มหาวิทยาลัยราชภัฏนครปฐม

9673204
Drying and Storage

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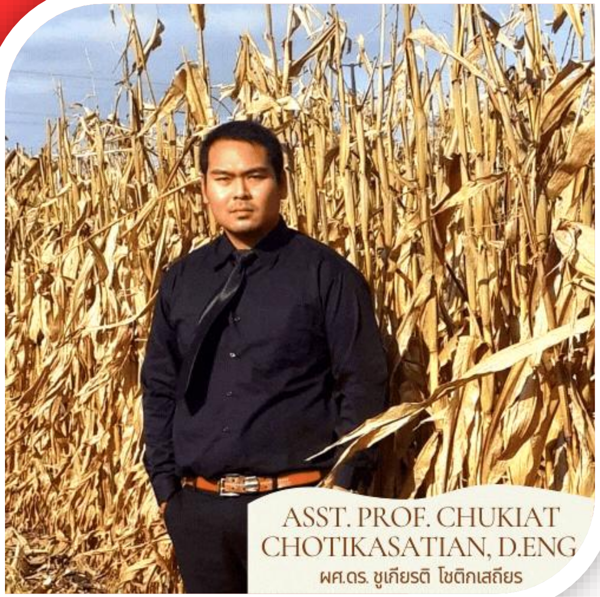
Nakhon Pathom Rajabhat University

Course Description

Theory of drying, sun drying, principles of air flow, drying of agricultural products by heated air, moisture content determination, relationship of moisture and temperature, equilibrium moisture content, design of dryers storage

Professional Interest Statement:

- Monitoring CO_2/O_2 concentrations to assess biological activity and reduce post-harvest losses
- Establishing verification criteria for unacceptable insect infestation levels
- Supporting fumigation and grain storage management decisions
- Developing agricultural product drying and intelligent drying systems



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Lecture 4 – Moisture Content

Study Questions – Lecture 4

1. *What is equilibrium moisture content, and why is it important in drying and storage of agricultural products?*
2. *How is water activity related to equilibrium moisture content and product deterioration?*
3. *What is equilibrium relative humidity, and how does it relate to material moisture equilibrium?*
4. *How can equilibrium moisture content be determined experimentally?*
5. *Why are mathematical models used to predict equilibrium moisture content?*

Lecture 4 – Moisture Content

Outline – Lecture 4

1. *Equilibrium Moisture Content*
2. *Water Activity*
3. *Equilibrium Relative Humidity*
4. *Methods for determining equilibrium moisture content*
5. *Mathematical models of equilibrium moisture content*

Why is Equilibrium Moisture Content Important?

