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Exploring the use of air-borne ultrasound in drying process

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1

The operation of drying

Some characteristics of drying

- One of the **most important** operations in industry
  - Reduction of storage and transport needs of products
  - Increase of self life of perishable products (foods,…)
- One of the **most energy demanding** operations
  - High cost operations
  - Environmental implications (global warming, air pollution,..)

2

The operation of drying

Drying techniques

- Osmotic drying (solid-liquid system)
- Convective drying (solid-gas system)
  - Drum drying
  - Bed drying…
- Sun drying
- Spray drying (liquid-gas system)
- Freeze drying (sublimation, vaccum)
- Atmospheric freeze drying (sublimation)…




3

The operation of drying

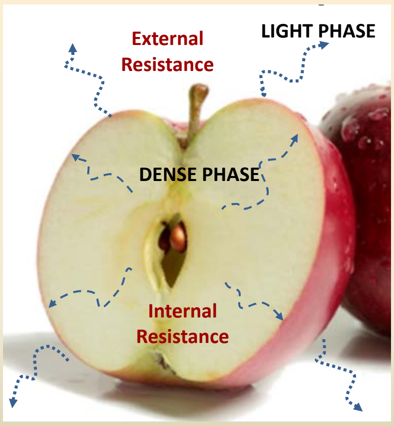
Drying techniques

- **Osmotic drying (solid-liquid system)**
- **Convective drying (solid-gas system)**
  - Drum drying
  - Bed drying…
- Sun drying
- Spray drying (liquid-gas system)
- **Freeze drying (sublimation, vaccum)**
- **Atmospheric freeze drying (sublimation)**…




4

Convective drying



Main drawbacks

- Energy needs (water phase change)
- Slow kinetics: labor and facilities needs
  - **Economic cost**
  - **Environmental impact**

INTENSIFICATION

Conventional alternatives to increase drying rate

- **Internal resistance: Increase air drying temperature**
  - Thermosensitive food nutrient degradation
  - Undesirable chemical/biochemical reactions
  - Collapse of raw structure
- **External resistance: Increase drying air velocity**
  - Structure could be affected: Case hardening
  - No significant drying rate increase at large air velocities

→ **Search the adequate drying methods for quality preservation (nutrient, structure,…)**

Drying process intensification

Process intensification

The **improvement** of traditional technologies and at the **development** of new techniques that will lead to **higher production** yield, notable **reduction** in **equipment size** (both principal and ancillary), **lower energy** use **and waste** production, and **increase** product **quality** and processing **safety**, therefore offering more **sustainable technologies**.

Drying intensification: Enhance **water removal rate** (mass and heat transfer) while simultaneously considering all their constraints.

Combine new alternative sources of energy with convective drying:

- Mechanical
- Thermal
- Hydrodinamic
- Electromagnetic
- Chemical
- …
- ACOUSTIC

7

Ultrasound application on convective drying

How ultrasound can intensify convective drying?

– Increasing drying rates
  - Internal resistance
    - "Sponge effect"
    - Creation of microchannels
  - External resistance
    - Alternating pressures
    - Microstirring at interfaces

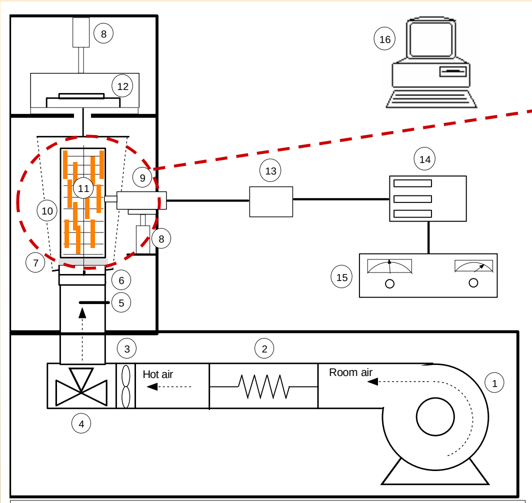
– Small heating effect: Quality preservation

→ Could contribute to **drying intensification** affecting
- Kinetics
- Product quality
- Energy consumption

8

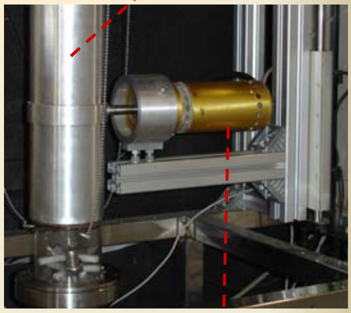
Ultrasound application on convective drying

Ultrasonic assisted convective drier



1. Fan, 2. Heating unit, 3. Anemometer, 4. 3-Way valve, 5. Thermocouple, 6. Sample loading chamber, 7. Coupling material, 8. Pneumatic moving arms, 9. Ultrasonic transducer, 10. Vibrating cylinder, 11. Sample loading tree, 12. Balance, 13. Impedance matching unit, 14. Power meter, 15. High power ultrasonic generator, 16. PC

