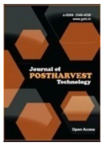

Journal of Postharvest Technology
2023, **11**(4): 49-57
www.jpht.in

RESEARCH ARTICLE

# Temperature profile of rice grain during its heating in the domestic microwave oven

**Ashok Kumar[1]*, Sneh Lata[2], Rewa Kulshrestha[3]**

[1]College of Food Technology, Central Agricultural University, Imphal, Manipur, India

[2]Department of mechanical Engineering, National Institute of Technology Arunachal Pradesh, India

[3]Department of Food Processing and Technology, Atal Bihari Vajpayee Vishwavidylaya, Bilaspur, Chhattisgarh, India

Received: 19.09.2023 Accepted: 18.10.2023

## ABSTRACT

Microwave puffing is an alternative of the sand and air puffing. Microwave heating of rice grain during its puffing in domestic microwave oven was modeled using finite element based COMSOL multiphysics 3.3a software. The 3D-geometry, consisting oven, waveguide, turntable and rice grain in oven, was drawn. A multiphysics model was developed by coupling the electromagnetic wave and general heat transfer modules. The Maxwell's equation of electromagnetics was solved for the electric field inside the oven cavity and the rice grain. The energy equation was solved for the temperatures profile inside the rice grain. Uneven heating of rice was observed that was influenced by the placement of rice grain on the turntable of the microwave oven. Rice grain, placed in the radial zones of 0 - 2.5 cm, 12.5-15 cm and 8.75-11.25 cm, did not absorb sufficient microwave energy, which resulted in mostly unpuffed or semi puffed rice. Rice grains placed in the puffing zone of 3.75 to 6.25 cm was absorbed sufficient energy and crossed glass transition temperature in 13-14 s, which resulted in mostly puffed rice. Apart from the location of puffing zone and heating time, revolution of rice grain on the turn table and the distribution of electromagnetic field also influenced the heating pattern.

**Keywords**: Microwave puffing, microwave power absorption density, rice puffing.

**Citation:** Kumar, A. Lata, A. and Kulshrestha, R. 2023. Temperature profile of rice grain during its heating in the domestic microwave oven. *Journal of Postharvest Technology*, **11** (4): 49-57.

## INTRODUCTION

Puffed or expanded rice has been a popular snack in India for centuries (Murugesan and Bhattacharya, 1986). The puffing method traditionally followed in India is sand-roasting in which hydrothermally treated, pre-conditioned (parboiled) rice at 8 to 10% moisture content (wb) is heated with hot sand at 200 $^{0}$C (Lata et al., 2023). In many countries, gun puffing is a common method where raw rice, at certain moisture content, is subjected to high temperature and high steam pressure inside a puffing gun and pressure is suddenly released to come to atmospheric pressure (Chandrasekhar and Chattopadhyay, 1988). Apart from these processes, puffing can also be achieved by heating parboiled rice in the hot air or oil (Gulati and Datta, 2016; Rajha et al., 2021; Swarnakar et al., 2014). Now-a-days microwave ovens have become a common kitchen appliance in developed countries. The use of microwave oven for puffing of cereals, viz, popcorn has become very popular because of consumers demand for fresh and crispy snack food. Microwave puffing is very hygienic process than the sand and air puffing method. Microwave puffing

---

* *For correspondence*: A. Kumar (Email: ashokcae03@gmail.com)

**ISSN: 2348-4330**

can be done in small volume with domestic models of microwave ovens while sand and air puffing are used for the bulk production of puffed food. Using the microwave for puffing one can easily avoid the storage of puffed cereals which is more susceptible to moisture gain and require more space than the unpuffed cereals. Apart from these benefits, microwave puffing is energy and time efficient process, consumes less specific energy without much wastage, and requires no labour at all (Chandrasekaran et al., 2013; Sumnu and Sahin, 2005).