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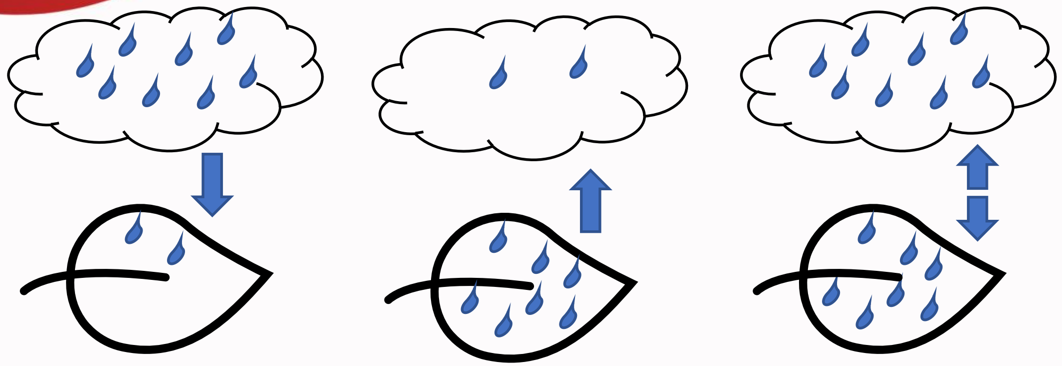
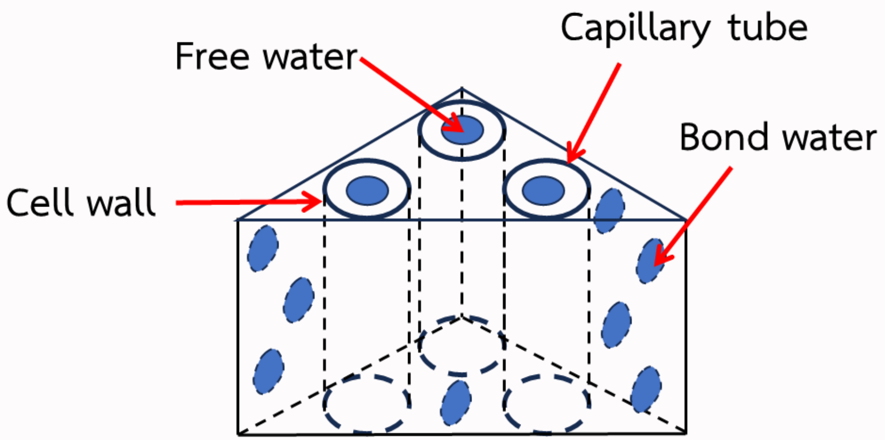
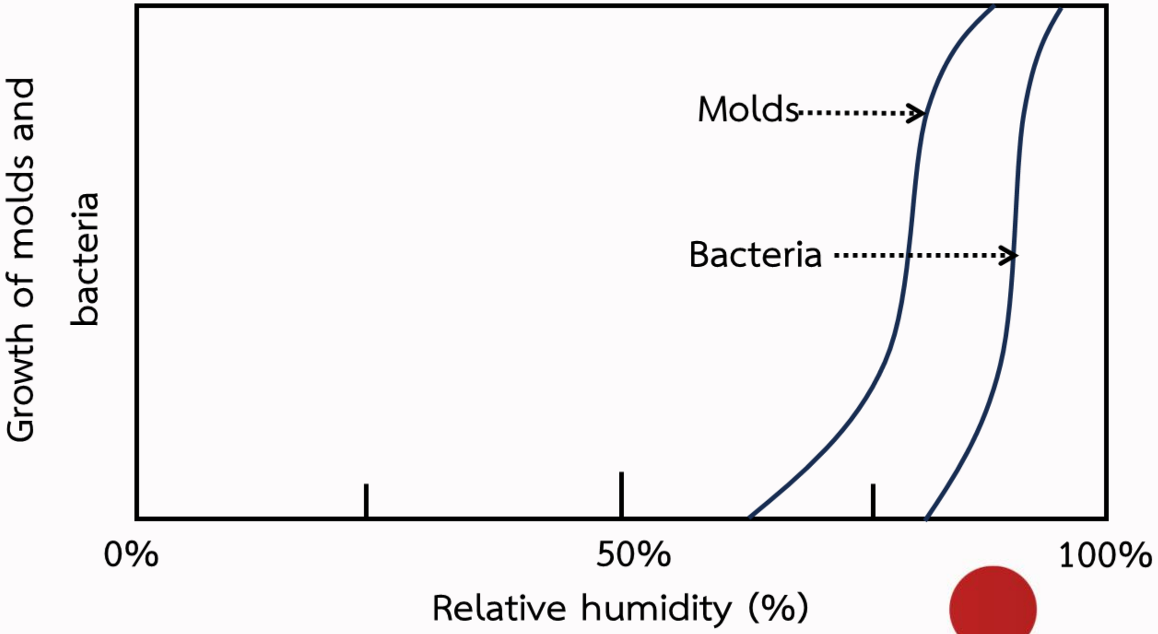
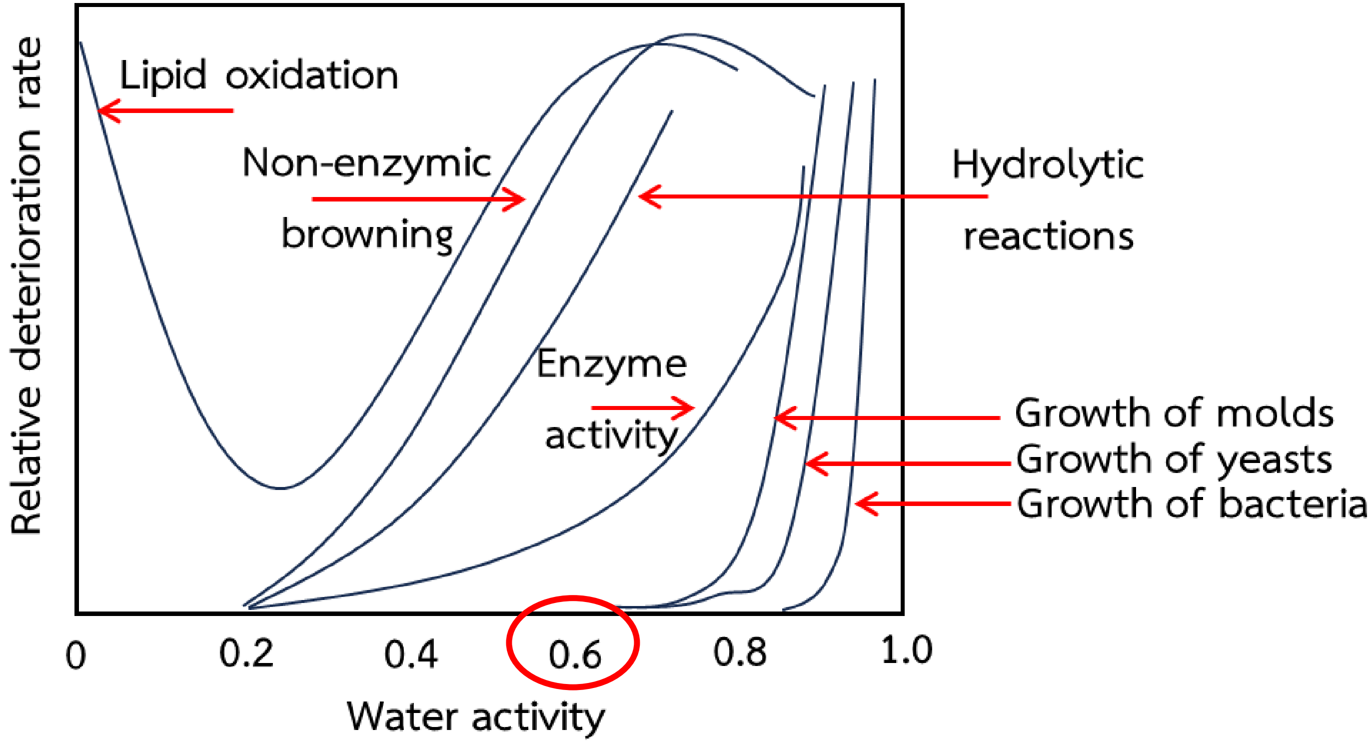