Cylindrical radiator



Ultrasonic vibrator

9

Ultrasound application on convective drying

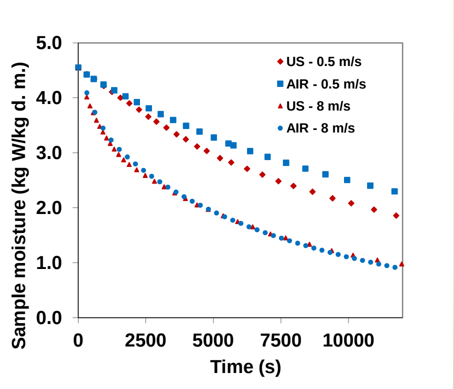
Ultrasonic assisted convective drier

10

Influence of process variables on ultrasonic effects

Air velocity

The influence of application of ultrasound in drying is high when low air velocities are applied. For some products this influence disappear at high air velocities. Usually, the effects of ultrasound are significant at air velocities lower than 2 m/s: **WHEN DRYING IS SLOWER**



- Experimental moisture evolution of **PERSIMMON** samples dried at two air velocities with an without ultrasound applications (75 W; 21.8 kHz). Data from: **Cárcel, J.A., García-Pérez, J.V., Riera, E., Mulet, A. (2007). Influence of high intensity ultrasound on drying kinetics of persimmon. Drying Technology, 25, 185-193**

11

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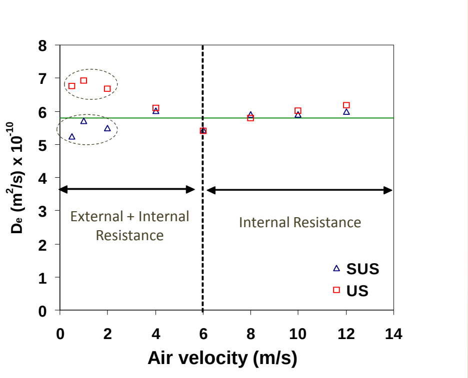

- Effective diffusivity of **PERSIMMON** samples dried (50 ºC) at different air velocities with an without ultrasound applications (75 W; 21.8 kHz). Data from: **Cárcel, J.A., García-Pérez, J.V., Riera, E., Mulet, A. (2007). Influence of high intensity ultrasound on drying kinetics of persimmon. Drying Technology, 25, 185-193**

12

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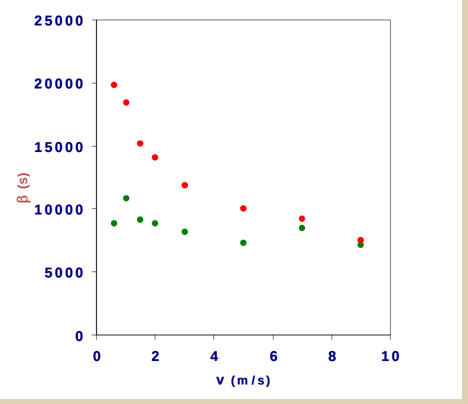
Hot-air drying kinetics of lemon peel slices assisted by power ultrasound (75 W) and without ultrasound application. b parameter from Weibull model. T = 40 ºC

Treatments:

- without ultrasound
- with ultrasound

García-Pérez, J.V., Cárcel, J.A., De la Fuente, S., Riera, E., 2006. Ultrasonic drying of foodstuff in a fluidized bed. Parametric study. Ultrasonics 44: e539-e543

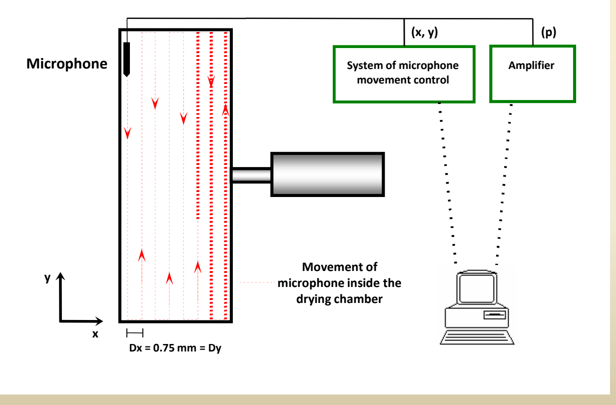


13

Influence of process variables on ultrasonic effects

Air velocity

Measurement of acoustic field inside the drying chamber. 1/8 inch microphone; sensibility of 1.06 mV/Pa. Signal emitted by the microphone was filtered.

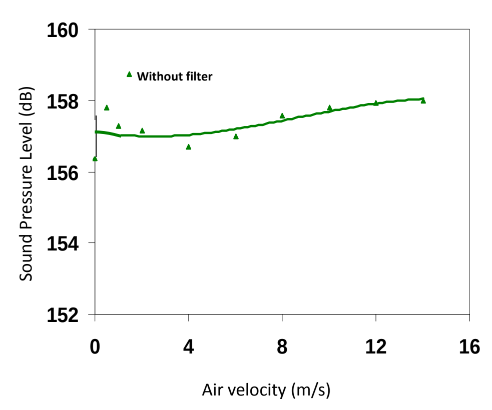


14

Influence of process variables on ultrasonic effects

Air velocity

The turbulence produced by high air velocities could disrupt the ultrasonic field affecting its effects

