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9673204
Drying and Storage

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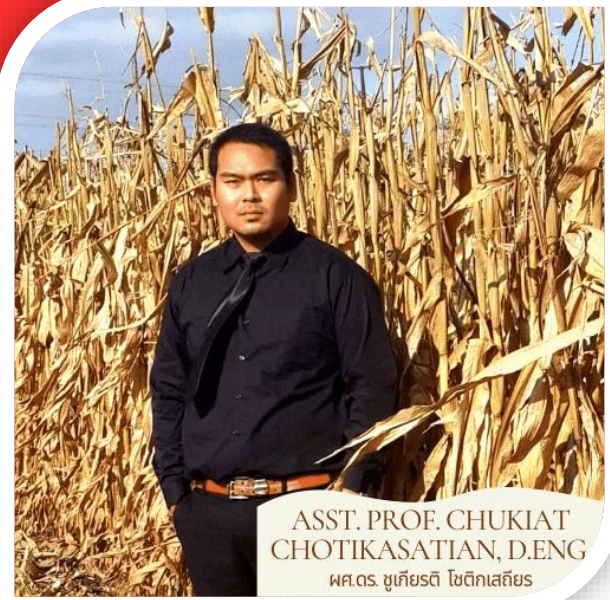
Course Description

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 5 – Physical and Thermal Properties of Agricultural Materials

Study Questions – Lecture 5

1. *Why are physical properties important in dryer and silo design?*
2. *How do bulk density and porosity influence airflow?*
3. *What is the relationship between moisture content and density?*
4. *How do thermal properties affect drying time?*
5. *Why does shrinkage occur during drying?*

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Lecture 5 – Physical and Thermal Properties of Agricultural Materials

Outline – Lecture 5

1. *Importance of Physical & Thermal Properties*
2. *Grain Structure*
3. *Size and Shape*
4. *Density and Porosity*
5. *Shrinkage*
6. *Thermal Properties*

Why are Physical Property of Agricultural Materials Important?

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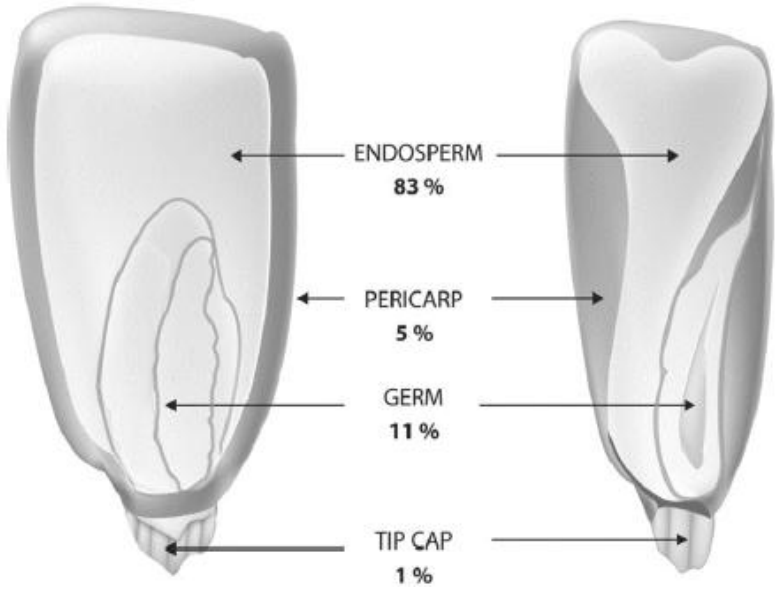
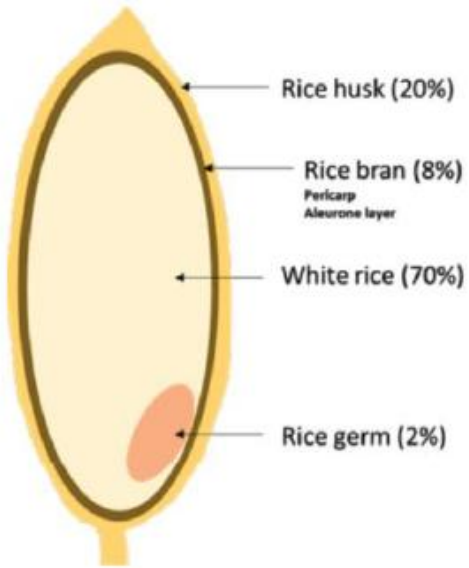
Using a 1,000 kg or 1,000 l Water Tank to Store 1,000 kg of Paddy Rice

A 1,000 kg or 1,000 l water tank might not fit all 1,000 kg of rice grains due to high **moisture content**, size and shape of the grains, and overall bulk density, resulting in large air voids in the grain pile.

