TICA
Thailand International Cooperation Agency

80th Anniversary
SILPAKORN UNIVERSITY

AITC course 2023 : The application of a parabolic greenhouse solar dryer together with raw material preparation techniques to extend shelf-life and enhance quality of agricultural products

Principle of drying of agricultural products.

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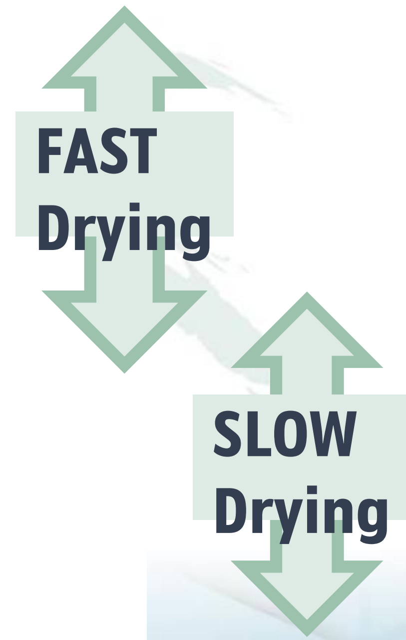
Principle of drying

- **Dryer: Parabolic Solar Dryer System**
- **Materials: Agricultural Products**
- **Principle of Drying:**
  - **Removed water from product**
    - Water (moisture content) / Dry Solid
  - **Key substances (active ingredients):**
    - Pharmacy / Bioactive / Food Ingredients (dry basis concentration)
  - **Effect of drying factors:**
    - External factors: Thermodynamic parameters in dryer
    - Internal factors: Physical structures of product

Principle of drying : Water in Products

- **Water in Products**
  - **Free water:**
    - Using thermodynamic data of pure water
  - **Bound water (able to move):**
    - Solutions (thermodynamic properties depending on concentration and solubility)
    - In depth water (in close pore, water proof membrane, can’t remove by heat or without breaking structure)
  - **Strong bound water (can’t move):**
    - Bound on solid surface (required heat of solution or sorption/desorption)
    - Inner structure of solid part



Principle of drying : Water in Products

- **Water mobility**
  - **Gas phase:** Water in Air (%RH)
    - Gas Diffusion (Diffusion in void / convective in flow)
  - **Liquid phase:** Water in solution (call hydrophilic phase)
    - Water in Solution (solvent in solution)
    - Diffuse in Gel / Sol-Gel
    - Solution in Pore structure / Diffuse through Membrane
  - **Solid phase:** high concentrated solution and bound with the dry solid
    - Water in dry product / close pore / nucleus of cell
    - Required high energy and destroy product structure in some case

Principle of drying : Water in Products

- **Water remove from product to the air**
  - **Boiling**
    - Temp. > Boiling Point at atmospheric pressure
    - Vapor Pressure of water at 100 °C equals 1 atm. (1000 mbar)
  - **Evaporation**
    - all temp. (from freezing point to boiling point)
    - Heat of evaporation is about 2,501 kJ/kg at 0 °C
    - Heat of evaporation is about 2,256 kJ/kg at 100 °C
  - **Sublimation**
    - System Pressure < Vapour pressure at atmospheric temp.
    - Vapor pressure of water at 0 °C equals 6.1 mbar
    - Vapor pressure of water at -20 °C equals 1.03 mbar

Principle of drying : Water in Products

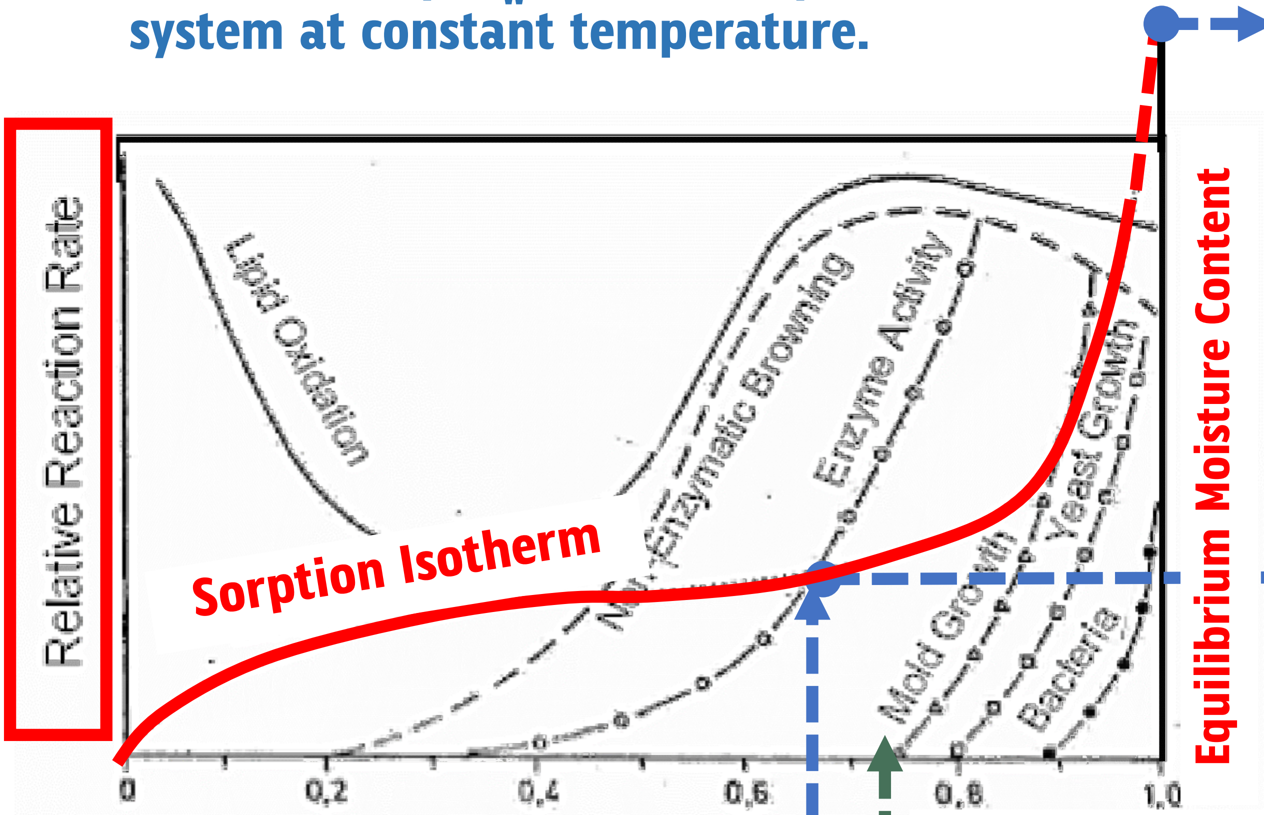
- **Various of Moisture Content**
  - **Wet basis ($\%MC_{wb}$):**
    - **$\% MC_{wb}$ = (wt. of water / total wt.) x 100**
  - **Dry basis (X):**
    - **total wt. = wt. of water + wt. of dry solid**
    - **wt. of dry solid is constant during drying.**
    - **X = wt. of water / wt. of dry solid**
    - **X = %MC / (100-%MC)**