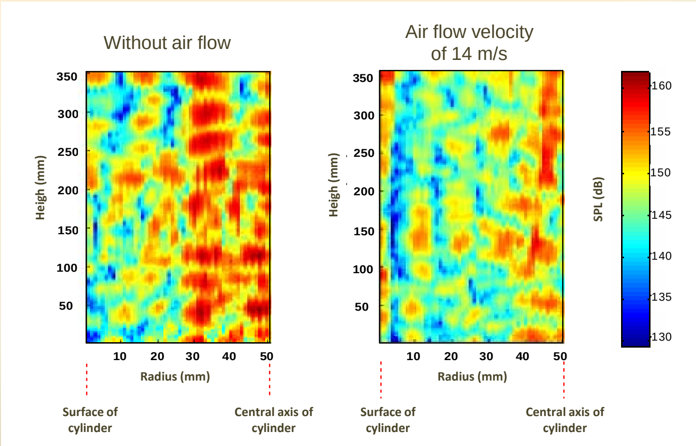


Measures of sound pressure level inside a drying chamber with ultrasound application at different air velocities.

15

Influence of process variables on ultrasonic effects

Air velocity



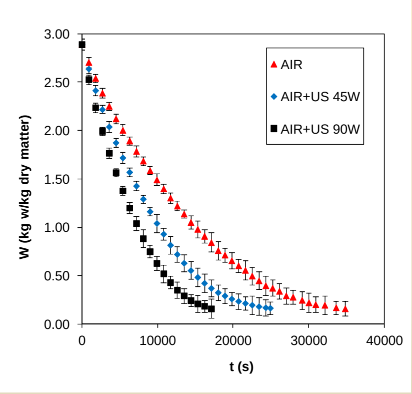
Structure of acoustic field inside a cylindrical drying chamber with and without air flow

16

Influence of process variables on ultrasonic effects

Power ultrasound applied

The effects of ultrasound depend on the **ultrasonic intensity** received by the samples: the higher the intensity, the greater the effects.



Experimental drying kinetics of **ORANGE PEEL** carried out at 40 °C and 1 m/s. Average value±standard deviation (three replicates). Data from: **Garcia-Perez, J.V., Ortuño, C., Puig, A., Carcel, J.A., Perez-Munuera, I. (2012). Enhancement of water transport and microstructural changes induced by high-intensity ultrasound application on orange peel drying. Food and Bioprocess Technology, 5, 2256-2265**

17

Influence of process variables on ultrasonic effects

Power ultrasound applied

The power applied affect both **internal and external resistance** to mass transfer.

UP (kW/m³)	D_e (10^{-10} m²/s)	k (10^{-3} kg W/m²/s)	VAR (%)	MRE (%)
0	8.9±1.0$_a$	1.87±0.2$_w$	99.9	0.9
6	11.8±2.7$_{ab}$	2.32±0.4$_w$	99.9	0.9
12	16.3±1.2$_{bc}$	3.35±0.3$_x$	99.9	0.7
19	17.8±4.1$_{cd}$	3.43±0.3$_x$	99.8	1.3
25	22.7±3.0$_{de}$	4.86±0.2$_y$	99.9	0.9
31	23.5±3.1$_{ef}$	4.79±0.7$_y$	99.9	1.0
37	27.9±3.6$_f$	6.16±0.9$_z$	99.8	1.4

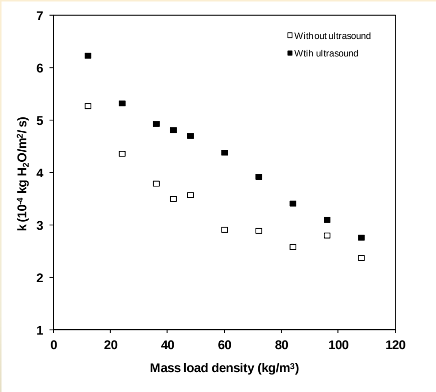
Effective diffusivity and mass transfer coefficient identified for **EGGPLANT** samples air dried (40 ºC and 1 m/s) with ultrasound application (21.8 kHz) at different power density. Data from: **García-Pérez, J. V., Ozuna, C., Ortuño, C., Cárcel, J. A. and Mulet, A. 2011. Modeling Ultrasonically Assisted Convective Drying of Eggplant. Drying Technology, 29: 1499–1509.**

18

Influence of process variables on ultrasonic effects

Power ultrasound applied

Other point of view of the influence of the ultrasonic power applied: the influence of mass load



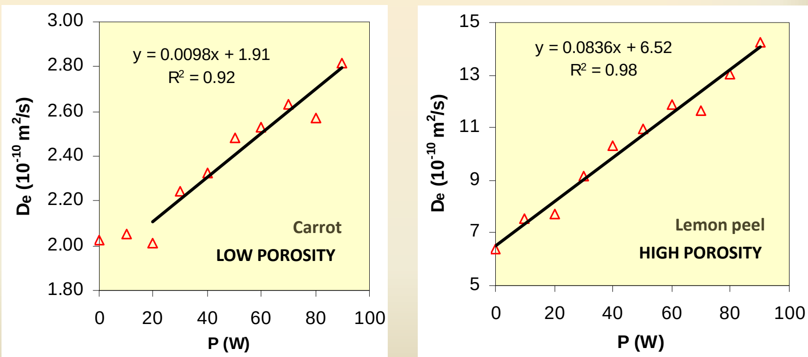
Mass transfer coefficients (k) identified using a diffusion model considering external resistance for drying experiments (40ºC and 1 m/s) carried out with and without ultrasound application at different mass load density. Data from: **Cárcel, J.A., Garcia-Perez, J.V., Riera, E., Mulet, A., 2011a. Improvement of convective drying of carrot by applying power ultrasound. Influence of mass load density.** ***Drying Technology*** **29: 174-182.**

19

Influence of process variables on ultrasonic effects

Power ultrasound applied

There is a threshold of power applied, above it is possible to identify the effects of ultrasound.