Water Activity (a_w)



Reference: adapted from Berg & Bruin, 1981, p.4

Chirife & Fontana, 2007, p.3

Water activity (a_w) is defined as the ratio of the vapor pressure of free water in the material to the vapor pressure of pure water at the same temperature and pressure

Water activity < 0.6 : reduce the deterioration of agricultural products

Water activity > 0.6 : this results in faster deterioration due to material degradation by molds, yeasts, and bacteria

Equilibrium Relative Humidity - ERH

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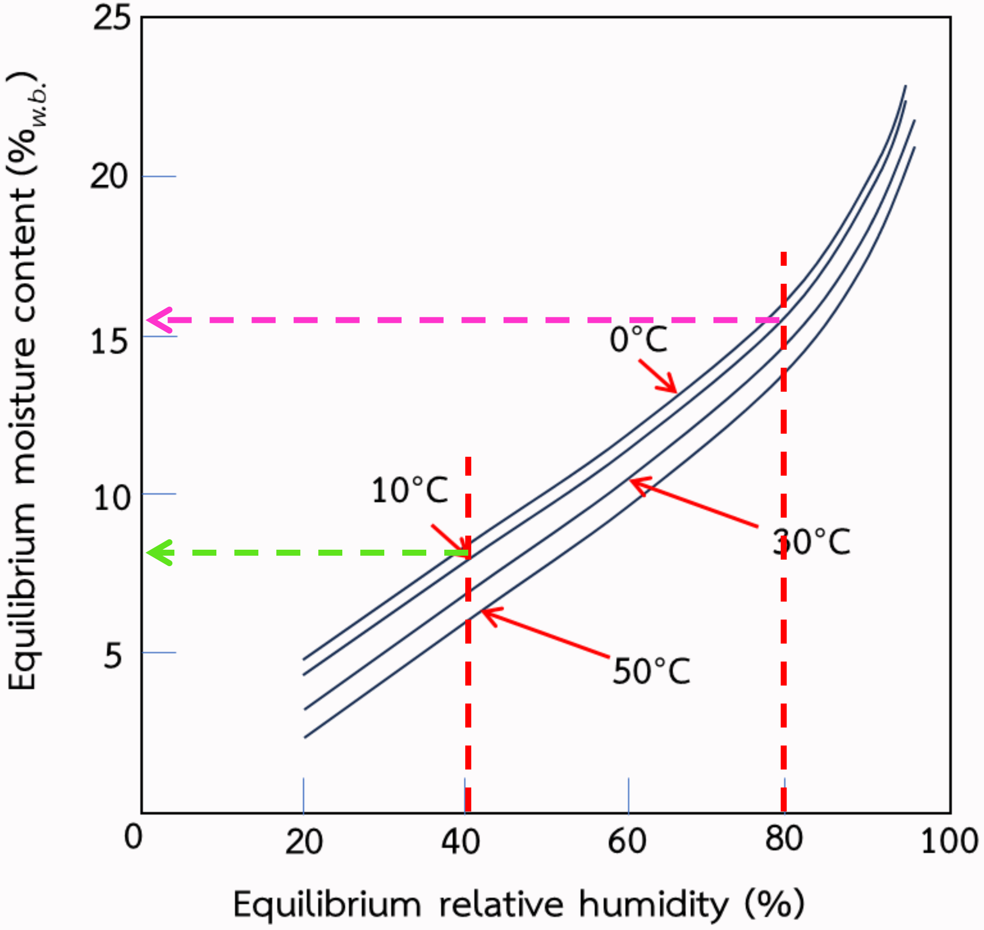

Reference: adapted from ASABE, 1999, p.524

- The relative humidity of air when a material is at equilibrium moisture content is referred to as the equilibrium relative humidity
- At a constant temperature of 10°C and an equilibrium relative humidity of 40%, the equilibrium moisture content of the material is approximately $7.5\%_{w.b.}$
- If the equilibrium relative humidity increases to 80%, the equilibrium moisture content increases to approximately $16\%_{w.b.}$

Equilibrium Moisture Content of Soybeans as a Function of Air Relative Humidity and Temperature