References: ChatGPT (OpenAI, 2023)

Grain Structure





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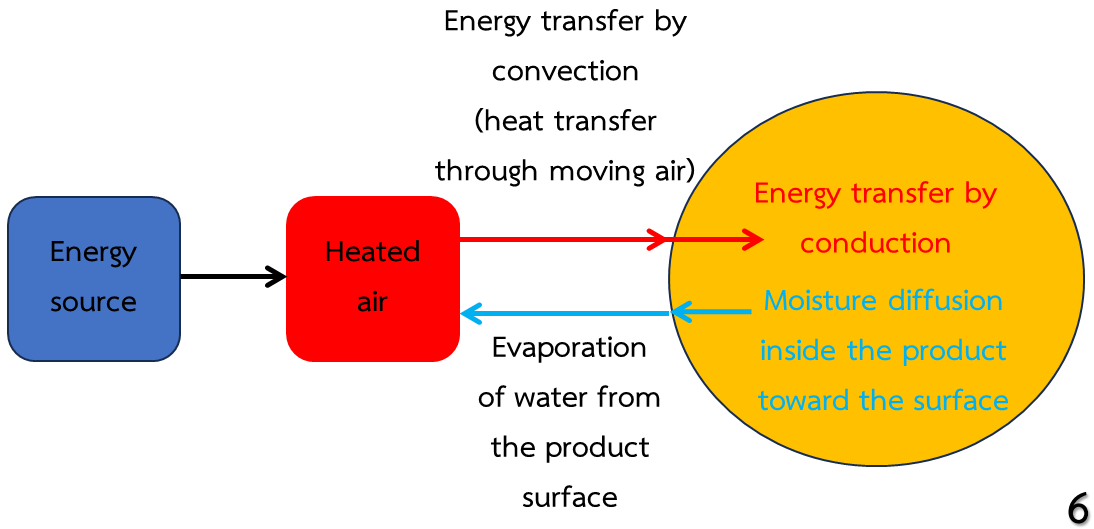
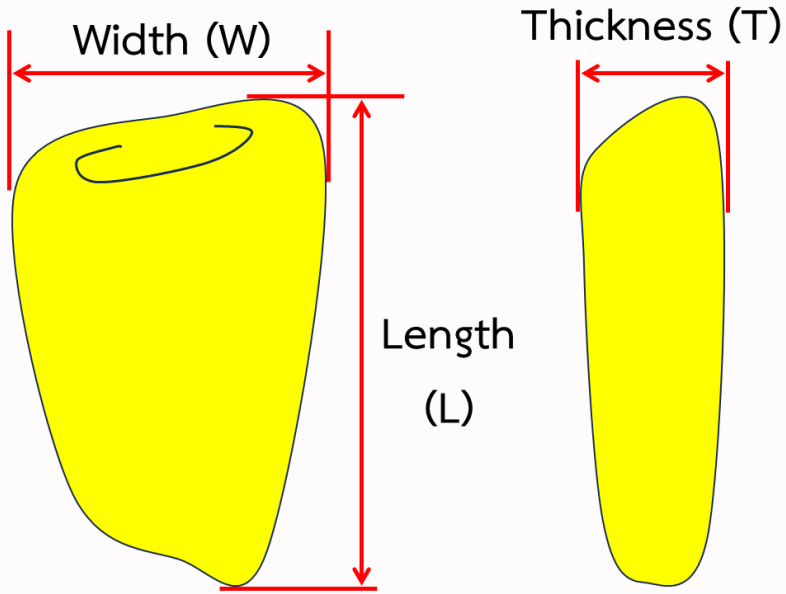
Grain	Pericarp (%)	Germ (%)	Endosperm (%)
Shell corn	4-6	6-11	79-84
Paddy rice	5-7	3-4	89-92
Wheat	13-17	2-3	80-85
Soybean	~9	~2	~90



Reference: Gwirtz & Garcia-Casal, 2014, p. 67;Shafie & Esa, 2017, p. 342
Rivera-Castro et al., 2020, p. 942; Laddomada et al., 2015, p. 15,668