Effective diffusivity identified in the drying of **carrots** and **lemon peel** at different ultrasonic power. Air temperature 40 ºC and air velocity 1 m/s.

20

Influence of process variables on ultrasonic effects

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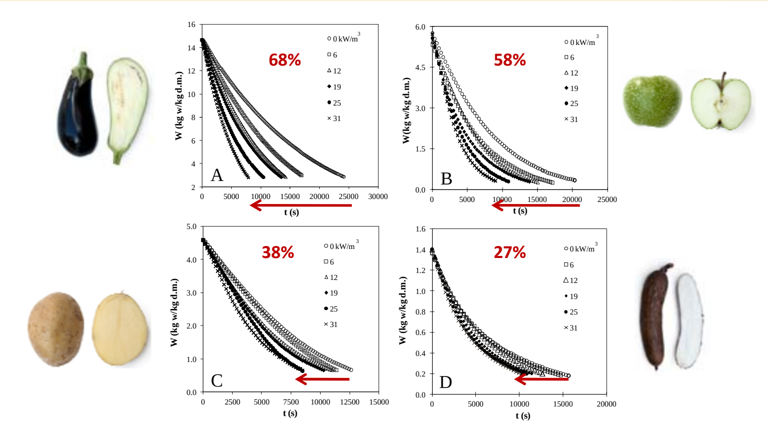
Power ultrasound applied

At the same **ultrasonic intensity** applied, the effects depends of the product treated.

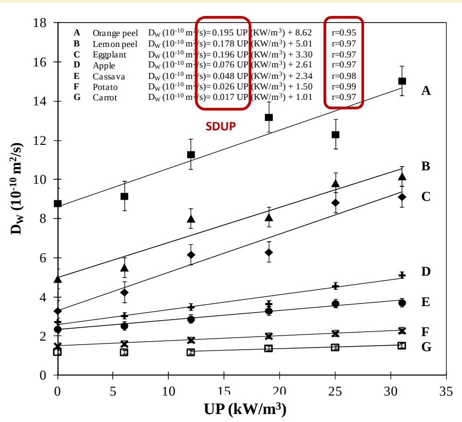


Drying kinetics (40 ºC and 1 m/s) of eggplant (1), apple (2), potato (3), cassava (2) dried at different acoustic powers.
(1) **García-Pérez, J.V., Ozuna, C., Ortuño, C., Cárcel, J.A., Mulet, A., 2011. Modeling ultrasonically assisted convective drying of eggplant. Drying Technology 29: 1499–1509.** (2) **Ozuna, C., Gómez, T., Riera, E., Cárcel, J. A., Garcia-Perez, J.V. 2014. Influence of Material Structure on Air-borne Ultrasonic Application in Drying. Ultrasonics Sonochemistry, 21, 1235-1243.** (3) **Ozuna, C., Cárcel, J.A., García-Pérez, JV., Mulet, A., 2011. Improvement of water transport mechanisms during potato drying by applying ultrasound. Journal of the Science of the Food and Agriculture, 91, 2511-2517.**

Influence of process variables on ultrasonic effects

Interaction between power ultrasound applied and product

At the same **ultrasonic intensity** applied, the effects depends of the product treated.



Relationship between effective diffusivity and ultrasonic power applied (40ºC; 1 m/s)

A- Orange peel
García-Pérez, J.V., Ortuño, C., Puig, A., Cárcel, J.A., Pérez-Munuera, I., 2012. Enhancement of water transport and microstructural changes induced by high-intensity ultrasound application on orange peel drying. *Food and Bioprocess Technology* 5: 2256-2265

B- Lemon peel
García-Pérez, J.V., Cárcel, J.A., Riera, E., Mulet, A. 2009. Influence of the applied acoustic energy on the drying of carrots and lemon peel. *Drying Technology*, 27: 281-287.

C- Eggplant
García-Pérez, J.V., Ozuna, C., Ortuño, C., Cárcel, J.A., Mulet, A., 2011. Modeling ultrasonically assisted convective drying of eggplant. Drying Technology 29: 1499–1509.