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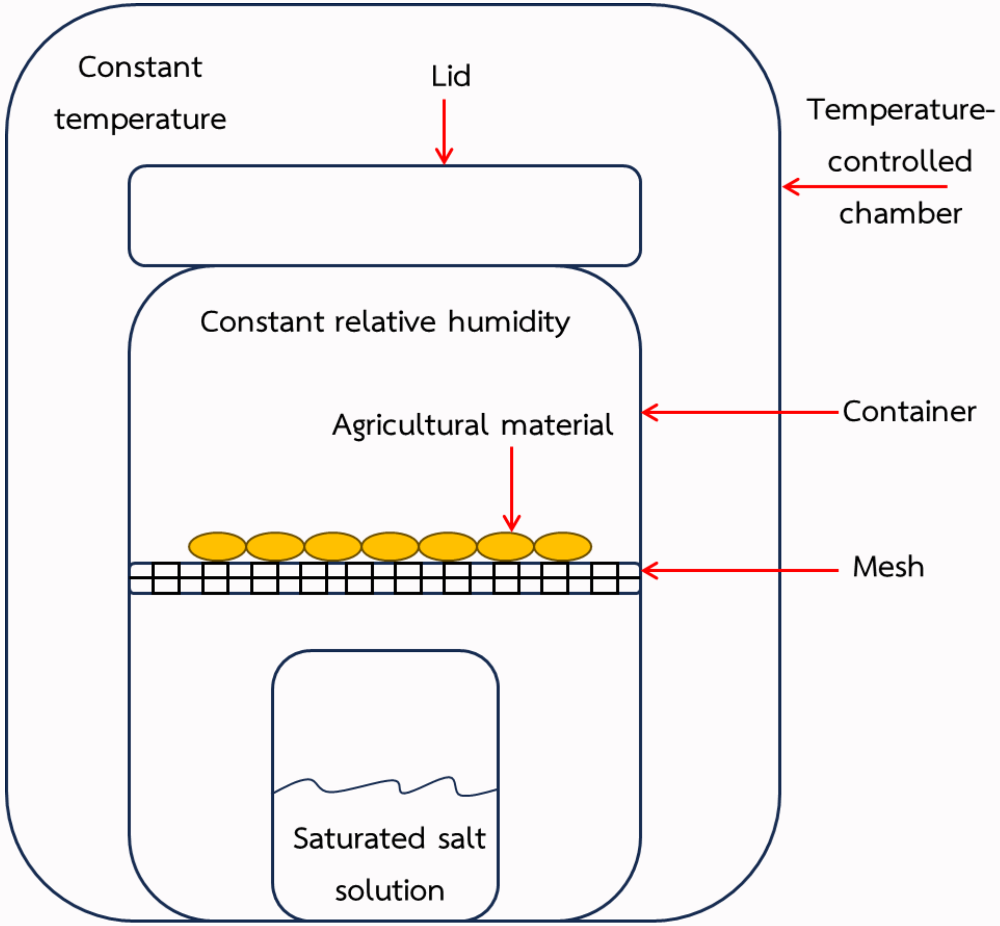
Temperature (°C)	Equilibrium relative humidity (ERH, %) / Equilibrium moisture content (EMC, $\%_{d.b.}$)												
5	ERH	13.8	14.7	38.4	39.2	58.6	60.1	68.4	68.8	75.3	74.5	80.3	80.5
	EMC	5.4	5.5	9.0	8.9	12.9	12.6	15.7	15.7	19.1	19.3	24.0	23.2
10	ERH	15.0	14.4	42.4	42.1	61.2	61.1	69.1	69.1	74.6	74.3	80.6	80.5
	EMC	5.5	5.2	8.6	8.7	12.7	12.7	15.7	15.6	18.8	18.3	23.2	23.2
15	ERH	16.9	16.6	45.4	45.3	62.0	63.0	69.8	69.2	74.1	75.8	80.7	81.1
	EMC	5.4	5.1	8.8	8.8	12.6	12.8	15.5	15.5	18.6	18.3	23.3	23.0
25	ERH	20.7	19.5	46.9	47.0	62.7	63.0	69.7	69.4	75.6	75.9	81.0	81.9
	EMC	5.5	5.1	9.0	8.7	12.8	12.4	15.5	15.0	17.9	19.1	23.1	22.9
35	ERH	21.4	21.4	49.3	49.9	64.1	64.2	71.1	70.3	76.7	76.0	82.8	81.7
	EMC	5.3	5.3	8.8	8.7	12.5	12.5	15.4	15.1	18.1	18.2	23.6	22.6

Reference: ASABE, 1999, p.521

Methods for Determining Equilibrium Moisture Content (EMC)



Static method

A material can reach equilibrium by two mechanisms: moisture adsorption and desorption with the air inside the container

When maintained under these conditions, the material eventually attains a constant mass, which is defined as the equilibrium moisture condition

Relative Humidity Levels at Different Temperatures above Saturated Salt Solutions

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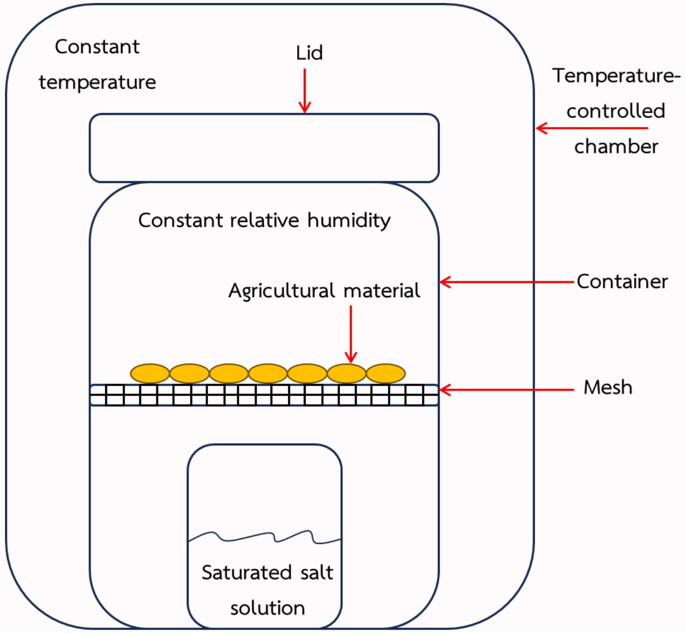

