5.17	1.89	8790.22	307.06	59.39	8.92	13.15	16.28	0	0.89	
BC_RUN_033	2025-09-10	2025-09-21	2025	recipe_2	static_tray	26.54	11	4.69	8.35	sucrose	42.47	mixed	5.73	4.31	5	2.12	2.82	1856.67	87.42	41.24	5.91	4.09	2.45	0	1.42	
BC_RUN_034	2025-09-29	2025-10-13	2025	recipe_1	static_tray	26.65	14	5.35	7.67	glucose	38.15	mixed	3.37	5.34	4	1.72	2.62	2799.45	122.82	71.41	10.69	9.68	4.48	0	1.77	
BC_RUN_035	2025-10-18	2025-11-05	2025	recipe_3	static_tray	29.33	18	6.06	8.32	glucose	61.55	mixed	3.97	3.1	7	4.49	2.09	12195.97	436.65	97.25	4.76	7.72	2.55	0	0.79	
BC_RUN_036	2025-11-07	2025-11-20	2025	recipe_1	static_tray	28.31	13	4.67	10.88	glucose	41.1	mixed	5.6	3.96	5	2.63	3.02	4548.92	160.65	61.08	10.63	13.77	9.74	0	0.69	

bc_treatments_2024_2025.csv

One row = one treated sample (a subset of a run)

Purpose: material quality prediction, comparing treatments, connecting processing → mech properties → surface class.

Identifiers

- treatment_id *(string, unique)* — e.g., TRT_2024_001_01
- run_id *(string; foreign key to bc_runs)*
- sample_id *(string; optional but recommended if you cut multiple pieces per tray)*
- tray_id *(string/int; optional if you want tray-level tracking)*
- treatment_date *(YYYY-MM-DD; optional)*

Allocation

- sample_area_m2 *(number)*
- sample_dry_mass_g *(number; after treatment)*
- sample_thickness_mm *(number; after treatment)*

Treatment Parameters

- drying_method *(air_dry | press_dry | oven_low | freeze_dry)*
- pressing_level *(none | light | heavy)*
- conditioning_rh_pct *(number; optional)*
- conditioning_temp_c *(number; optional)*
- final_moisture_pct *(number; optional but powerful)*
- plasticizer_type *(none | glycerol | sorbitol | other)*
- plasticizer_pct *(number; blank if none)*

Material Properties

- tray_count *(int)*
- tray_area_m2 *(number; total surface area across trays)*
- liquid_depth_cm *(number)*

Run outputs (at harvest)

- tensile_strength_mpa *(number)*
- elongation_pct *(number)*
- youngs_modulus_mpa *(number)*

Surface class (your categorical label)

- surface_class *(contaminated | fiber_texture | non_uniform | uniform)*

Notes

- notes *(string; optional)*

Couple of Clarifications

- tray_area_m2 in **Runs** is **total area**, not per-tray. You can always compute per-tray if needed.
- dry_mass_total_g is the **run harvest output**, while sample_dry_mass_g is **post-treatment** and can differ (loss, plasticizer uptake, etc.).
- surface_class belongs in **Treatments**, because the same run can yield multiple surface outcomes depending on drying/pressing.