Principle of drying : Water in Products

- **Various of Moisture Content**
  - **Moisture Ratio (MR):**
    - $\%MC_{eq}$ is equilibrium moisture content (at the certain Pressure, Temperature and Relative Humidity, %RH)
    - Wet basis: $MR_A = \%MC_t / \%MC_0$, $MR_B = (\%MC_t - \%MC_{eq}) / (\%MC_0 - \%MC_{eq})$
    - Dry basis: $MR_A = X_t / X_0$, $MR_B = (X_t - X_{eq}) / (X_0 - X_{eq})$
    - MR start from 1 and convergence to $\%MC_{eq}/\%MC_0$ (A-case) or 0 (B-case)

Principle of drying : MC of dry product

- **Equilibrium Moisture Content (%MC_{eq}, EMC)**
  - **Labuza's Work (1972) :**
    - Water activity (a_w) is Humidity (%RH/100) inside the close system at constant temperature.



higher this MCc, water acting like pure water (%RH=100)

this MC is required moisture content of dry product to storage at this temperature

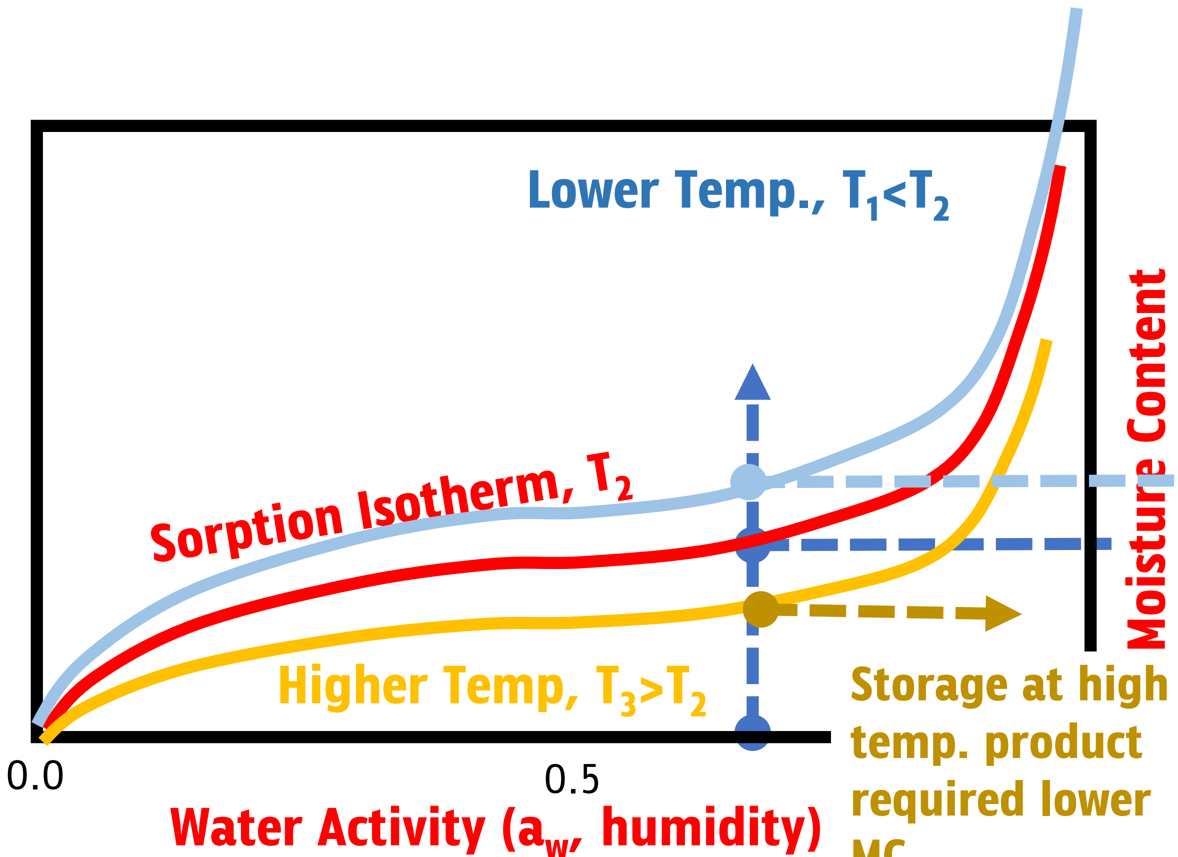
Humidity = (%RH/100)

$a_w < 0.65$ is normal using for storage

$a_w < 0.75$ save from mold, yeast and bacteria (at this temperature)

Principle of drying : MC of dry product

- **Application of Sorption Isotherm (a_w vs MC_{eq})**
  - **Storage dry products:**
    - Design storage temperatures ($T_1 < T_2 < T_3$)



Storage at low temp. product can have higher MC

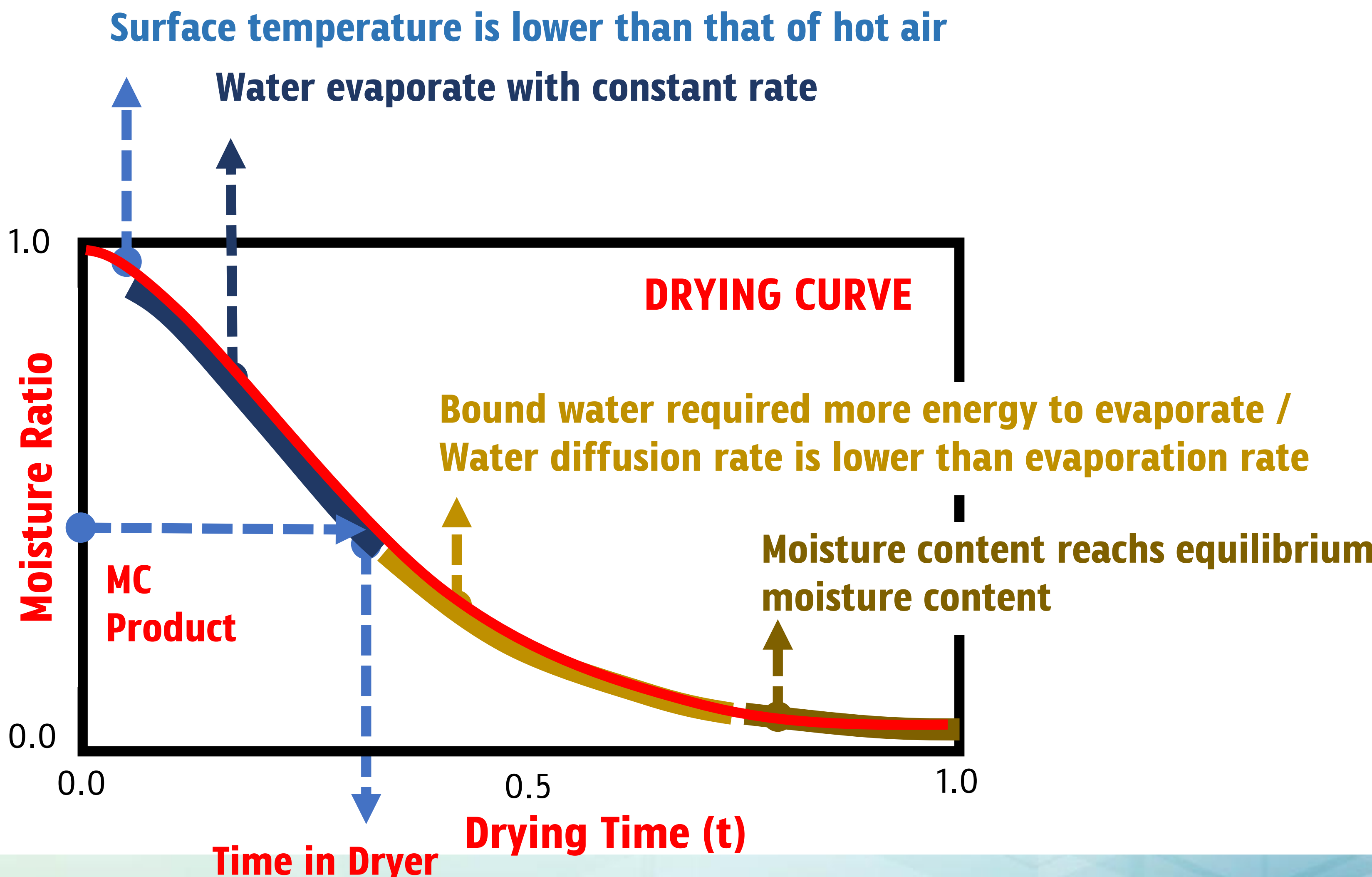
this MC is required moisture content of dry product to storage at T_2