Salt solution	Temperature (°C)								
	10	15	20	25	30	35	40	45	50
	Relative humidity (%)								
$ZnCl_2$	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
NaOH	8.5	8.0	7.5	7.0	7.0	7.0	6.6	6.3	6.0
LiCl	14.5	14.0	13.5	13.0	11.5	11.5	11.0	11.0	11.0
$KC_2H_3O_2$	25.5	25.0	25.0	25.0	22.0	22.0	20.0	19.5	19.0
$MgCl_2$	34.0	33.0	32.8	32.5	32.5	32.5	32.0	31.5	31.5
NaI	38.0	38.0	38.0	38.0	36.0	34.0	32.5	N/A	29.0
$K2CO_3$	47.0	44.0	N/A	43.0	N/A	41.5	41.0	41.0	41.0
KNO_2	49.0	48.5	48.5	47.5	47.0	46.5	46.0	N/A	N/A
$Mg(NO_3)_2$	58.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
NaBr	63.9	61.0	N/A	57.5	N/A	54.5	53.0	51.5	49.5
$NaNO_2$	66.0	66.0	65.5	64.0	63.0	62.0	61.5	61.0	60.0
NaCl	75.5	75.5	75.0	75.0	75.0	75.0	75.0	75.0	74.5
KCl	88.0	86.5	85.0	85.0	84.5	83.0	82.0	81.0	80.5
KNO_3	96.0	95.5	93.5	92.5	91.0	89.5	88.0	86.5	85.0

Note: N/A = not applicable.

Reference: Hong et al., 2002, p.35

Methods for Determining Equilibrium Moisture Content (EMC) (Cont.)

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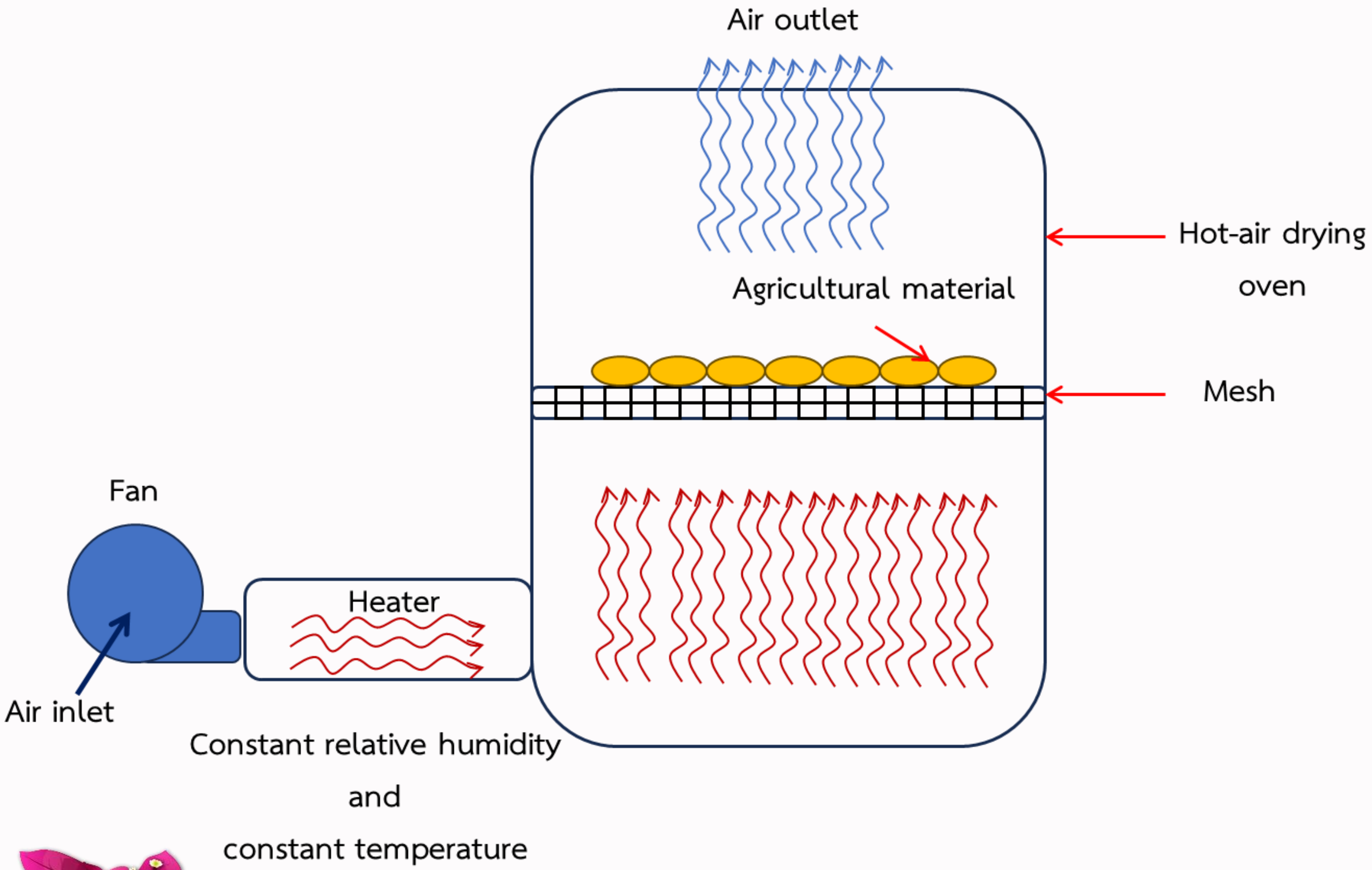