AI_FARMER

bc_treatments_2024_2025.csv

bc_treatments_2024_2025

treatment_id	run_id	sample_id	tray_id	treatment_date	sample_area_m2	sample_dry_mass_g	sample_thickness_mm	drying_method	pressing_level	conditioning_rh_pct	conditioning_temp_c	final_moisture_pct	plasticizer_type	plasticizer_pct	tensile_strength_mpa	elongation_pct	youngs_modulus_mpa	surface_class	notes
TRT_0001	BC_RUN_001	S1	T3	2024-01-23	2.513	162.44	5.74	press_dry	none	54.8	22.6	15.4	none	9.2	57.46	10.72	2815.1	contaminated	
TRT_0002	BC_RUN_001	S2	T4	2024-01-23	2.238	144.66	5.98	press_dry	heavy	60.8	24.4	9.3	none	9.0	70.62	5.17	2471.0	uniform	
TRT_0003	BC_RUN_002	S1	T9	2024-02-05	1.805	195.12	4.16	press_dry	heavy	41.4	23.5	6.8	glycerol	0.7	133.59	23.35	1720.6	uniform	
TRT_0004	BC_RUN_002	S2	T2	2024-02-05	1.76	190.26	4.4	oven_low	heavy	46.6	22.2	16.3	glycerol	0.0	139.28	17.58	2851.8	fiber_texture	
TRT_0005	BC_RUN_002	S3	T4	2024-02-05	1.74	188.09	4.94	oven_low	light	54.3	21.2	16.6	glycerol	8.4	60.37	7.66	1352.4	fiber_texture	
TRT_0006	BC_RUN_003	S1	T2	2024-02-19	0.763	65.47	6.06	air_dry	none	60.5	24.4	7.4	glycerol	4.0	84.65	13.2	2458.6	uniform	
TRT_0007	BC_RUN_003	S2	T3	2024-02-19	0.809	69.42	6.65	press_dry	none	42.5	20.2	14.4	glycerol	10.0	138.88	24.39	2713.1	contaminated	
TRT_0008	BC_RUN_003	S3	T3	2024-02-19	0.783	67.19	6.76	press_dry	none	59.6	22.8	6.1	none	7.6	82.52	22.85	2662.7	contaminated	
TRT_0009	BC_RUN_004	S1	T7	2024-03-08	2.47	178.88	5.31	oven_low	none	48.5	24.8	17.1	glycerol	3.2	75.76	7.45	1770.8	contaminated	
TRT_0010	BC_RUN_004	S2	T6	2024-03-08	2.431	176.05	5.17	air_dry	heavy	41.2	21.5	13.6	glycerol	0.7	139.02	16.87	1517.3	fiber_texture	
TRT_0011	BC_RUN_005	S1	T1	2024-03-31	1.453	62.73	10.26	oven_low	none	63.4	21.2	14.8	glycerol	1.0	95.59	19.79	1818.3	contaminated	
TRT_0012	BC_RUN_005	S2	T1	2024-03-31	1.416	61.13	9.93	air_dry	none	57.1	20.0	12.9	none	9.2	92.01	6.7	2301.0	fiber_texture	
TRT_0013	BC_RUN_005	S3	T4	2024-03-31	1.533	66.18	11.57	air_dry	light	57.9	24.0	14.4	glycerol	9.7	129.17	11.83	1736.3	non_uniform	
TRT_0014	BC_RUN_006	S1	T4	2024-04-11	1.807	198.93	10.09	press_dry	light	60.9	24.1	13.6	glycerol	4.0	51.34	8.05	2768.5	non_uniform	
TRT_0015	BC_RUN_006	S2	T3	2024-04-11	1.928	212.25	9.16	air_dry	none	54.4	24.1	15.6	none	4.3	99.81	21.25	1686.3	uniform	
TRT_0016	BC_RUN_007	S1	T4	2024-05-12	0.571	46.29	5.04	press_dry	heavy	45.5	21.5	14.8	none	10.6	89.76	20.7	1719.4	contaminated	
TRT_0017	BC_RUN_007	S2	T3	2024-05-12	0.506	41.02	5.18	air_dry	light	44.2	21.8	15.8	none	5.2	113.13	18.6	2069.7	uniform	
TRT_0018	BC_RUN_007	S3	T1	2024-05-12	0.503	40.78	5.18	air_dry	light	50.3	23.5	8.4	glycerol	1.0	133.49	12.9	2462.4	uniform	
TRT_0019	BC_RUN_008	S1	T2	2024-05-30	1.699	134.31	7.77	oven_low	heavy	64.7	24.7	11.5	none	2.8	51.2	10.53	1798.5	uniform	