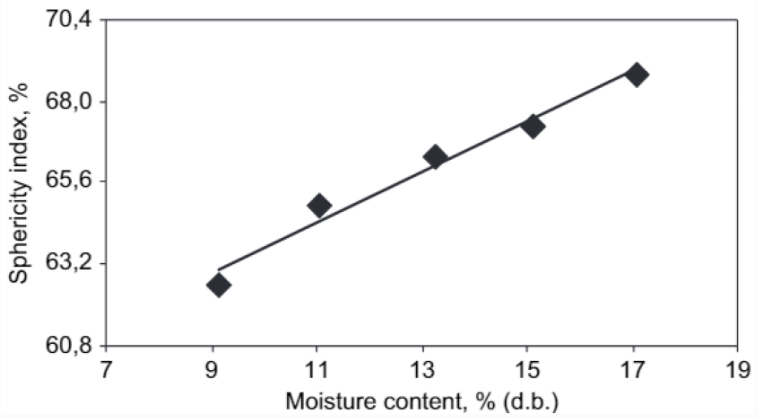
Size and Shape



$$Sphericity\,(\%) = \frac{(LWT)^{\frac{1}{3}}}{L} \times 100$$

$$Kernel\ volume = \frac{\pi WTL^2}{6 \times (2L - \sqrt{WT})}$$

$$Kernel\ surface\ area = \frac{\pi \sqrt{WT}\, L^2}{2L - \sqrt{WT}}$$



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- If the grain has low sphericity (i.e., it deviates significantly from a spherical shape), the movement of moisture from the center of the kernel to its surface takes a longer time
- This extended internal diffusion path increases the resistance to moisture migration, which consequently reduces the drying rate of the grain

Apparent Density (ρ_{app})

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- Apparent density is defined as the ratio of the mass of a material to the volume of the solid portion of that material
- A common method for determining apparent density is the water displacement technique
- The increase in the water level from the initial 500 ml mark represents the volume of water displaced by the solid material
- This displaced volume is considered equal to the solid volume of the material

Reference: Generated using Google Gemini AI, 2026

Bulk Density (ρ_b)

$$\rho_b = \frac{\text{Mass of material inside the container}}{\text{Volume of the container}}$$

- Prepare a container with a known, fixed volume
- Position a funnel approximately 15 cm above the top of the container
- Pour the material into the container until it is completely filled
- Carefully level the surface by removing excess material with a straight edge, ensuring a flat and even top surface
- Weigh the filled container

Reference: Generated using Google Gemini AI, 2026

Porosity (ε)

$$\varepsilon\ (\%) = \frac{\rho_{app} - \rho_b}{\rho_{app}} \times 100$$

When

ρ_{app} = *a*pparent density (kg·m^{-3})

ρ_b = *bulk* density (kg·m^{-3})

Effect on Airflow Resistance

- Lower porosity → fewer air spaces → higher airflow resistance
- Increased resistance results in:
  - Higher pressure drop
  - Reduced air velocity through the grain bed
  - Non-uniform airflow distribution

Effect on Heat Transfer

- Convective heat transfer depends strongly on air velocity
- Reduced air velocity leads to:
  - Lower convective heat transfer coefficient
  - Slower heating of grain surfaces
  - Decreased moisture evaporation rate

Example 1

A sample of 1,000 oat kernels was collected and measured. The average width, length, and thickness were found to be 2.67 mm, 10.84 mm, and 2.03 mm, respectively. Calculate the following physical properties of the oat kernels: sphericity, volume and surface area.

Example 1 (Cont.)

A sample of 1,000 oat kernels was collected and measured. The average width, length, and thickness were found to be 2.67 mm, 10.84 mm, and 2.03 mm, respectively. Calculate the following physical properties of the oat kernels: sphericity, volume and surface area.

$$Sphericity\,(\%) = \frac{(LWT)^{\frac{1}{3}}}{L} \times 100$$

$$Kernel\ volume = \frac{\pi WTL^2}{6 \times (2L - \sqrt{WT})}$$

$$Kernel\ surface\ area = \frac{\pi \sqrt{WT}\, L^2}{2L - \sqrt{WT}}$$

$$Sphericity\,(\%) = \frac{(LWT)^{\frac{1}{3}}}{L} \times 100$$

$$Sphericity\,(\%) = \frac{(10.84 \times 2.67 \times 2.03)^{\frac{1}{3}}}{10.84} \times 100$$

$$Sphericity\,(\%) = 35.86\%$$

Example 1 (Cont.)

A sample of 1,000 oat kernels was collected and measured. The average width, length, and thickness were found to be 2.67 mm, 10.84 mm, and 2.03 mm, respectively. Calculate the following physical properties of the oat kernels: sphericity, volume and surface area.

$$Kernel\ volume = \frac{\pi WTL^2}{6 \times (2L - \sqrt{WT})}$$

$$Kernel\ volume = \frac{\pi WTL^2}{6 \times (2L - \sqrt{WT})}$$

$$Kernel\ volume = \frac{\pi \times 2.67 \times 2.03 \times 10.84^2}{6 \times [(2 \times 10.84) - \sqrt{2.67 \times 2.03}]}$$

$$Kernel\ volume = 17.22\ mm^3$$

$$Kernel\ surface\ area = \frac{\pi \sqrt{WT}\, L^2}{2L - \sqrt{WT}}$$

Example 1 (Cont.)