D- Apple
Ozuna, C., Gómez, T., Riera, E., Cárcel, J. A., Garcia-Perez, J.V. 2014. Influence of Material Structure on Air-borne Ultrasonic Application in Drying. Ultrasonics Sonochemistry, 21, 1235-1243

E- Cassava
Ozuna, C., Gómez, T., Riera, E., Cárcel, J. A., Garcia-Perez, J.V. 2014. Influence of Material Structure on Air-borne Ultrasonic Application in Drying. Ultrasonics Sonochemistry, 21, 1235-1243

F- Potato
Ozuna, C., Cárcel, J.A., García-Pérez, JV., Mulet, A., 2011. Improvement of water transport mechanisms during potato drying by applying ultrasound. Journal of the Science of the Food and Agriculture, 91, 2511-2517

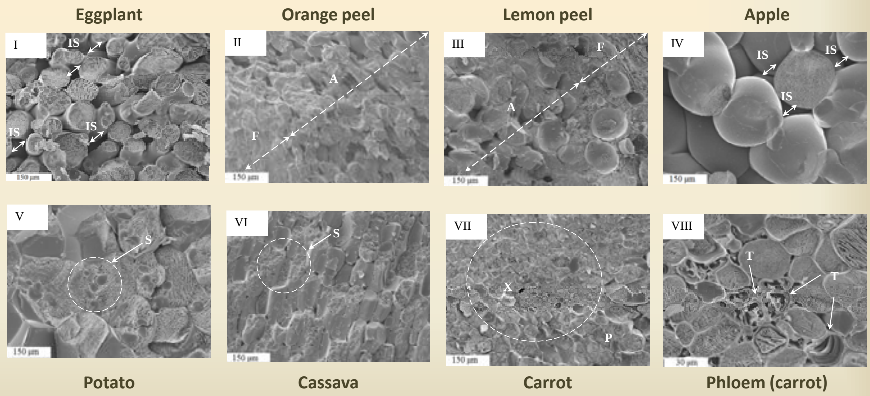
G- Carrot
García-Pérez, J.V., Ozuna, C., Ortuño, C., Cárcel, J.A., Mulet, A., 2011. Modeling ultrasonically assisted convective drying of eggplant. Drying Technology 29: 1499–1509.

Slope of linear relationship of D_W and **UP (SDUP):** Constitute a measurement of how the product is prone to the effectiveness of ultrasonic assisted drying

Influence of process variables on ultrasonic effects

Interaction between applied ultrasound power and product

Products studied have different internal structure.



Cryo-SEM images. Figs. I-VII (x200) and VIII (x1000). **(I) Eggplant**. **(II) Orange peel**. **(III) Lemon peel**. **(IV) Apple**. **(V) Potato**. **(VI) Cassava**. **(VII) Carrot**. **(VIII) Details of phloem**. IS: intercellular space; F: flavedo; A: albedo; S: starch; X: xylem, P: phloem and T: tracheid element.

23

Influence of process variables on ultrasonic effects

Interaction between applied ultrasound power and product

The different structure implies that the products have different physical characteristics.

Product	Porosity	H (N)	Z (MRayl)	TC
Eggplant	0.423±0.020	9.90±2.73	0.143	0.011
Orange peel	0.330±0.025	9.88±2.09	-	-
Lemon peel	0.370±0.017	15.07±1.39	-	-
Apple	0.233±0.026	25.92±1.63	0.177	0.009
Cassava	0.029±0.014	38.28±1.01	0.251	0.007
Potato	0.060±0.010	31.25±1.79	0.660	0.003
Carrot	0.031±0.016	44.37±1.53	0.286	0.006

Average values and standard deviation.

Porosity, hardness (H), acoustic impedance (Z) and air/solid transmission coefficient (TC) values measured for the different products tested. Average values and standard deviation.

Impedance (Z): The difference of impedance determine the coupling between solid material and air.

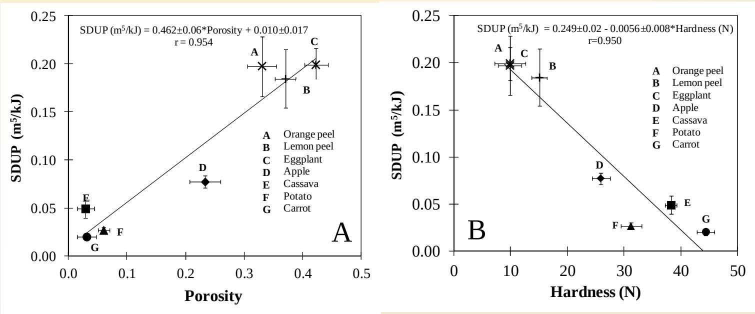
Air/solid transmission coefficient (TC): Constitute a measurement of the fraction of acoustic energy that penetrate in the solid

24

Influence of process variables on ultrasonic effects

Interaction between applied ultrasound power and product

The different structure implies that the products have different physical characteristics.



Influence of **POROSITY (A)** and **HARDNESS (B)** on the **ultrasound effectiveness (SDUP)** during the drying of different fruits and vegetables (40 ºC, 1 m/s). **Ozuna, C., Gómez, T., Riera, E., Cárcel, J. A., Garcia-Perez, J.V. 2014. Influence of Material Structure on Air-borne Ultrasonic Application in Drying. Ultrasonics Sonochemistry, 21, 1235-1243.**

25

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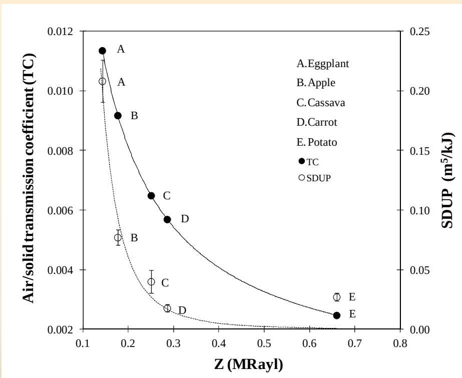