Storage at high temp. product required lower MC

a_W < 0.65 is normal using for storage

Principle of drying : Drying Stage

- Simple hot air dryer



Principle of drying: External Factors

- **Drying Cloth (example)**

SUMMER
Hot and moist air

Temp.

INDOOR
Dried but long time

%RH

WINTER
Cold but dried air

%RH

RAINING
Wet and moist air

STOVE
Dried with other heat sources

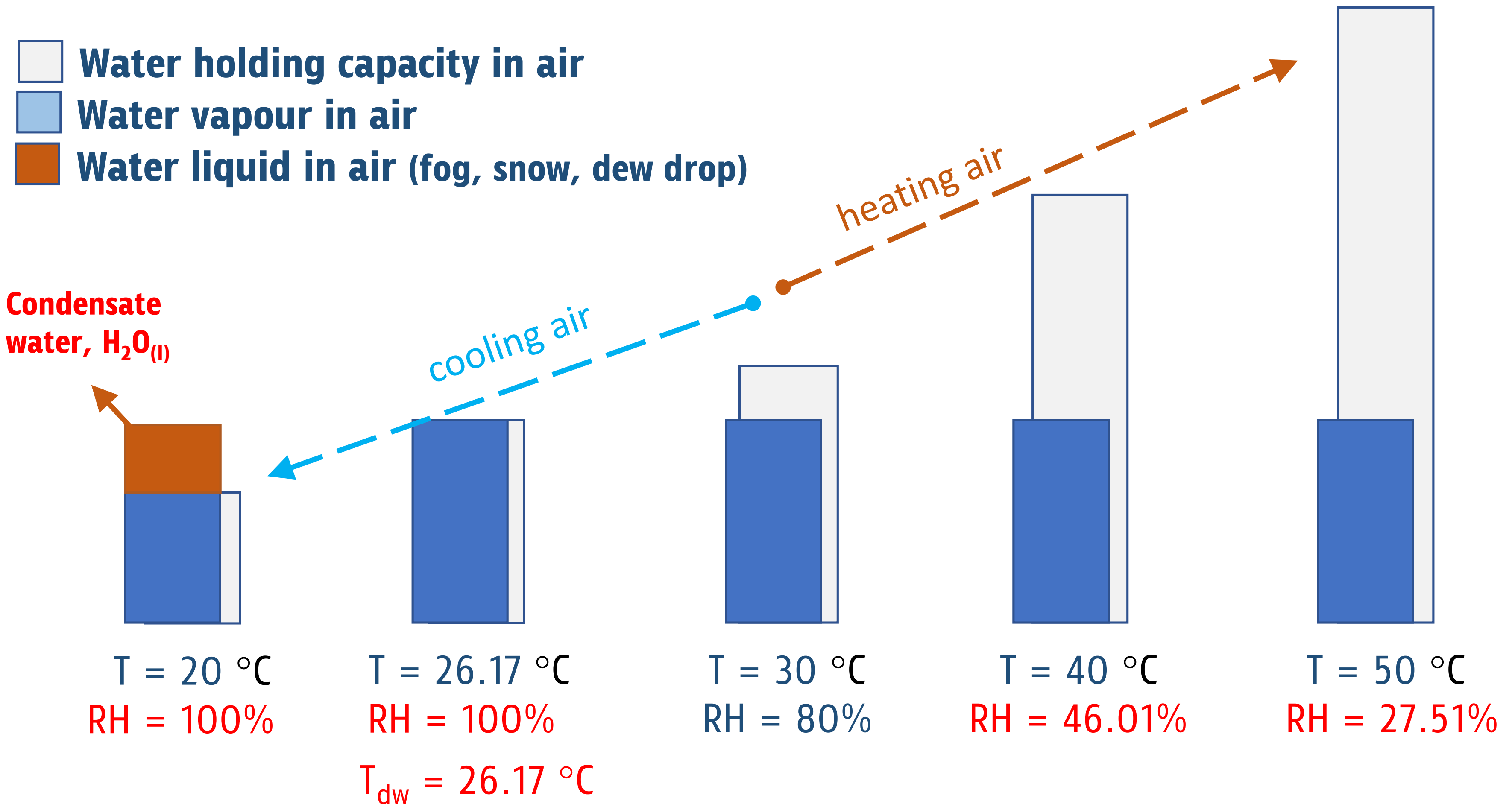
Temp.

Velocity

FAN
Dried and faster

Principle of drying: External Factors

- **Factors: %Relative Humidity ($P_{water}/P_{water,sat}$ x 100)**

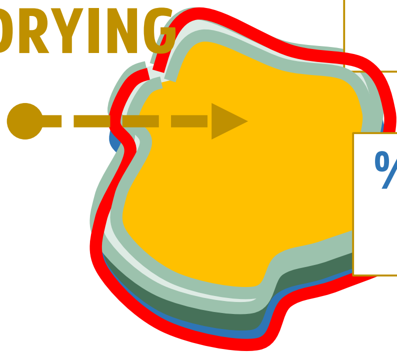


Principle of drying: External Factors

- **Factors:**

Temperature: T ↑ Drying Time ↓
(reducing heat of evaporation, increasing mass diffusivity)

HOT AIR DRYING



Velocity: v ↑ Drying Time ↓
(increasing convective heat & mass transfer coefficient)

%RH: %RH ↓ Drying Time ↓
(increasing water holding capacity, increasing mass transfer)

SOLAR DRYER

Solar: Intensity ↑ Drying Time ↓
(increasing surface temperature regarding heat absorption)

MICROWAVE VACUUM DRYER

Pressure: P ↓ Drying Time ↓
(reducing P, increasing evaporation rate)

Microwave: Intensity ↑ Drying Time ↓
(heat induce from inside the product)

Principle of drying: Water Properties

- Thermodynamic parameter of **pure** water (free water)
  - Size: 2.75 Angstrom, A° (0.275 nm, 2.75×10^{-10} m)
  - Boiling point: 100 °C (at atmospheric pressure, 1 atm)
  - Freezing point: 0 °C (1 atm)
  - Liquid
    - Density: 997.77 kg/m^3 at 22 °C
    - Heat Capacity: 4,184 J/kg-K at 20 °C
    - Heat Conductivity: 0.598 W/m·K at 20 °C
  - Ice
    - Density: 920 kg/m^3 at <0 °C
    - Heat Capacity: 2,093 J/kg-K.
    - Heat Conductivity: 2.18 W/m·K
  - Gas (Water Vapor)
    - Density: 0.598 kg/m^3
    - Heat Capacity: 1,864 J/kg-K
    - Heat Conductivity: 0.020 W/m·K