A sample of 1,000 oat kernels was collected and measured. The average width, length, and thickness were found to be 2.67 mm, 10.84 mm, and 2.03 mm, respectively. Calculate the following physical properties of the oat kernels: sphericity, volume and surface area.

$$Kernel\ surface\ area = \frac{\pi \sqrt{WT}\, L^2}{2L - \sqrt{WT}}$$

$$Kernel\ surface\ area = \frac{\pi \times \sqrt{2.67 \times 2.03} \times 10.84^2}{(2 \times 10.84) - \sqrt{2.67 \times 2.03}}$$

$$Kernel\ surface\ area = 44.39\ mm^2$$

Example 2

An avocado has a mass of 240 g. A container filled with water alone has a total mass of 1,200 g. When the avocado is placed into the water-filled container, the combined mass of the container, water, and avocado becomes 1,410 g. The temperature of the water at the time of measurement is 20°C. Determine the apparent density of the avocado.

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Example 2 (Cont.)

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An avocado has a mass of 240 g. A container filled with water alone has a total mass of 1,200 g. When the avocado is placed into the water-filled container, the combined mass of the container, water, and avocado becomes 1,410 g. The temperature of the water at the time of measurement is 20°C. Determine the apparent density of the avocado.

Given:

Mass of avocado =240 g

Mass of container + water =1,200 g

Mass of container + water + avocado = 1,410 g

Water temperature: 20°C → $\rho_w \approx 0.998$ g·ml^{-1}

Find the mass of displaced water

1,410 – 1200 = 210 g

Convert displaced water mass to displaced volume

$$Volume = \frac{210\ g}{0.9982\ \frac{g}{cm^3}} = 210.38\ cm^3$$

Example 2 (Cont.)

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Calculate apparent density of the avocado

$$\rho_{app} = \frac{240\ g}{210.38\ cm^3} = 1.1408\ g \cdot\ cm^{-3}$$

Thus, the apparent density of the avocado is 1.1408 g·cm^{-3}

- It can be observed that the density of the avocado is very close to the density of water
- Therefore, when the avocado is placed into a container filled with water, it will sink below the water surface

Reference: Generated using Google Gemini AI, 2026

Mathematical Models

type	moisture content ($\%_{w.b.}$)	bulk density ($kg \cdot m^{-3}$)
Barley	15-40	$\rho_b = 705.4 - 1{,}142\ (MC_{w.b.}) + 1{,}950\ (MC_{w.b.})^2$
Corn	15-40	$\rho_b = 1{,}086.3 - 2{,}971\ (MC_{w.b.}) + 4{,}810\ (MC_{w.b.})^2$
	10-35	$\rho_b = 701.9 + 1{,}676\ (MC_{w.b.}) - 11{,}598\ (MCw.b.)^2 + 18{,}240\ (MC_{w.b.})^3$
Oats	15-40	$\rho_b = 773.0 - 2{,}311\ (MC_{w.b.}) + 3{,}630\ (MC_{w.b.})^2$
Rye	15-40	$\rho_b = 974.8 - 2{,}052\ (MC_{w.b.}) + 2{,}850\ (MC_{w.b.})^2$
Sorghum	15-40	$\rho_b = 829.1 - 643\ (MC_{w.b.}) + 660\ (MC_{w.b.})^2$
Soybeans	15-40	$\rho_b = 734.5 - 219\ (MC_{w.b.}) + 70\ (MC_{w.b.})^2$
Wheat	15-40	$\rho_b = 885.3 - 1{,}631\ (MC_{w.b.}) + 2{,}640\ (MC_{w.b.})^2$
	3-24	$\rho_b = 774.4 - 703\ (MC_{w.b.}) + 18{,}510\ (MC_{w.b.})^2 - 148{,}960\ (MC_{w.b.})^3 + 311{,}600\ (MC_{w.b.})^4$

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- Describing the relationship between the moisture content of cereal grains and their bulk density