TRT_0020	BC_RUN_008	S2	T7	2024-05-30	1.816	143.55	9.01	oven_low	heavy	59.1	23.5	7.5	none	0.6	114.99	19.39	1203.4	non_uniform	
TRT_0021	BC_RUN_009	S1	T2	2024-06-08	1.869	180.17	11.35	oven_low	light	60.0	24.2	8.6	glycerol	5.2	117.69	14.09	1640.0	non_uniform	
TRT_0022	BC_RUN_009	S2	T6	2024-06-08	2.079	200.42	10.85	air_dry	heavy	54.4	24.5	10.1	glycerol	8.2	72.1	15.33	2851.1	non_uniform	
TRT_0023	BC_RUN_010	S1	T2	2024-06-29	2.452	145.48	9.16	press_dry	heavy	47.5	23.7	14.3	glycerol	8.8	127.84	14.78	2158.5	contaminated	
TRT_0024	BC_RUN_010	S2	T1	2024-06-29	2.368	140.49	8.71	oven_low	light	42.6	20.6	12.5	glycerol	3.4	102.98	14.63	2077.6	non_uniform	
TRT_0025	BC_RUN_011	S1	T4	2024-07-18	0.732	72.61	7.41	oven_low	none	63.1	22.9	13.7	glycerol	4.5	74.83	22.45	2307.0	uniform	
TRT_0026	BC_RUN_011	S2	T4	2024-07-18	0.722	71.62	8.23	press_dry	none	64.4	21.4	11.8	none	1.4	94.22	27.32	2104.6	contaminated	
TRT_0027	BC_RUN_011	S3	T1	2024-07-18	0.759	75.29	7.24	press_dry	light	48.8	23.3	15.0	glycerol	2.3	68.95	16.18	1821.5	non_uniform	
TRT_0028	BC_RUN_012	S1	T1	2024-07-31	1.852	196.61	7.25	oven_low	heavy	61.6	22.8	15.9	glycerol	4.2	100.75	12.84	2757.1	uniform	
TRT_0029	BC_RUN_012	S2	T6	2024-07-31	1.987	210.94	7.83	press_dry	none	63.1	21.6	10.3	glycerol	7.2	115.19	5.4	2644.4	contaminated	
TRT_0030	BC_RUN_013	S1	T4	2024-08-27	0.645	33.37	5.6	oven_low	light	60.6	22.7	8.2	none	3.4	101.31	17.26	1362.2	contaminated	
TRT_0031	BC_RUN_013	S2	T2	2024-08-27	0.701	36.27	6.04	press_dry	light	51.1	23.8	8.9	none	1.1	96.63	27.77	1626.1	contaminated	
TRT_0032	BC_RUN_013	S3	T4	2024-08-27	0.699	36.17	5.73	air_dry	heavy	56.5	24.0	10.9	none	1.9	90.2	13.64	2019.2	fiber_texture	
TRT_0033	BC_RUN_014	S1	T7	2024-09-04	1.775	134.17	8.78	press_dry	none	41.0	23.5	14.9	glycerol	2.9	61.47	17.93	1917.9	uniform	
TRT_0034	BC_RUN_014	S2	T1	2024-09-04	1.851	139.92	8.94	air_dry	light	64.8	20.8	9.6	none	2.1	76.69	12.9	2280.0	contaminated	
TRT_0035	BC_RUN_014	S3	T8	2024-09-04	1.836	138.78	9.68	air_dry	none	52.8	23.3	7.7	glycerol	5.0	130.01	8.51	2158.5	non_uniform	
TRT_0036	BC_RUN_015	S1	T4	2024-10-02	0.844	42.01	8.4	press_dry	light	42.3	21.5	14.9	none	5.1	121.27	9.18	2129.2	fiber_texture	
TRT_0037	BC_RUN_015	S2	T3	2024-10-02	0.873	43.45	8.34	oven_low	none	58.2	24.0	16.8	none	2.4	127.22	22.77	2644.4	uniform	
TRT_0038	BC_RUN_015	S3	T1	2024-10-02	0.845	42.06	8.18	press_dry	heavy	64.9	20.5	15.4	none	6.7	45.43	18.8	1718.2	non_uniform	
TRT_0039	BC_RUN_016	S1	T1	2024-10-19	1.101	130.82	9.5	oven_low	none	41.4	23.4	6.2	none	10.6	101.68	19.14	1311.4	uniform	
TRT_0040	BC_RUN_016	S2	T2	2024-10-19	1.047	124.4	8.9	air_dry	none	60.5	23.1	7.4	none	11.7	56.98	20.61	2252.3	uniform	
TRT_0041	BC_RUN_017	S1	T4	2024-11-01	2.181	122.59	9.24	press_dry	light	60.0	22.1	6.8	glycerol	2.6	121.9	15.27	1527.9	fiber_texture	