Dynamic method

The dynamic method involves passing air at a constant temperature and relative humidity over the material until its mass no longer changes

Mathematical Models of Equilibrium Moisture Content

Modified Henderson	$RH = 1 - \exp[-A \times (T + C) \times (MC_{d.b.})^{B}]$
Modified Chung-Pfost	$RH = \exp\left[-\dfrac{A}{T+C} \times \exp(-B \times MC_{d.b.})\right]$
Modified Halsey	$RH = \exp\left[-\dfrac{\exp(A + (B \times T))}{(MC_{d.b.})^{C}}\right]$
Modified Oswin	$RH = \left[\left(\dfrac{A + (B \times T)}{MC_{d.b.}}\right) + 1\right]^{-1}$

When

RH is the air relative humidity (decimal)

T is the air temperature (°C)

$MC_{d.b.}$ is the moisture content on a dry basis ($\%_{d.b.}$)

A, B, and C are constants

Reference: ASABE, 1999, p.512

Mathematical Models of Equilibrium Moisture Content (Cont.)

Agricultural Product	*A*	*B*	*C*
Modified Henderson			
Shelled corn	6.6612×10^{-5}	1.9677	42.143
Oats	0.000085511	2.0087	37.811
Rough rice, long grain	0.000041276	2.1191	49.828
Sunflower seed	0.00031	1.7459	66.603
Modified Chung-Pfost			
Barley	475.12	0.14843	71.996
Shelled corn	374.34	0.18662	31.696
Oats	442.85	0.21228	35.803
Rough rice, long grain	412.02	0.17528	39.016
Sunflower seed	399.472	32.1403	53.4887

Agricultural Product	*A*	*B*	*C*
Modified Halsey			
Peanuts, kernels	3.9916	-0.017856	2.2375
Sunflower seed	3.2945	-0.0143	1.8641
Soybeans, Britain	3.0446	-0.0054321	1.5245
Modified Oswin			
Shelled corn	15.303	-0.10184	31.6960
Oats	12.412	-0.060707	2.9397
Rough rice, long grain	14.431	-0.07886	3.1370
Peanuts, kernels	6.9812	-0.04387	3.7021

Reference: ASABE, 1999, p.525

Example 1

A farmer stores rough rice (long grain) in a tightly sealed sack and keeps it in a temperature-controlled room at 30°C. During storage, the farmer installs a sensor to measure air temperature and relative humidity in the headspace above the grain inside the sack. After 48 hours, the sensor reports 30°C and 70% relative humidity on a mobile application. Determine the moisture content of the rough rice (long grain) using the Modified Chung–Pfost equation.

Example 1 (Cont.)

A farmer stores rough rice (long grain) in a tightly sealed sack and keeps it in a temperature-controlled room at 30°C. During storage, the farmer installs a sensor to measure air temperature and relative humidity in the headspace above the grain inside the sack. After 48 hours, the sensor reports 30°C and 70% relative humidity on a mobile application. Determine the moisture content of the rough rice (long grain) using the Modified Chung–Pfost equation.

Given: $T = 30°C$ $RH = 70\% = 0.70$

Agricultural Product	*A*	*B*	*C*
Modified Chung-Pfost			
Rough rice, long grain	412.02	0.17528	39.016

$$RH = \exp\left[-\frac{A}{T+C} \times \exp(-B \times MC_{d.b.})\right]$$

Example 1 (Cont.)

$$RH = \exp\left[-\frac{A}{T+C} \times \exp(-B \times MC_{d.b.}) \right]$$

$$0.70 = \exp\left[-\frac{412.02}{30+39.016} \times \exp(-0.17528 \times MC_{d.b.}) \right]$$

$$\ln(0.70) = \left[-\frac{412.02}{30+39.016} \times \exp(-0.17528 \times MC_{d.b.}) \right]$$

$$-0.35667 = -5.96992 \times \exp(-0.17528 \times MC_{d.b.})$$

$$\ln\left(\frac{-0.35667}{-5.96992}\right) = -0.17528 \times MC_{d.b.}$$

$$-2.81768 = -0.17528 \times MC_{d.b.}$$

$$MC_{d.b.} = 16.07\ \%_{d.b.}$$

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Given: T = 30°C RH = 70% = 0.70

Agricultural Product	*A*	*B*	*C*
Modified Chung-Pfost			
Rough rice, long grain	412.02	0.17528	39.016

Ans. The moisture content of rough rice (long grain) is $16.07\%_{d.b.}$

Example 2

A farmer stores shelled corn in the field and dries it using sun drying until the equilibrium moisture content reaches $18\%_{d.b.}$. However, at this moisture level, the product cannot be safely stored due to the high moisture content. Therefore, the farmer designs a hot-air drying system in which heated air is blown through a grain bed at an air temperature of 45°C and a relative humidity of 40%. Determine whether, under these air conditions, the moisture content of the shelled corn can be reduced to $11\%_{d.b.}$. Use the Modified Henderson model for the analysis

Example 2 (Cont.)

A farmer stores shelled corn in the field and dries it using sun drying until the equilibrium moisture content reaches $18\%_{d.b.}$. However, at this moisture level, the product cannot be safely stored due to the high moisture content. Therefore, the farmer designs a hot-air drying system in which heated air is blown through a grain bed at an air temperature of 45°C and a relative humidity of 40%. Determine whether, under these air conditions, the moisture content of the shelled corn can be reduced to $11\%_{d.b.}$. Use the Modified Henderson model for the analysis

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Given: T = 45°C RH = 40% = 0.40

Agricultural Product	*A*	*B*	*C*
Modified Henderson			
Shelled corn	6.6612×10^{-5}	1.9677	42.143

$$RH = 1 - \exp[-A \times (T + C) \times (MC_{d.b.})^{B}]$$

Example 2 (Cont.)