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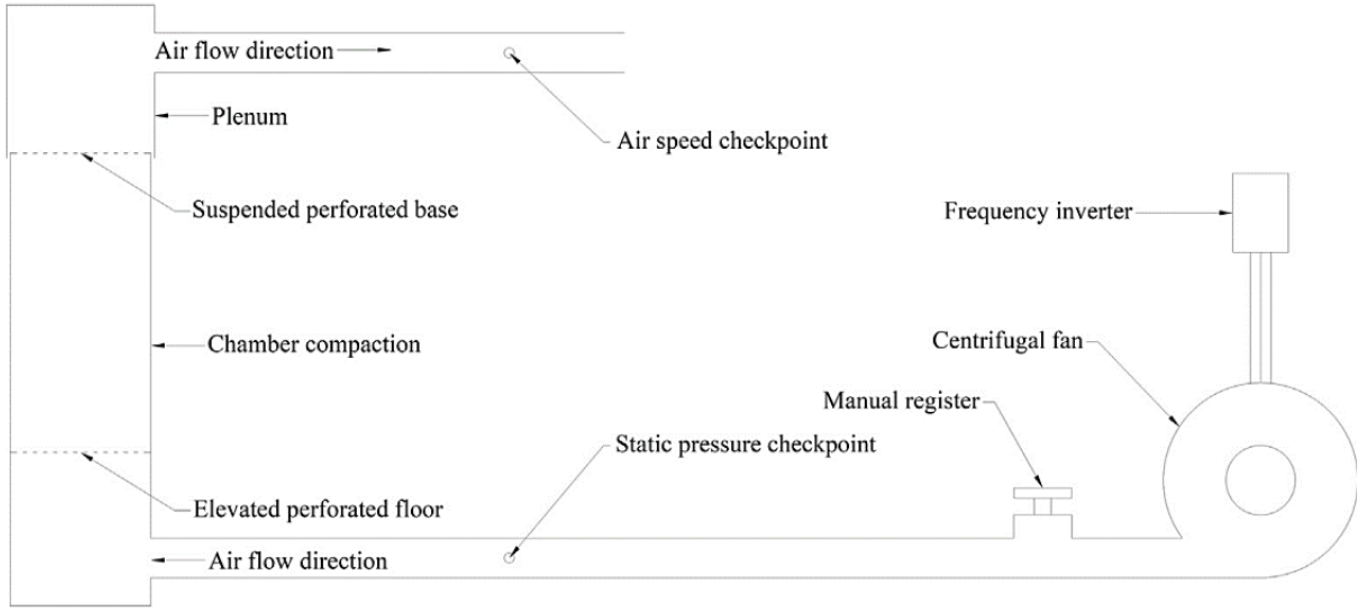
Reference: ASABE, 2000, p. 505