Influence of acoustic impedance (Z, MRayl) of different fruits and vegetables on the ultrasound effectiveness (SDUP, m^5/kJ) during the drying of different fruits and vegetables (40 ºC, 1 m/s) and the air/solid transmission coefficient (TC). **Ozuna, C., Gómez, T., Riera, E., Cárcel, J. A., Garcia-Perez, J.V. 2014. Influence of Material Structure on Air-borne Ultrasonic Application in Drying. Ultrasonics Sonochemistry, 21, 1235-1243.**

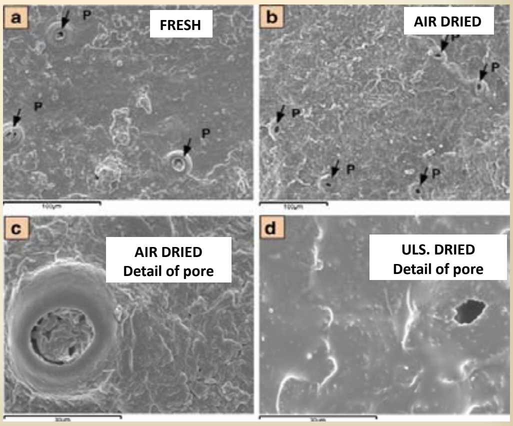
26

Influence of process variables on ultrasonic effects

Influence of ultrasound treatment in treated products

The ultrasound affected the structure of treated product

- Drying: Spread out of the waxy compound of flavedo (the outside structure of orange peel)
- Application of ultrasound **amplify the spread**: probably by alternating pressures and the microstirring at the interfaces



Cryo-SEM micrographs of cuticle surface **ORANGE PEEL**: a (×500); b (40 ºC; 1 m/s; ×350); c (×2,000); d (40 ºC; 1 m/s; 90 W; ×2,000). **P** pores. Data from: **García-Pérez, J.V., Ortuño, C., Puig, A., Cárcel, J.A., Pérez-Munuera, I., 2012a. Enhancement of water transport and microstructural changes induced by high-intensity ultrasound application on orange peel drying. *Food and Bioprocess Technology* 5: 2256-2265**

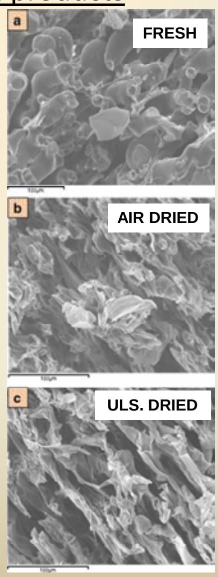
27

Influence of process variables on ultrasonic effects

Influence of ultrasound treatment in treated products

The ultrasound affected the structure of treated product

- **During conventional air drying**:
  - Albedo (inner structure of orange peel) is disrupted
  - Cell tubular shape disappear: water removal collapse the typical cell structure.
- **Ultrasonic-assisted drying**
  - **More intense disruption** of the albedo cells than air dried samples
  - **High degradation** of the cellular structure generating **large intercellular space**.
  - Ultrasonic stress: sponge effect and the creation of microchannels



- Cryo-SEM micrographs of albedo cells from **ORANGE PEEL**: **a** fresh (×350); **b** air dried (40 ºC; 1 m/s; ×500); **c** ultrasound-assisted drying (40 ºC; 1 m/s; 90 W; ×500)Data from: **García-Pérez, J.V., Ortuño, C., Puig, A., Cárcel, J.A., Pérez-Munuera, I., 2012a. Enhancement of water transport and microstructural changes induced by high-intensity ultrasound application on orange peel drying. *Food and Bioprocess Technology* 5: 2256-2265.**

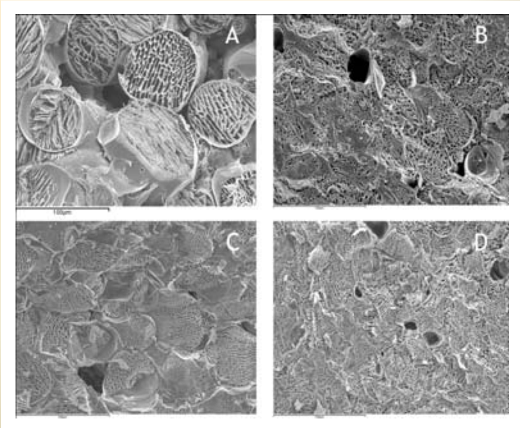
28

Influence of process variables on ultrasonic effects

Influence of ultrasound treatment in treated products

The ultrasound affected the structure of treated product

- Conventional convective drying involved microstructural changes in the endocarp: a high degree of degradation and a compacting process).
- In general application of ultrasound **reduced** the drying changes: increase the mechanical stress but reduce the drying time.
- There is an **optimum ultrasonic power:** 45W treated samples maintained better the original structure than 90W treated samples