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$$RH = 1 - \exp[-A \times (T + C) \times (MC_{d.b.})^{B}]$$

$$0.40 = 1 - \exp[-6.6612 \times 10^{-5} \times (45 + 42.143) \times (MC_{d.b.})^{1.9677}]$$

$$0.6 = \exp[-6.6612 \times 10^{-5} \times (45 + 42.143) \times (MC_{d.b.})^{1.9677}]$$

$$\ln(0.6) = -6.6612 \times 10^{-5} \times (45 + 42.143) \times (MC_{d.b.})^{1.9677}$$

$$(MC_{d.b.})^{1.9677} = \frac{\ln(0.6)}{-6.6612 \times 10^{-5} \times (45 + 42.143)}$$

$$(MC_{d.b.})^{1.9677} = 88.0010$$

$$MC_{d.b.} = 9.73\ \%_{d.b.}$$

Given: T = 45°C RH = 40% = 0.40

Agricultural Product	*A*	*B*	*C*
Modified Henderson			
Shelled corn	6.6612×10^{-5}	1.9677	42.143

<u>**Ans.**</u> Under the given air conditions, the moisture content of shelled corn can be reduced to $11\%_{d.b.}$, since the mathematical model predicts that the moisture content can be lowered to approximately $9.73\%_{d.b.}$.

Summary

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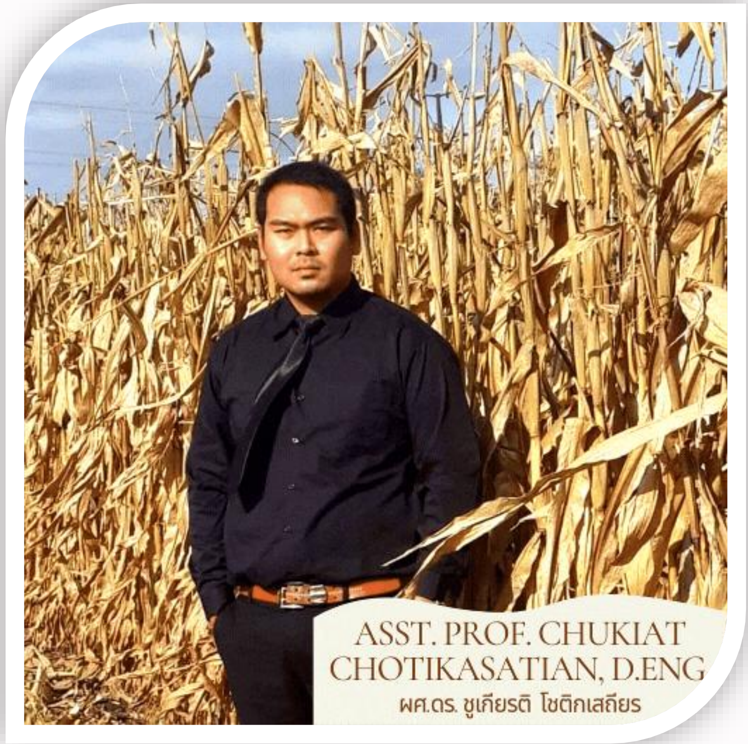
1. After drying, grains stored under controlled air temperature and relative humidity tend to reach moisture equilibrium with the surrounding air.

2. In this chapter, learners can estimate the equilibrium moisture content (EMC) of materials from air temperature and relative humidity.

3. EMC estimation is based on mathematical models developed by various researchers.

4. Knowledge of EMC helps in determining suitable air conditions for safe storage of agricultural products.



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Thank you very much for your kind attention.

Questions?

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Study Questions – Lecture 4

1. *What is equilibrium moisture content, and why is it important in drying and storage of agricultural products?*
2. *How is water activity related to equilibrium moisture content and product deterioration?*
3. *What is equilibrium relative humidity, and how does it relate to material moisture equilibrium?*
4. *How can equilibrium moisture content be determined experimentally?*
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Assignment – Lecture 4

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1. A farmer harvests sunflower seeds from the field and finds that their moisture content is high. The farmer therefore dries the seeds under controlled conditions at an air temperature of 55°C and a relative humidity of 30%. Determine the minimum moisture content to which the sunflower seeds can be dried under these air conditions. Compare the results obtained using the Modified Henderson model and the Modified Chung–Pfost model.

Assignment – Lecture 4 (Cont.)

2. A farmer wants to store 300 rice seeds for planting. The seeds will be stored using the static method at a constant temperature of 10°C, and the target equilibrium moisture content (EMC) is 5.0–5.5%$_{d.b.}$, based on the data in the tables. Determine which saturated salt solution should be selected and what relative humidity level must be maintained to achieve this EMC range.