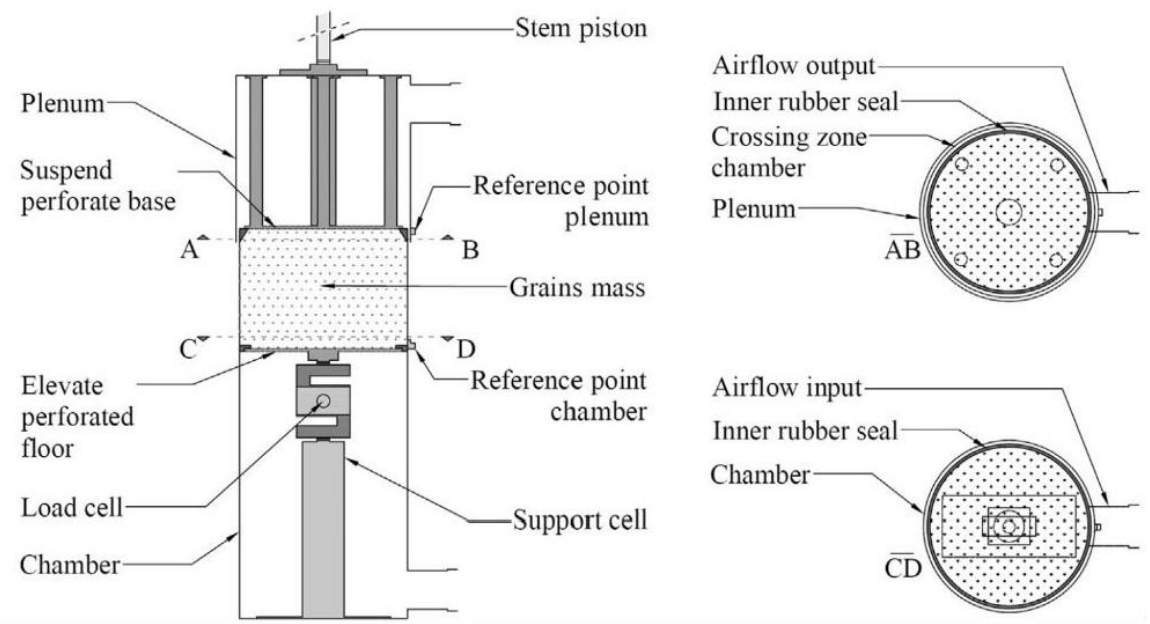
Importance of Bulk Density and Porosity

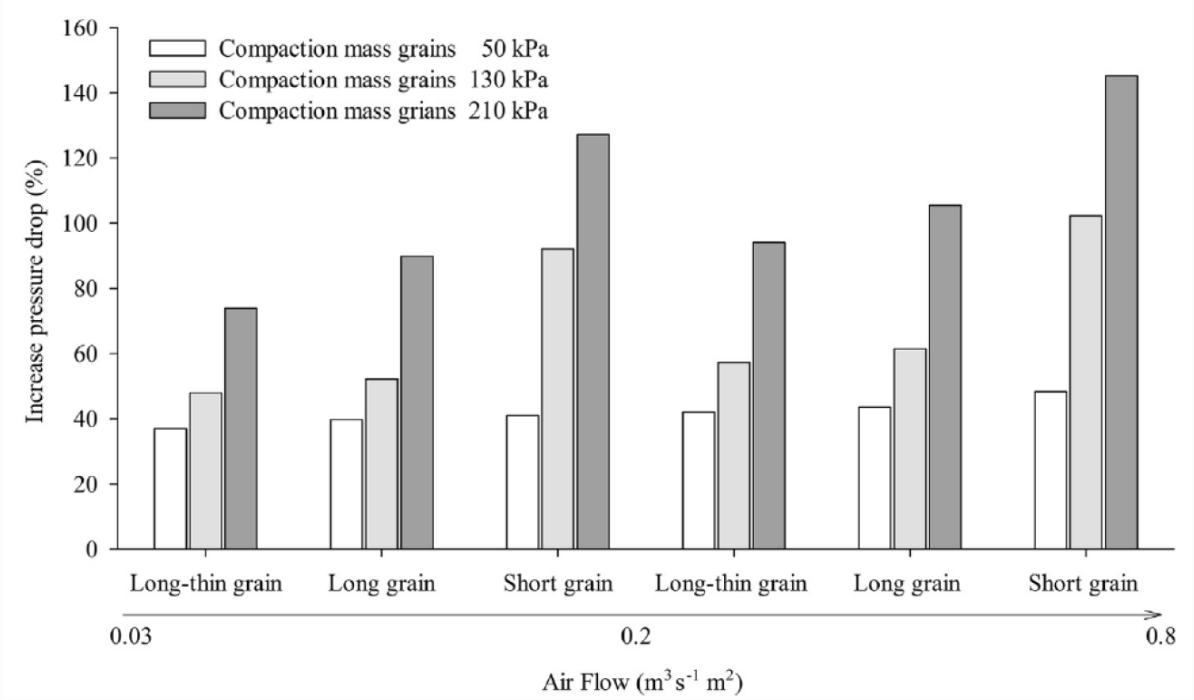
Parameters	Rice grain classification		
	Long thin	Long	Short
Length (mm)	$9.60^{a} \pm 0.22$	$9.50^{a} \pm 0.19$	$6.60^{b} \pm 0.14$
Width (mm)	$2.30^{b} \pm 0.03$	$3.20^{a} \pm 0.07$	$3.10^{a} \pm 0.06$
Thickness (mm)	$1.90^{c} \pm 0.00$	$2.20^{a} \pm 0.03$	$2.10^{b} \pm 0.03$
Sphericity (dimensionless)	$0.37^{c} \pm 0.00$	$0.42^{b} \pm 0.00$	$0.53^{a} \pm 0.00$
Equivalent diameter (mm)	$3.50^{b} \pm 0.04$	$4.0^{a} \pm 0.06$	$3.60^{b} \pm 0.06$
Surface area (mm^2)	$36.00^{b} \pm 0.92$	$47.00^{a} \pm 1.52$	$33.90^{b} \pm 1.16$
Aspect ratio (adm)	$0.24^{c} \pm 0.00$	$0.33^{b} \pm 0.00$	$0.47^{a} \pm 0.00$
Volume (mm^3)	$23.05^{b} \pm 0.79$	$37.30^{a} \pm 1.81$	$24.60^{b} \pm 1.28$
Bulk density ($kg\ m^{-3}$)	$617.80^{c} \pm 0.98$	$621.30^{b} \pm 0.93$	$634.20^{a} \pm 1.09$
Kernel density ($kg\ m^{-3}$)	$1450^{a} \pm 64.30$	$1386^{b} \pm 58.20$	$1289^{c} \pm 63.50$
Porosity (%)	$57.40^{a} \pm 0.30$	$55.20^{b} \pm 0.17$	$50.80^{c} \pm 0.19$
Thousand weight of grains (g)	$27.60^{b} \pm 0.08$	$36.20^{a} \pm 0.05$	$25.80^{c} \pm 0.04$
Moisture content (%, w.b.)	$13.10^{a} \pm 0.15$	$12.80^{a} \pm 0.30$	$12.80^{a} \pm 0.22$



Reference: Rocha et al., 2020, p. 28-32

Importance of Bulk Density and Porosity (Cont.)





Reference: Rocha et al., 2020, p. 28-33

Shrinkage

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The loss of water from a material results in a decrease in its moisture content

During the initial stage of moisture removal, shrinkage is clearly observable because the material structure is still highly influenced by its water content

However, as the moisture content continues to decrease and approaches zero, the rate of shrinkage gradually declines

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Example 3

A cylindrical tank with a diameter of 6.4 m can store 20 tons of corn at a moisture content of 15%$_{w.b.}$

Calculate the following:

- The height of the corn bulk before drying
- The height of the corn bulk after drying, when the final moisture content is reduced to 12%$_{w.b.}$
- The percentage shrinkage of the corn after drying

Example 3 (Cont.)