In order to exploit the benefits of microwave puffing with optimum energy input, understanding the heat transfer characteristic in microwave oven would be beneficial. The mechanism of energy transfer for microwave to the material is quite different from conventional heating by conduction, convection and radiation technique. Microwave energy is received by polar molecules like water, which oscillate under the fast changing electromagnetic field and causing sufficient vibration energy imparted to the water molecules (Sumnu and Sahin, 2005). The vibration is transferred into thermal energy and dissipated to other parts of the food. Cereals containing sufficient moisture absorb microwave energy and try to melt starch. Melted starch expends rapidly because of the high pressure of water vapour trapped in the starch melt that ultimately s the expansion of the product (Lata et al., 2023; Gulati and Datta, 2016).

Compared with conventional heating, heat transfer is typically more difficult to study due to the complex interaction of the microwaves with the cavity and food. The two key issues in microwave heating of food are: (a) the magnitude of energy deposited by the microwaves and (b) the uniformity of the energy deposition (Datta et al., 2005). In microwave heating, heat is generated volumetrically in the food. The dielectric properties (dielectric constant and dielectric loss factor) of the food are largely responsible for magnitude and uniformity of energy absorbed together with various other factors. Those properties that govern whether a material may be successfully heated by microwaves are permittivities or dielectric properties. The imaginary part, dielectric loss factor, of the permittivity is related to the dissipation (or loss) of energy within the medium. The real part, dielectric constant, of the permittivity is related to the stored energy within the medium. It indicates how well a material will sustain an electric field. In other words, how much of microwave energy generated in microwave oven is concentrated in material (Datta et al., 2005).

Dielectric properties of food materials depend on composition, temperature and frequency and are must for a better understanding and analysis of microwave heating of food and biological materials (Kumar and Shrivastava, 2019). During microwave and high frequency heating/processing many variables in the food affect the heating performance. Among these the most significant is the permittivity of food since it describes how a material interacts with microwaves. Other factors that affect the microwave heating of food are size, shape, composition of food, thermal (thermal conductivity and specific heat capacity)and mechanical (density for solid, and viscosity for liquid products) properties of food. The heating rate depends on the thermal properties while absorbed power on the dielectric properties (Buffler, 1993). The experimental measurement of temperature is quite difficult in the microwave heating process due to the interference of measuring devices with electromagnetic field. The objective of the paper was to develop a mathematical model for microwave heating of single rice grain during its puffing and prediction of temperature profile of the rice grain.

## MATERIALS AND METHODS

### Collection of rice sample

Rice (variety Hira) in the form of preconditioned parboiled rice was collected from nearby village named Bondeuli, West Midnapur, West Bengal. With the consideration of good puffing quality and local availability, Hira variety of rice was selected for the present study. This variety of rice has the dimension of length 8.5 mm, breadth 1.9 mm and thickness 1.9 mm. The bulk density and particle density of the rice are 834.4 kg/m$^3$and 1451 kg/m$^3$ respectively at the moisture content 10.57% (db). Thousand grain weight of the rice is 18.55 g. The preconditioning of rice improves its heating characteristics due to infusion of salt into it. This process involves mixing of parboiled rice and salt solution and further drying up to 10.5% (wb) moisture content (Mohapatra et al., 2012).

### Microwave heating of rice

The microwave oven (SAMSUNG, model number: M197DL) was used for heating of preconditioned rice grain for 30 s at different power levels. The microwave oven has a cavity 335 * 230 * 345 mm (width * height * depth) and houses a turntable 315 * 6 mm (diameter * height) that rotates at 4 rpm. It has various power level ranging from 100W to 1000W when operated at 230V and 50Hz AC power source.

The microwave oven is a 3D cavity connected to a 1 kW, 2.45 GHz microwave source via a rectangular waveguide operating in the TE10 mode. Electric and magnetic field patterns inside the cavity are called mode. The rectangular port is excited by a transverse electric (TE) wave, which is a wave that has no electric field component in the direction of propagation but magnetic field dose. The TE10 mode has one semi-sinusoidal variation in x direction and is constant in the y direction. At an excitation frequency of 2.45 GHz, the TE10 mode is the only propagating mode through the rectangular waveguide (Dibben, 2001).