TRT_0042	BC_RUN_017	S2	T4	2024-11-01	2.107	118.43	8.9	air_dry	heavy	61.5	21.6	6.4	glycerol	7.1	99.6	9.8	1438.1	fiber_texture	
TRT_0043	BC_RUN_018	S1	T4	2024-11-21	0.817	94.67	3.71	air_dry	none	61.2	20.8	7.5	none	2.1	118.12	7.06	2404.0	fiber_texture	
TRT_0044	BC_RUN_018	S2	T2	2024-11-21	0.758	87.83	4.07	oven_low	none	41.0	21.5	12.6	glycerol	5.8	108.46	26.97	2733.7	contaminated	
TRT_0045	BC_RUN_019	S1	T1	2025-01-23	1.263	134.84	8.72	press_dry	none	42.6	22.2	11.2	none	6.3	134.08	17.07	3166.7	uniform	
TRT_0046	BC_RUN_019	S2	T7	2025-01-23	1.295	138.25	10.2	oven_low	light	42.0	21.4	14.3	none	9.1	93.01	9.3	2450.2	fiber_texture	
TRT_0047	BC_RUN_019	S3	T2	2025-01-23	1.395	148.93	8.87	air_dry	heavy	42.9	23.1	9.2	none	10.9	123.21	7.03	2713.8	uniform	
TRT_0048	BC_RUN_020	S1	T5	2025-02-02	1.38	113.77	8.12	air_dry	none	45.5	22.2	16.7	none	1.6	100.55	26.32	1375.4	non_uniform	
TRT_0049	BC_RUN_020	S2	T1	2025-02-02	1.296	106.84	7.4	oven_low	heavy	61.4	21.0	16.5	glycerol	6.9	79.81	12.05	2149.2	non_uniform	
TRT_0050	BC_RUN_020	S3	T4	2025-02-02	1.47	121.19	8.62	oven_low	heavy	41.0	20.8	10.0	glycerol	4.3	47.33	4.47	2291.2	contaminated	
TRT_0051	BC_RUN_021	S1	T6	2025-02-22	1.349	81.43	5.29	oven_low	light	63.9	20.8	8.7	none	9.9	64.42	26.16	1699.6	fiber_texture	
TRT_0052	BC_RUN_021	S2	T1	2025-02-22	1.404	84.75	6.24	oven_low	none	49.0	20.0	13.8	glycerol	9.0	129.48	21.12	1276.9	non_uniform	
TRT_0053	BC_RUN_021	S3	T5	2025-02-22	1.438	86.8	5.68	air_dry	heavy	54.3	23.4	17.1	none	6.4	65.17	4.75	1687.7	fiber_texture	
TRT_0054	BC_RUN_022	S1	T2	2025-03-17	1.044	109.23	5.61	air_dry	light	57.4	22.8	11.7	glycerol	11.7	125.19	7.08	1960.1	fiber_texture	

Bridge Outputs

- **Uniformity**
    - **defects_pct** (highest signal, if defects are scored consistently)
    - **avg_process_deviation_pct** (process instability → non-uniform pellicle)
    - **Derived: thickness_variation_pct** *(add this!)*

- **Stiffness (**stiffness ↑ with crystallinity ↑ and density/areal density ↑**)crystallinity_index_pct** (higher crystallinity → higher stiffness, generally)
    - **areal_density_gm2** *(you have it as yield_per_m2_gm2 but that's dry mass/area; good proxy)*
    - **Derived: density_gcm3** *(addable)* from dry mass + thickness + area
- **Tensile Strength**
    - **areal_density_gm2** / **dry_mass_yield_g** (to a point; thicker/denser sheets often test stronger)
    - **crystallinity_index_pct** (often positive association)
    - **defects_pct** (negative association; pinholes/tears crush strength)
- **Elongation**
    - **water_holding_capacity_pct** (more water retention / less brittle sheet often → higher elongation)
    - **crystallinity_index_pct** (often *inverse* with elongation; more crystalline tends to be stiffer/brittler)
    - **Post-process moisture / plasticizer** (critical; see below)