Air

Density: 1.293 kg/m^3

Heat Capacity: 1,005 J/kg-K

Heat Conductivity: 0.0262 W/m·K

Moist Air (100% RH, 25°C)

Density: 1.17 kg/m^3

kg_water/kg_dry air = 0.0201

Principle of drying Water Properties

- **Transportation properties: Diffusivity (m^2/s)**
  - **Water diffusivity in Air**
    - 2.42×10^{-5} m^2/s at 20°C
  - **Water diffusivity in Sugar solution**
    - Self-diffusion 2.299×10^{-9} m^2/s
    - Using equi-molar diffusion (sugar and water)
      - 5×10^{-10} m^2/s (sucrose)
6.6×10^{-10} m^2/s (glucose)
  - **Water diffusion in solid < 10^{-15} m^2/s**

Water Diffusivity

- Corn (3.27×10^{-7})
- Beef Sausage (1.13×10^{-7})
- Malt (8.73×10^{-8})
- Cheese (2.02×10^{-8})

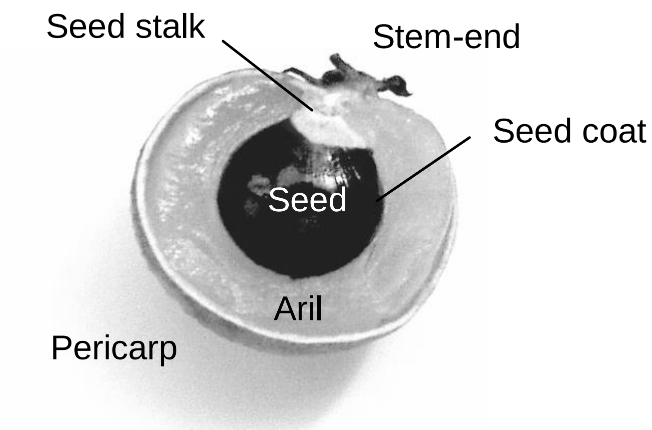
- Carrot (2.05×10^{-9})
- Broccoli (1.29×10^{-9})
- Apple (6.64×10^{-10})
- Milk Powder (6.58×10^{-10})
- Beef (5.6×10^{-10})
- Corn starch (2.25×10^{-10})

- Rice grain (1.53×10^{-11})
- Potato starch (6.91×10^{-12})

Sources: Transport Properties of Foods, George D. Saravacos and Zacharias B. Maroulis

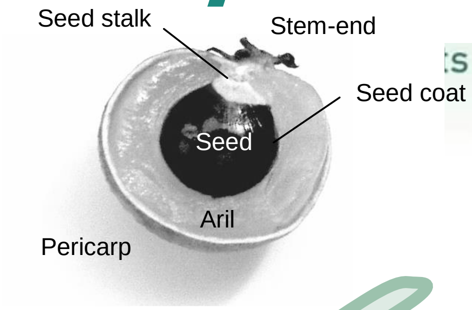
Principle of drying: Water pathway

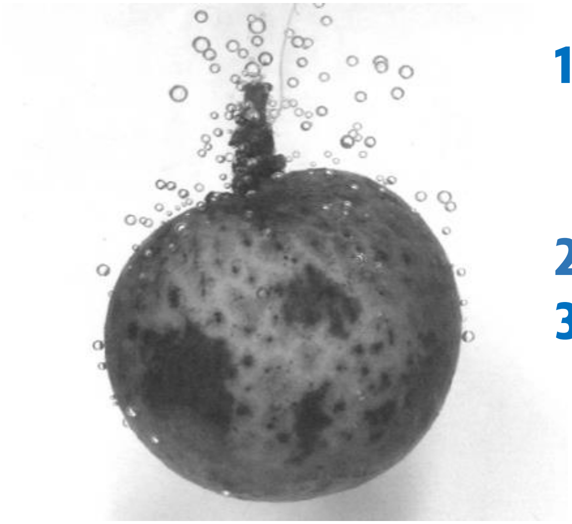
- **Longan case:**
  - **Initial Moisture Content**
    - **Seed ~ 40%**
    - **Aril ~ 80%**
    - **Peel ~ 30-40%**
    - **Whole fruit ~ 70%**
    - **How the moisture content of each part can be different value?**



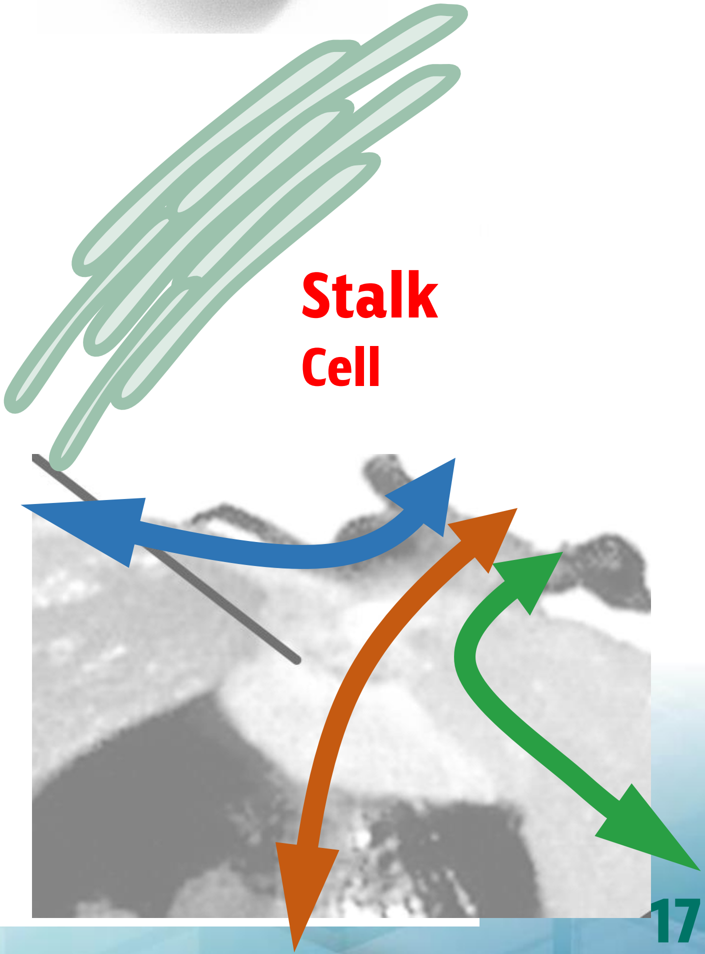
Principle of drying: Water pathway

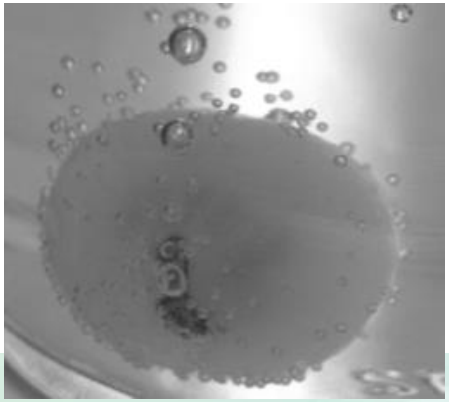
- **Drying Experiment:**
  - Immerge in Silicon Oil
  - Using Vacuum Dryer