A cylindrical tank with a diameter of 6.4 m can store 20 tons of corn at a moisture content of 15% wet basis (w.b.)

Calculate the following:

- The height of the corn bulk before drying

type	moisture content ($\%_{w.b.}$)	bulk density ($kg \cdot m^{-3}$)
Corn	15-40	$\rho_b = 1{,}086.3 - 2{,}971\ (MC_{w.b.}) + 4{,}810\ (MC_{w.b.})^2$
	10-35	$\rho_b = 701.9 + 1{,}676\ (MC_{w.b.}) - 11{,}598\ (MCw.b.)^2 + 18{,}240\ (MC_{w.b.})^3$

$$\rho_b = \frac{\text{Mass of material inside the container}}{\text{Volume of the container}}$$

$$Volume = \frac{20\ ton \times \dfrac{1{,}000\ kg}{1\ ton}}{753.91\ \dfrac{kg}{m^3}} = 26.83\ m^3$$

$$\rho_b = 701.9 + 1{,}676\ (MC_{w.b.}) - 11{,}598\ (MC_{w.b.})^2 + 18{,}240\ (MC_{w.b.})^3$$

$$\rho_b = 701.9 + 1{,}676\ (0.15) - 11{,}598\ (0.15)^2 + 18{,}240\ (0.15)^3$$

$$\rho_b = 753.91\ kg \cdot m^{-3}$$

$$\frac{\pi D^2 H_1}{4}$$

$$H_1 = \frac{26.83\ m^3 \times 4}{\pi (6.4\ m)^2} = 0.8251\ m$$

Example 3 (Cont.)

A cylindrical tank with a diameter of 6.4 m can store 20 tons of corn at a moisture content of 15% wet basis (w.b.)

Calculate the following:

- The height of the corn bulk after drying, when the final moisture content is reduced to 12%$_{w.b.}$

$$G_w = \frac{G_d \times 100\%}{100 - MC_{w.b.}}$$

$$G_d = \frac{G_w (100 - MC_{w.b.})}{100}$$

Because the dry matter weight of the corn remains constant, it can be assumed that only water is removed during the drying process, while the dry solid mass does not change

$$\rho_b = \frac{\text{Mass of material inside the container}}{\text{Volume of the container}}$$

$$20{,}000\ kg \times (100 - 15) = G_w (100 - 12)$$

$$G_w = \frac{20{,}000\ kg \times (100 - 15)}{(100 - 12)} = 19{,}318.18\ kg$$

$$\rho_b = 701.9 + 1{,}676\ (MC_{w.b.}) - 11{,}598\ (MC_{w.b.})^2 + 18{,}240\ (MC_{w.b.})^3$$

$$\rho_b = 701.9 + 1{,}676\ (0.12) - 11{,}598\ (0.12)^2 + 18{,}240\ (0.12)^3$$

$$\rho_b = 767.52\ kg \cdot m^{-3}$$

$$Volume = \frac{19313.18\ kg}{767.52\ \frac{kg}{m^3}} = 25.17\ m^3$$

$$\frac{\pi D^2 H_2}{4} \rightarrow H_2 = \frac{25.17\ m^3 \times 4}{\pi (6.4\ m)^2} = 0.7828\ m$$

Example 3

A cylindrical tank with a diameter of 6.4 m can store 20 tons of corn at a moisture content of 15% wet basis (w.b.)

Calculate the following:

- The percentage shrinkage of the corn after drying

15%$_{w.b.}$

$$Volume = \frac{20\ ton \times \frac{1{,}000\ kg}{1\ ton}}{753.91\ \frac{kg}{m^3}} = 26.83\ m^3$$

12%$_{w.b.}$

$$Volume = \frac{19313.18\ kg}{767.52\ \frac{kg}{m^3}} = 25.17\ m^3$$

$$Shrink\ (\%) = \frac{(26.83 - 25.17)\ m^3}{26.83\ m^3} \times 100 = 6.19\ \%$$

Thermal Properties of Agricultural Materials

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- Thermal properties describe how agricultural materials respond to heat transfer during processes such as drying, heating, cooling, and storage
- Understanding these properties is essential for designing efficient drying systems and predicting temperature distribution within bulk materials
- **Specific Heat (C_{sg}) :** specific heat is the amount of energy required to raise the temperature of 1 kg of material by 1°C
- **Thermal Conductivity (C_{cond}) :** thermal conductivity is the ability of a material to conduct heat