### Mathematical modeling of microwave heating of rice

COMSOL multiphysics 3.3a software (Comsol Inc., Burlington, MA) was used for mathematical modelling of microwave heating of rice grain. A 3D-geometry consisting oven, waveguide, turntable and rice grain in oven was drawn as shown in Figure 1. The parameters used for development of model are listed in Table 1. The benefit of symmetrical geometry was used to reduce the calculation time. Tetrahedral grid was generated in 3D geometry as shown in Figure 1. Fine mesh was generated within the rice grain. Stationary equation solver was used to solve the Maxwell's equation of electromagnetics and volumetric heat generation within the rice grain was calculated (Lata et al., 2023). Volumetric heat generation term was coupled with general heat transfer equation and transient equation solver was used to obtain the temperatures profile inside the rice grain (Campañone et al., 2012; Geedipalli et al., 2007; Zheng et al., 2013). In order to analyze the process of heat transport during microwave heating of a rice grain, the following assumptions were made: Since the microwave field is operating in TE10 mode, it is propagated in a rectangular waveguide in z axis direction with only a component in y axis direction; No variations of electromagnetic field in y direction; The product is homogeneous and isotropic; Negligible mass transfer during heating; Negligible Volume changes during heating; Uniform initial temperature within products to be heated; Convective boundary conditions.

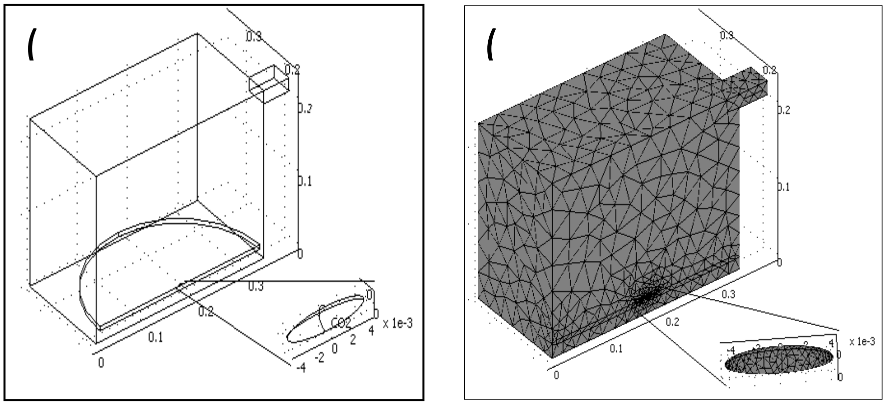

Figure 1: The model 3D geometry with rice grain placed at center of the turntable (a); Mesh generation in 3D geometry (b)

**Table 1: Input parameters in the modeling of microwave heating of rice**

| **Parameters** | **Value** |
|---|---|
| Oven interior dimension (cm) | 33.5 x 23.0 x 24.5 |
| Wave guide dimension (cm) | 5.0 x 1.8 x 7.8 |
| Turntable (cm) | D=31.5; thickness=0.6 |
| Input power (W) | 1000 |
| Frequency (GHz) | 2.45 |
| Cut-off frequency (GHz) | 1.9217 |
| Oven air temperature (K) | 298.15 |
| Heat transfer coefficient (W/m$^2$-K) | 5 |
| Air dielectric property | 1 |
| Glass dielectric property | 2.55 |
| Rice properties | |
| Dimension (mm) | 8.5x1.9x1.9 |
| Density (kg/m$^3$) | 1451 |
| Specific heat (J/kg-K) | 1598 |
| Thermal conductivity (W/m-K) | 0.179 |
| Dielectric properties | 4 - 0.8*i |
| Heating time (s) | 25 |
| Initial grain temperature (K) | 298.15 |

Electromagnetic field: The electromagnetic field distribution inside a microwave cavity is governed by Maxwell's equations. The electromagnetic field was solved into the rice grain according to the theory of Maxwell's equations. For TE10 in plane wave propagation mode, the electric field was solved using the following equation (Lata et al., 2023; Salvi et al., 2011):

$$\nabla \times (\mu_r^{-1} \nabla \times E_z) - \left(\in_r - \frac{j\sigma}{\omega \in_\circ}\right) k_0^2 E_z = 0 \tag{1}$$

Where, $\mu_r$ = magnetic permeability of material (1); $E_z$ = electric field propagating in z-direction (V/m); $\varepsilon_r$ = electrical permittivity of material (1); j=imaginary number (√-1); σ = electrical conductivity (S/m); ω= angular frequency of the microwaves (1/s); $\varepsilon_0$ = permittivity of free space ($\varepsilon_\circ = 8.85 \times 10^{-12}\mathrm{F/m}$); $k_0$ = wave number (1)