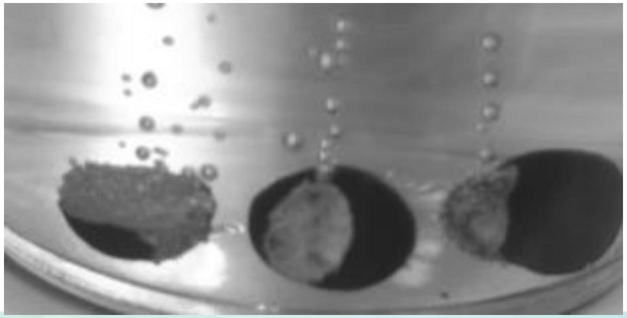




1) Water can transport at seed stalk and some surface area
2) Seed Coat is water proof
3) There are special stalk cell for each part





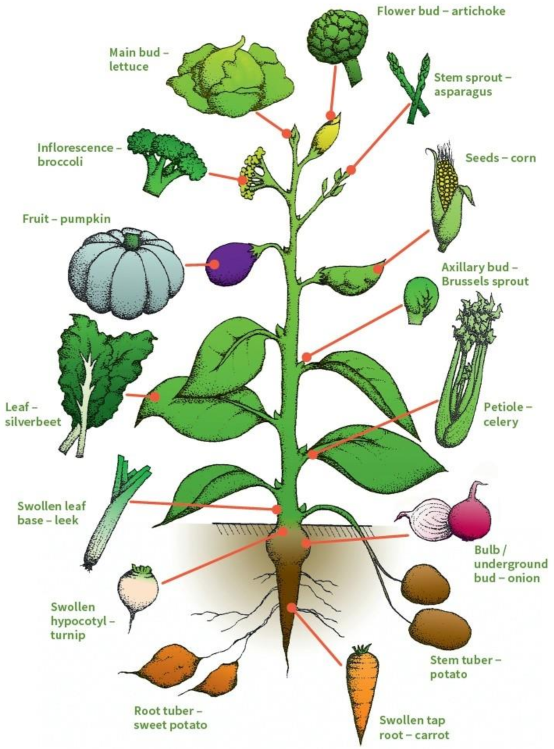


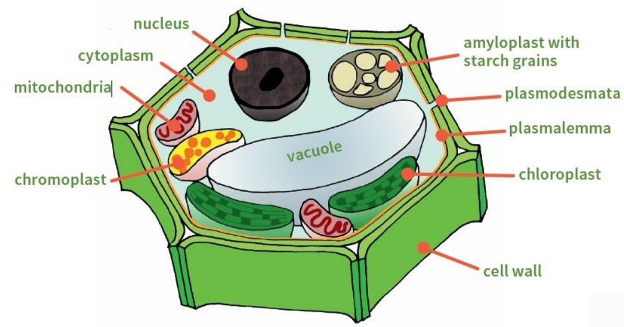
Principle of drying

Water

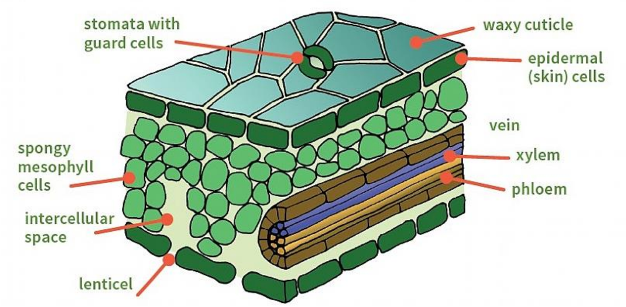
Size: : 2.75 A° or 0.000275μm

- **Agricultural products:**





Fruit cell: size about 30,000-60,000 μm^2 (Apple)

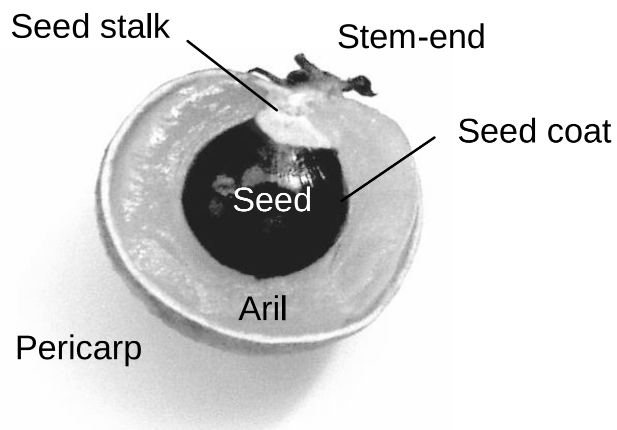


Cell wall: stomata (320-390 per mm^2, dia. 13-33 μm, 15-25 μm^2)

Nearly 97 % of water from plants is lost through stomatal transpiration, so the more stomata, the higher the transpiration rate.

Sources: [1]-[4]

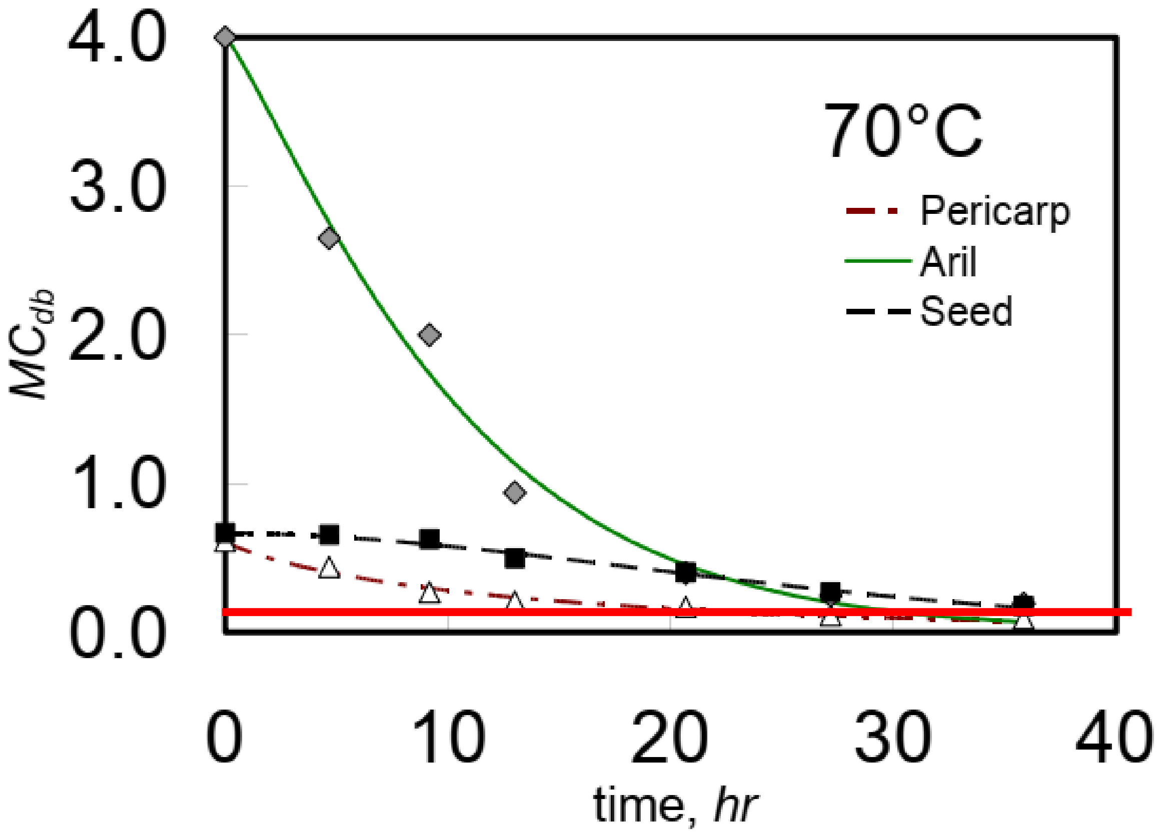
Principle of drying: Water pathway



- **Longan case:**
  - **Initial Moisture Content**
    - Seed ~ 40%
    - Aril ~ 80%
    - Peel ~ 30-40%
    - Whole fruit ~ 70%
    - How the moisture content of each part can be different value?
  - **Drying Time**
    - Seed ~ 4 hr.
    - Aril ~ 8 hr.
    - Peel ~ 2 hr.
    - Whole fruit >32 hr (~ 72 hr.)
    - Why the whole fruit need very long drying time ? (customer need this)