Type	Moisture content ($\%_{w.b.}$)	Temperature range (°C)	Specific heat (C_{sg}) ($kJ\cdot(kg\cdot K)^{-1}$)	Thermal Conductivity (C_{cond}) ($W\cdot(m\cdot K)^{-1}$)
Corn	0.9	12.2 to 28.8	1.532	0.1405
	9.8	8.7 to 23.3	1.834	0.152
	14.7	12.2 to 28.8	2.026	0.1591
	24.7	8.7 to 23.3	2.374	0.17
Rough rice	10 to 20	-	0.921	0.0866
Hard wheat	9.2	-	1.549	0.1402
Soft wheat	0.7 to 20.3	10.7 to 32.2	1.398	0.117

Reference: ASABE, 2001, p. 521

Summary

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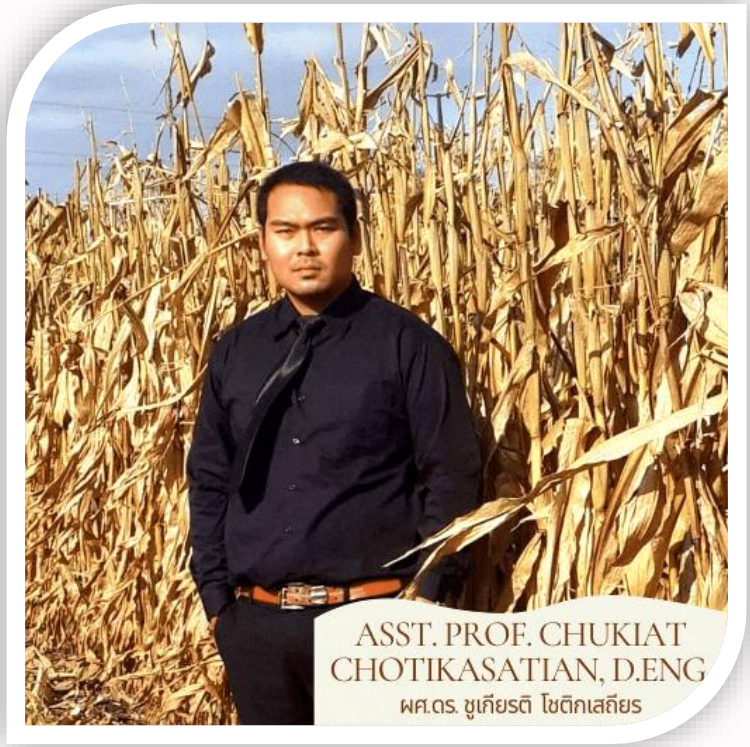
1. Physical properties such as size, dimensions, bulk density, and porosity are essential parameters in drying and storage system design.

2. Bulk density determines storage capacity and structural loading, while porosity directly influences airflow resistance and pressure drop during drying.

3. Moisture reduction during drying causes shrinkage; however, the shrinkage rate decreases as moisture content approaches zero.

4. Thermal properties, including specific heat and thermal conductivity, increase with moisture content due to the influence of water molecules, significantly affecting energy requirements and heat transfer efficiency



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Thank you very much for your kind attention.

Questions?

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Study Questions – Lecture 5

1. *Why are physical properties important in dryer and silo design?*
2. *How do bulk density and porosity influence airflow?*
3. *What is the relationship between moisture content and density?*
4. *How do thermal properties affect drying time?*
5. *Why does shrinkage occur during drying?*

Assignment – Lecture 5

1. Calculate the following physical properties of the oat kernels: sphericity, volume and surface area.

$MC_{d.b.}$ ($\%_{d.b.}$)	L (mm)	W (mm)	T (mm)	$(LWT)^{\frac{1}{3}}$ (mm)	Sphericity (%)	Volume (mm^3)	Surface area (mm^2)
9.12	9.87	7.41	3.25				
11.08	10.15	7.90	3.58				
13.24	10.46	8.25	3.90				
15.11	10.80	8.85	4.05				
17.06	11.09	9.25	4.37				

Assignment – Lecture 5 (Cont.)

2. Using the data provided in the table, calculate the porosity (ε) of the material.

$MC_{d.b.}$ ($\%_{d.b.}$)	Weight of 1,000 kernels (g)	ρ_{app} (kg m^{-3})	ρ_b (kg m^{-3})	ε (%)
9.12	220	1,315	765	
11.08	232	1,295	748	
13.24	246	1,275	732	
15.11	259	1,253	714	
17.06	268	1,232	698	

2.1 From the data in Questions 1–2, summarize the influence of moisture content on the physical properties of the material based on the calculated results.

Assignment – Lecture 5 (Cont.)

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3. A cylindrical tank with a diameter of 8 m can store 32 tons of oats at a moisture content of 25%$_{w.b.}$

Calculate the following:

The height of the oat bulk before drying.

The height of the oat bulk after drying, when the final moisture content is 15% wet basis (w.b.).

The percentage shrinkage of the oat bulk after drying

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