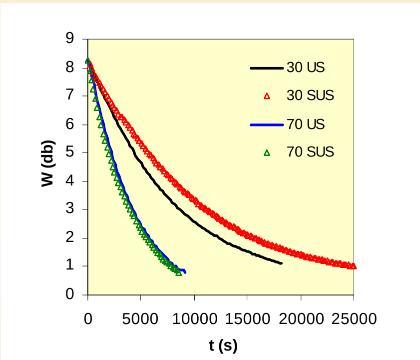
Cryo-SEM. Endocarp from raw **EGGPLANT** (**A**) and dried eggplant samples (40 ºC; 1 m/s) : conventionally (**B**) and with ultrasound application at 45 W (**C**) and 90 W (**D**). Data from: **A. Puig, I. Perez-Munuera, J.A. Carcel, I. Hernando, J.V. Garcia-Perez. 2012. Moisture loss kinetics and microstructural changes in eggplant (Solanum melongena L.) during conventional and ultrasonically assisted convective drying. Food and Bioproducts Processing 90, 624-632.**

29

Influence of process variables on ultrasonic effects

Drying temperature

The increase of drying rate produced by ultrasound is higher at low than at high temperature



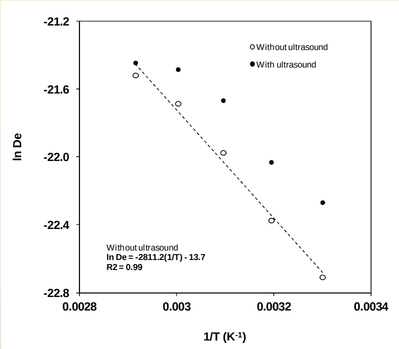
Effective diffusivity identified for the drying of **CARROT** cubes (40 ºC; 1 m/s) with (US: 75 W; 21.8 kHz) and without (AR) application of ultrasound at different drying temperatures. Data from: **García-Pérez, J. V., Rosselló, C., Cárcel, J. A., De la Fuente, S. and Mulet, A. (2006). Effect of air temperature on convective drying assisted by high power ultrasound. Defect and Diffusion Forum, 258-260**

30

Influence of process variables on ultrasonic effects

Drying temperature

The effects of ultrasound are reduced at temperatures higher than 70 ºC, being more intense at lower temperatures **WHEN DRYING KINETICS IS SLOWER**.



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Influence of process variables on ultrasonic effects

Drying temperature

The application of ultrasound during drying reduce drying time and can contribute to **reduce the energy consumption**.

	US	AIR	Difference (%)
Effective diffusivity (10^{-9} m^2/s)	6.13	4.04	51.7
Mass transfer coefficient (10^{-3} kg water/m^2s)	2.43	1.17	107.7
Drying time (h)	5.0	9.7	-48.4
Energy consumption (kWh)	1.20	1.65	-37.5

Effective diffusivity and mass transfer coefficient identified for the drying of **ORANGE PEEL** (40 ºC; 1 m/s) with (US: 90 W; 21.8 kHz) and without (AIR) application of ultrasound. Drying process extended until achieve the loss of the 80 % of initial weight .Data from: **García-Pérez, J.V., Ortuño, C., Puig, A., Cárcel, J.A., Pérez-Munuera, I., 2012. Enhancement of water transport and microstructural changes induced by high-intensity ultrasound application on orange peel drying. Food and Bioprocess Technology 5: 2256-2265.**

Influence of process variables on ultrasonic effects

Drying at low temperature

Removal of solvents at low temperature (**below** or **close to freezing point**) is an **slow** process used in different industrial areas (food, chemical, pharmaceutical or cosmetic) to **preserve quality attributes.**

Main example **Vacuum Freeze Drying**

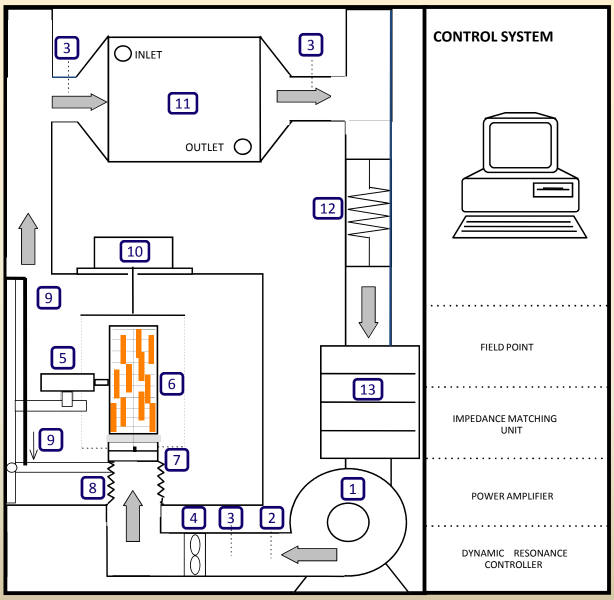
- Provide high quality products
- Very expensive process: batch production (vacuum)
- Only applied to obtain high added value products (special foods, chemical or pharmaceutical products,…)

Alternative: **Atmospheric Freeze Drying**

- High quality products as vacuum freeze drying
- Continuous production: lower cost than vacuum freeze drying
- Very slow process: **need of intensification**

33

Drying at low temperature assisted by ultrasound



1. Fan
2. Pt 100
3. Temperature and relative humidity sensor
4. Anemometer
5. Ultrasonic transducer
6. Vibrating cylinder
7. Sample load device
8. Retreating pipe
9. Slide actuator
10. Weighing module
11. Heat exchanger
12. Heating elements
13. Desiccant tray chamber