Principle of drying: Water pathway

- **Drying whole longan (Drying curve of each part)**



Dry whole longan

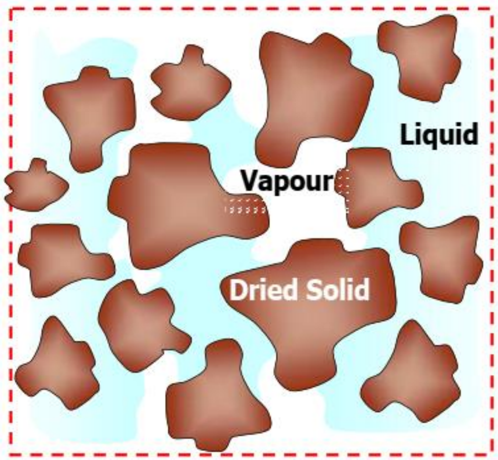
Specification:

MC_{wb} = 12%

X=0.13

Principle of drying: Water pathway

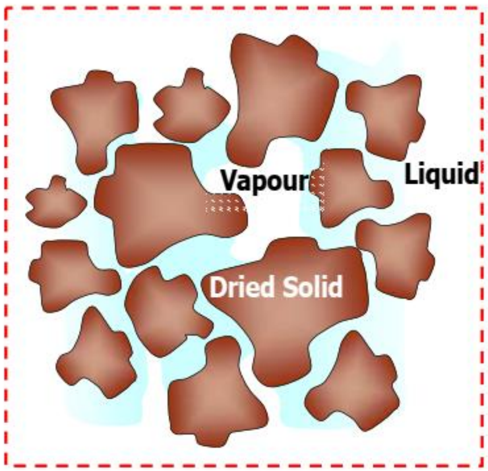
- **Drying whole longan (shrinkage effect of seed and aril)**



non-shrinkage

$$\frac{dV}{dt} = 0$$

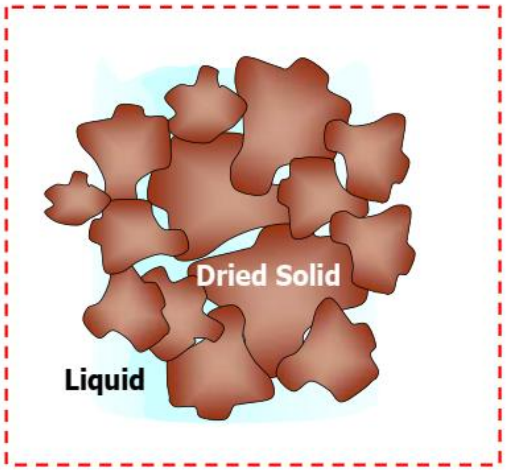
$$\frac{dV_{vap}}{dt} = -\frac{dV_{liq}}{dt}$$