Temperature (°C)		Equilibrium relative humidity (ERH, %) / Equilibrium moisture content (EMC, %$_{d.b.}$)											
5	ERH	13.8	14.7	38.4	39.2	58.6	60.1	68.4	68.8	75.3	74.5	80.3	80.5
	EMC	5.4	5.5	9.0	8.9	12.9	12.6	15.7	15.7	19.1	19.3	24.0	23.2
10	ERH	15.0	14.4	42.4	42.1	61.2	61.1	69.1	69.1	74.6	74.3	80.6	80.5
	EMC	5.5	5.2	8.6	8.7	12.7	12.7	15.7	15.6	18.8	18.3	23.2	23.2
15	ERH	16.9	16.6	45.4	45.3	62.0	63.0	69.8	69.2	74.1	75.8	80.7	81.1
	EMC	5.4	5.1	8.8	8.8	12.6	12.8	15.5	15.5	18.6	18.3	23.3	23.0
25	ERH	20.7	19.5	46.9	47.0	62.7	63.0	69.7	69.4	75.6	75.9	81.0	81.9
	EMC	5.5	5.1	9.0	8.7	12.8	12.4	15.5	15.0	17.9	19.1	23.1	22.9
35	ERH	21.4	21.4	49.3	49.9	64.1	64.2	71.1	70.3	76.7	76.0	82.8	81.7
	EMC	5.3	5.3	8.8	8.7	12.5	12.5	15.4	15.1	18.1	18.2	23.6	22.6

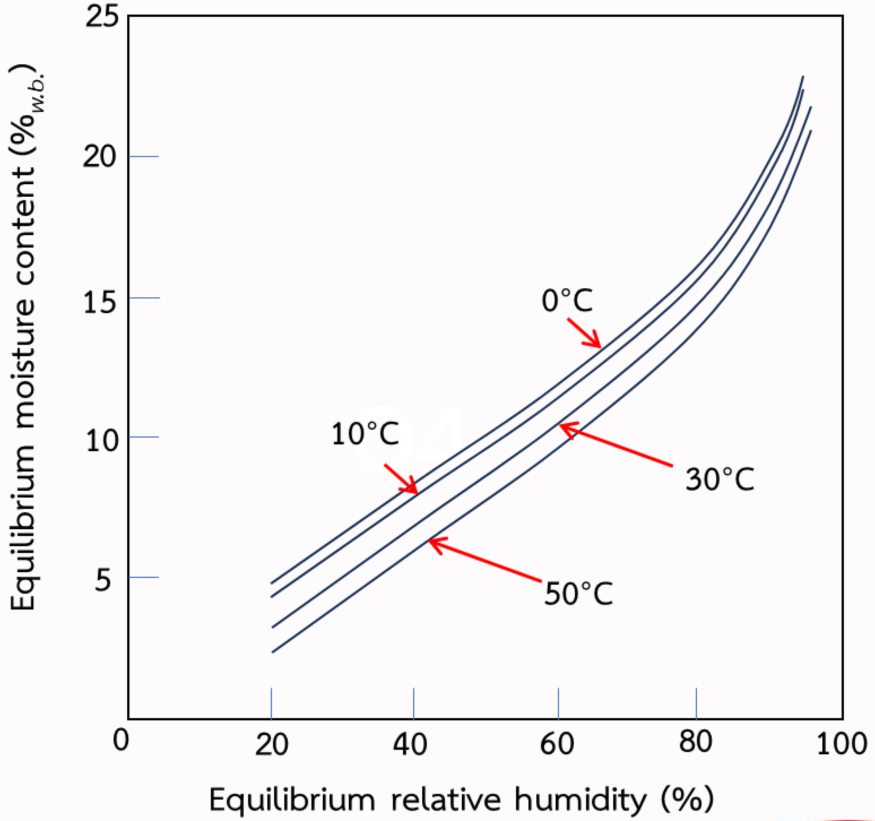
Salt solution	Temperature (°C)								
	10	15	20	25	30	35	40	45	50
	Relative humidity (%)								
$ZnCl_2$	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
NaOH	8.5	8.0	7.5	7.0	7.0	7.0	6.6	6.3	6.0
LiCl	14.5	14.0	13.5	13.0	11.5	11.5	11.0	11.0	11.0
$KC_2H_3O_2$	25.5	25.0	25.0	25.0	22.0	22.0	20.0	19.5	19.0
$MgCl_2$	34.0	33.0	32.8	32.5	32.5	32.5	32.0	31.5	31.5
NaI	38.0	38.0	38.0	38.0	36.0	34.0	32.5	N/A	29.0
$K2CO_3$	47.0	44.0	N/A	43.0	N/A	41.5	41.0	41.0	41.0
KNO_2	49.0	48.5	48.5	47.5	47.0	46.5	46.0	N/A	N/A
$Mg(NO_3)_2$	58.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
NaBr	63.9	61.0	N/A	57.5	N/A	54.5	53.0	51.5	49.5
$NaNO_2$	66.0	66.0	65.5	64.0	63.0	62.0	61.5	61.0	60.0
NaCl	75.5	75.5	75.0	75.0	75.0	75.0	75.0	75.0	74.5
KCl	88.0	86.5	85.0	85.0	84.5	83.0	82.0	81.0	80.5
KNO_3	96.0	95.5	93.5	92.5	91.0	89.5	88.0	86.5	85.0

Assignment – Lecture 4 (Cont.)

3. Based on the information shown in the figure, explain and compare the equilibrium moisture content obtained from drying under the following two conditions:

3.1 When the drying air is controlled at a constant temperature of 30°C and relative humidities of 30%, 50%, and 70%, respectively.

3.2 When the drying air is controlled at a constant relative humidity of 50% and temperatures of 0°C, 10°C, 30°C, and 50°C.



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