Heat generation: The volumetric power absorbed by dielectric material was calculated from the local electric field strength into the product.

$$Q = 2\pi f \in_{\circ} \in'' E^2 \tag{2}$$

Where, Q=volumetric power absorbed (W/m$^3$); f = microwave frequency (Hz); ε″= dielectric loss factor (1); E= electric field (V/m)

Boundary condition: The walls of the oven and the waveguide are good conductors. The model approximated these walls as perfect conductors, represented by the boundary condition

$$n \times E = 0 \tag{3}$$

The symmetry cut has mirror symmetry for the electric field and was represented by the boundary condition

$$n \times H = 0 \tag{4}$$

Where, n is normal vector; E= electric field (V/m); H= magnetic field (A/m)

Heat transfer: Microwaves heat food volumetrically. Hence, power absorbed by the food due to application of microwaves was added as a source in the heat transfer equation. The transient diffusion equation with the microwave source term was solved to obtain temperatures inside the food:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{Q}{\rho C_p} \tag{5}$$

Where, T= temperature of food (K); α = thermal diffusivity of food (m$_2$/s); ρ = density of food (kg/m$^3$); $C_p$= specific heat of food (J/kg-K)

Heat transfer boundary condition: Heat loss due airflow was modeled by specifying the convective heat transfer coefficient at the surface of the rice grain.

$$-K\nabla T = h_c(T - T_a) \tag{6}$$

where $h_c$ is the convection heat transfer coefficient over a surface, T is surface temperature of rice grain and $T_a$ is the temperature of air inside the oven. The initial temperature of the air and food inside the oven is constant at 25˚C.

## RESULTS AND DISCUSSION

### Microwave power absorbed by the rice grain

Rice grains were heated for 30 s in microwave oven. The simulated microwave power absorption density (W/m$^3$) absorbed by the rice grains, placed in different radial distance and revolving in that fixed radius, is shown in Figure 2. The total microwave energy absorbed by the rice grain placed at the different radial distance from the center of the turntable is depicted in the Figure 3. The turn table revolved at the speed of 4 rpm. Hence, rice grains covered two revolutions in 30 s. The absorbed average power density increased and then decreased with maximum value around 6.25 cm away from the center of the turn table. The maximum value of the simulated average power density absorbed by rice grain was about 1.38×10$^7$ W/m$^3$ at the radial distance of 6.25 cm and minimum value was 2.51×10$^6$ W/m$^3$ at the center of the turn table. The rice grain placed at the center remained at same position and received same amount of power throughout the two revolutions. Rice grains placed at different radial distance experienced fluctuation in microwave power absorption density in one/two revolutions. Rice puffing, being high temperature and short time process, might have greatly influenced puffing characteristics. Rice grains placed in puffing zone of

6.25 cm on the turn table experienced maximum power absorption value and maximum puffing percentage. Fluctuation in microwave power absorption density by food materials with location were reported by other researchers (Lata et al., 2023).