34

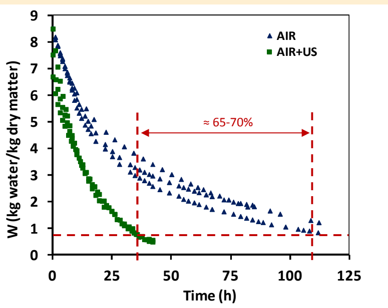
Drying at low temperature assisted by ultrasound

Equipment

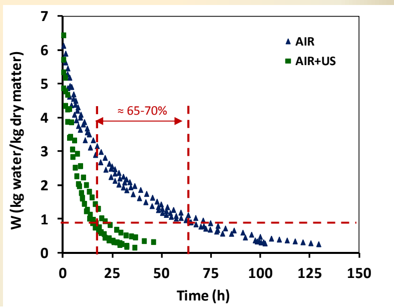
PROCESS SETTINGS

- Temperature (-15 to 80 ºC)
- Air velocity (0.1 to 20 m/s)
- Parallel or through air flow
- Solids and semisolids
- HPU Devices: tube and plates
- HPU Powers: until 40 kW/m³ (160 dB)

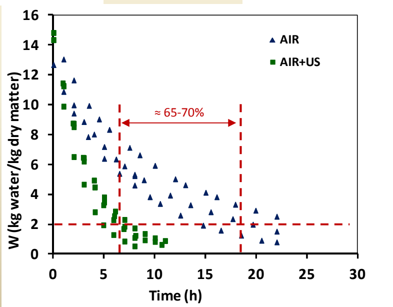
Drying at low temperature assisted by ultrasound



Carrot



Apple



Eggplant

Drying kinetics of different products (-14 ºC; 2 m/s; 19.5kW/m³) . Data from: **García-Pérez, J.V., Cárcel, J.A., Riera, E., Rosselló, C., Mulet, A., 2012. Intensification of low-temperature drying by using ultrasound. *Drying Technology* 30: 1199-1208**

Drying at low temperature assisted by ultrasound

From modelling

		D_e (10^{-11} m^2/s)	Increment (%)	k (10^{-5} kg water/m^2 s)	Increment (%)	Explained variance(%)
Carrot	AIR	0.8±0.1		3.3±1.5		99.6
	AIR+US	4.2±0.4	+ 425	8.3±2.3	+ 152	99.8
Apple	AIR	1.4±0.7		4.8±0.2		99.5
	AIR+US	7.4±2.1	+ 428	9.4±0.9	+ 96	99.9
Eggplant	AIR	4.4±1.7		23.7±4.3		99.9
	AIR+US	22.3±4.7	+ 407	64.1±10.4	+ 170	99.9

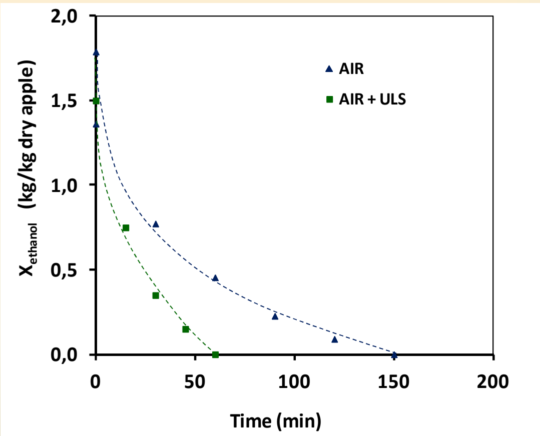
- Ultrasound increased de mass transfer coefficient
  REDUCTION OF EXTERNAL RESISTANCE
- Ultrasound increased de diffusion coefficient:
  REDUCTION OF INTERNAL RESISTANCE

Data from: **García-Pérez, J.V., Cárcel, J.A., Riera, E., Rosselló, C., Mulet, A., 2012. Intensification of low-temperature drying by using ultrasound. *Drying Technology* 30: 1199-1208.**

37

Drying at low temperature assisted by ultrasound

Ultrasound can be used to enhance mass transfer in removal solvents process at low temperature



Kinetics (-14 ºC; 2 m/s; 19.5kW/m³) of ethanol elimination from apple previously impregnated. Data from: **García-Pérez, J.V., Cárcel, J.A., Riera, E., Rosselló, C., Mulet, A., 2012. Intensification of low-temperature drying by using ultrasound. *Drying Technology* 30: 1199-1208.**

38

CONCLUSIONS

- Ultrasound, adequately applied (design of efficient equipment), **enhances** the **moisture transport** during drying
- The **effects** of ultrasound depended mainly of the **actual acoustic energy applied** that is influenced by process variables such as air velocity (turbulence), power applied, mass load density or product treated.
- Therefore, each particular application needs a **previous study** to determine the optimum process variables to achieve the maximum effects of ultrasound
- The **effectiveness** of ultrasound **increases** when lower energy are available in the medium: **at low temperatures and air velocities.**
- Thus, the ultrasonically assisted drying at low temperature can be an **interesting alternative** to an expensive and high demanding energy process such as freeze-drying.

39

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Exploring the use of air-borne ultrasound in drying processes

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40