semi-shrinkage

$$\frac{dV}{dt} = (\beta)\frac{dV_{liq}}{dt}$$

$$\frac{dV_{vap}}{dt} = (\beta - 1)\frac{dV_{liq}}{dt}$$



shrinkage

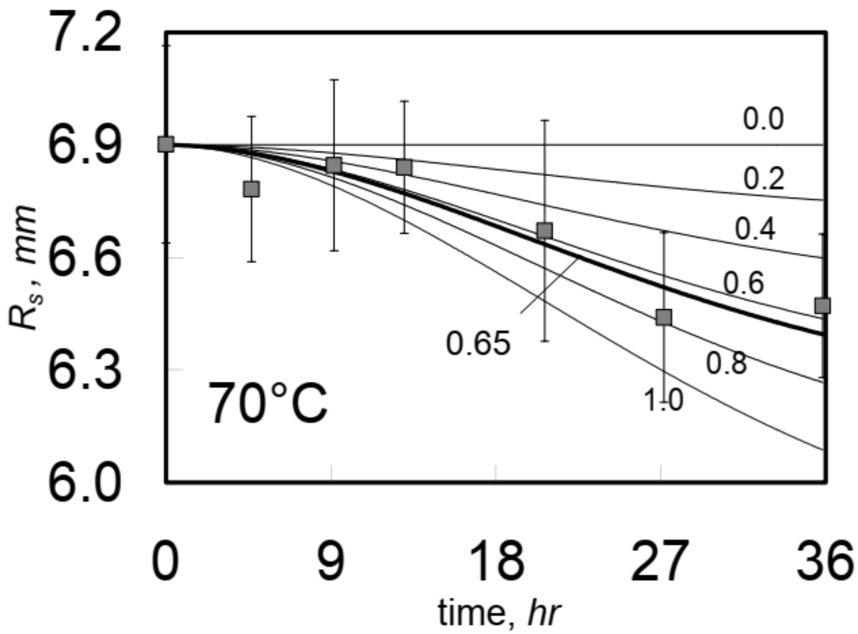
$$\frac{dV}{dt} = \frac{dV_{liq}}{dt}$$

$$\frac{dV_{vap}}{dt} = 0$$

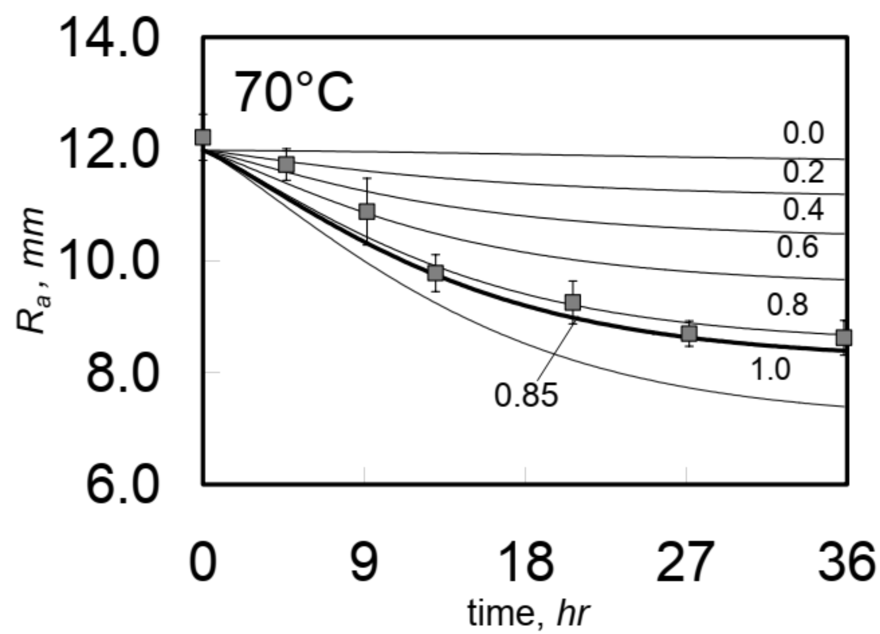
Principle of drying: Water pathway

- **Drying whole longan (shrinkage effect of seed and aril)**

SEED: β = 0.65

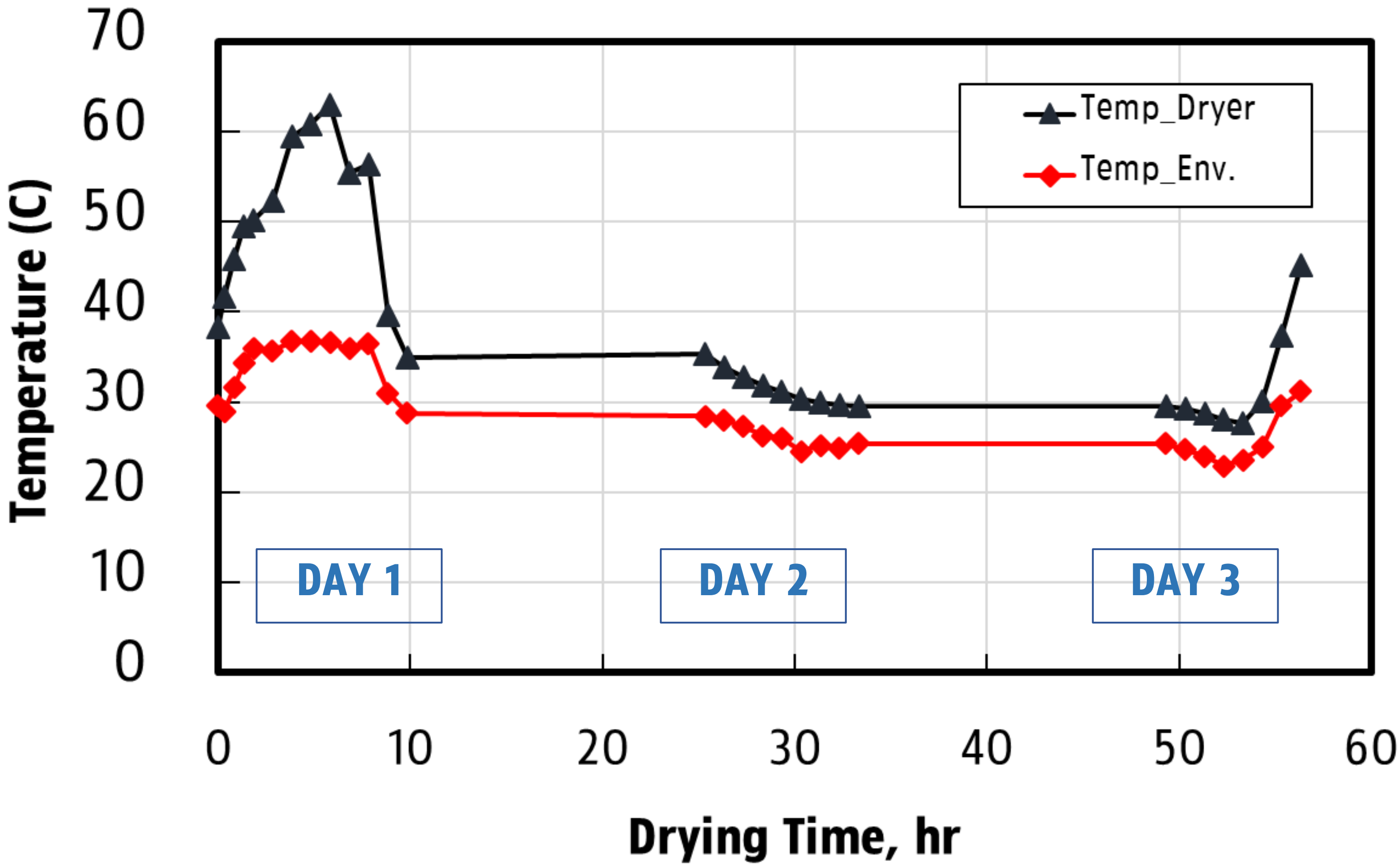


ARIL: β = 0.85



Drying Curve in Parabolic Solar Dryer

- Osmotic dehydrated tomato (8x20.8 m^2, 1.3 tons fresh)



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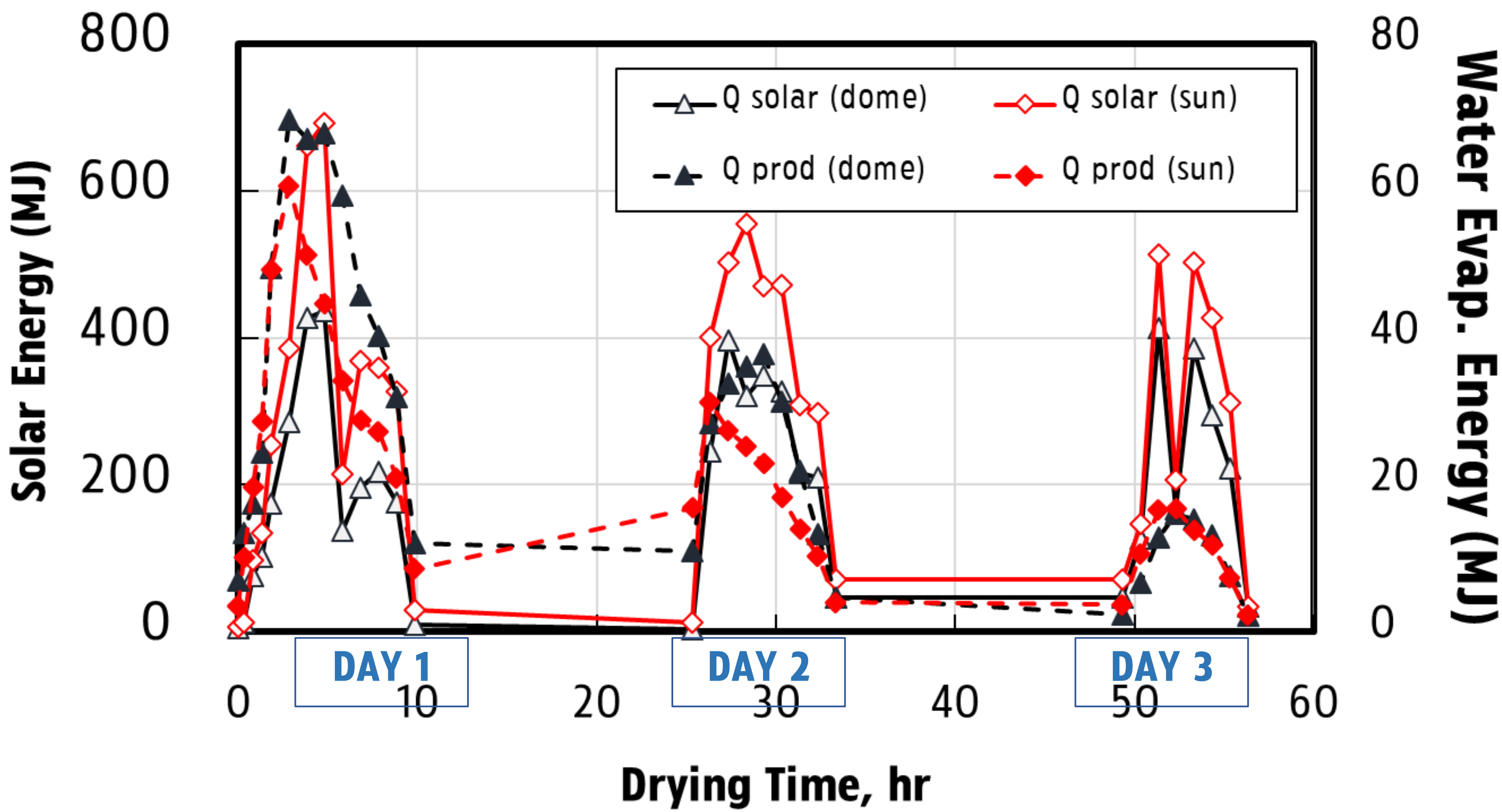

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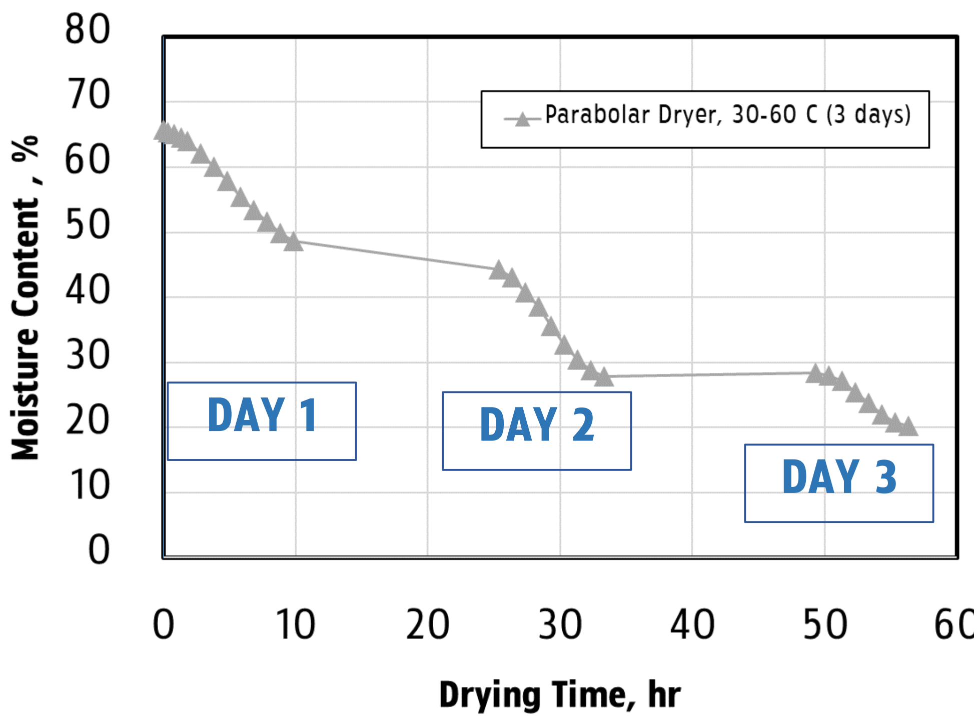

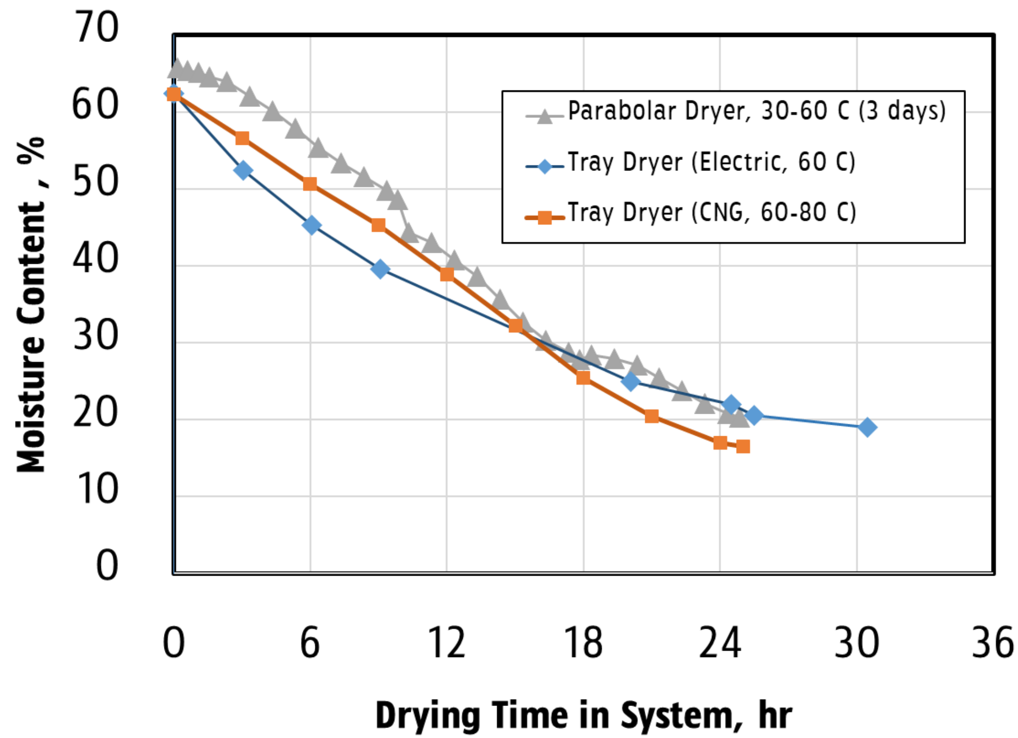

Principle of drying

- **Preparation before drying:**
  - **What's dry product?**
    - Quality, Quantity and Geometry (ex: whole fruit or cutting).
    - Pretreatment before drying process.
  - **What's the storage temperature?**
    - Preparing for Sorption Isotherm
  - **What's the moisture content of final product?**
    - Required Sorption Isotherm
  - **How long does it drying?**
    - Required Drying Curve (to estimate the drying time)
  - **Regarding to Parabolic Solar Dryer**
    - Velocity is very low, water vapour (%RH) was removing by the fan, and temperature depending on weather.
    - For controlling the quality, you might understand the water pathway from the product during drying.

Sources:

- [1] https://www.postharvest.net.au/postharvest-fundamentals/vegetable-physiology/structure-and-composition/
- [2] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2685799/
- [3] https://www.researchgate.net/figure/Stomatal-size-and-distribution-in-cv-Fuerte-avocado-fruit-in-relation-to-its_tbl1_267220198
- [4] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4301182/#:~:text=Stomata%20also%20varied%20 widely%20in,from%2019.1%20to%2071.5%20%CE%BCm.
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- https://www.processsensing.com/en-us/humidity-calculator/rotronic/
- https://www.vaisala.com/en/lp/humidity-calculator?utm_medium=cpc&utm_source=google&utm_campaign=VIM-APAC-EN-DISTR-HUM-India&gclid=CjwKCAjw0ZiiBhBKEiwA4PT9zwv1Z5VJfwijRsa2_Q--__Io3TIHQpi1y-eGjv_Zvl8a-kNbHkgdfhoCLrgQAvD_BwE