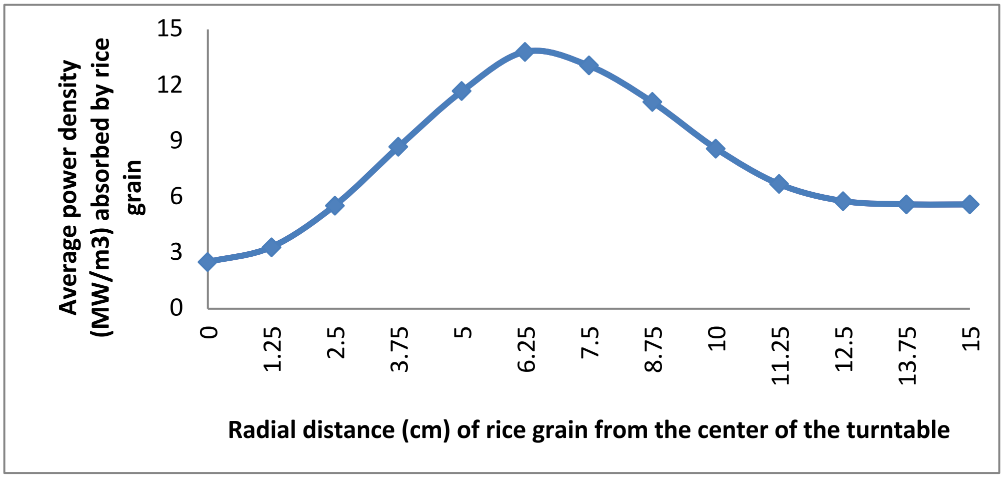

**Figure 2: Variation in average power density (MW/m3) absorbed by the rice grain placed at the different radial distance from the center of the turntable**

The distribution of electromagnetic field and hence the microwave power absorption inside rice grains were influenced by the dielectric properties of rice starch, grain shape and location of grain inside oven (Zhang and Datta, 2001). Hence, different heating patterns were observed for grains revolving in different radius on the turn table of microwave oven. Variation in power absorption at central region and corner regions of the grain was because of corner effect. The electromagnetic waves bend towards the normal on the food surface and this phenomenon is more dominant near the corner compared to the other part of the grain (Zhang and Datta, 2001). Thus denser electric field was formed near the corner regions then the central region of the rice grain. Hence, uneven heating within the rice grain was observed. Lata et al., 2023 reported some semi- puffed rice with one end remained unpuffed , unpuffed rice and completely puffed rice during microwave puffing that was due to uneven heating within the grain.

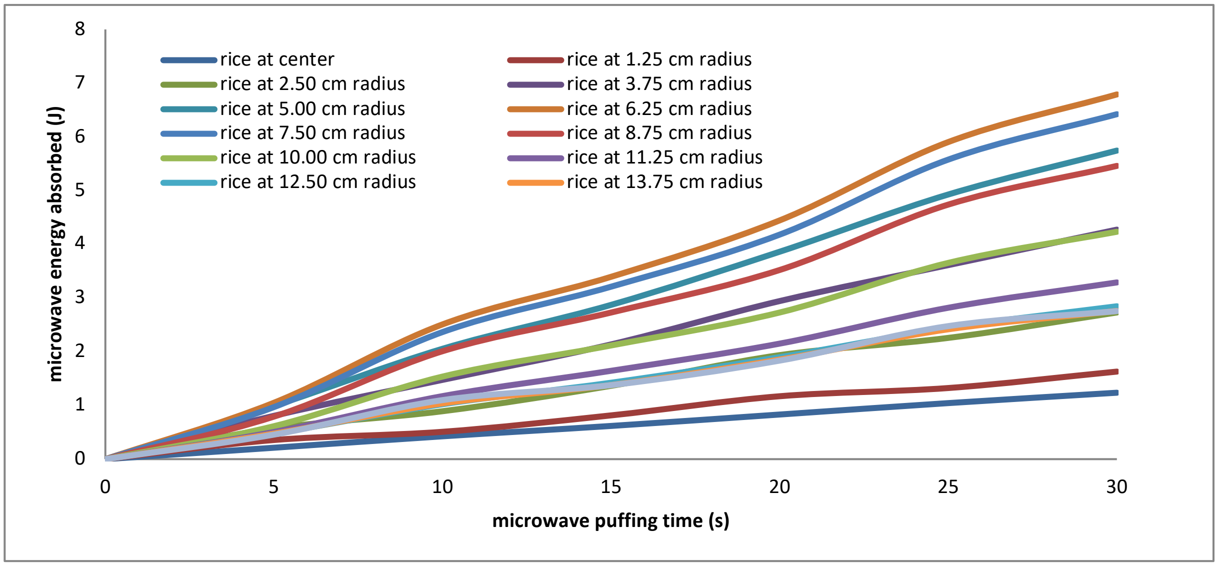

**Figure 3: Total microwave energy absorbed by the rice grain placed at the different radial distance from the center of the turntable**

### Change in temperature of rice grain during microwave puffing

The Figure 4 shows change in the average temperature of the rice grain revolving at different radius on the turn table of microwave oven during microwave puffing. The rice grains placed in the radial zones of 0 - 2.5 cm and 12.5-15 cm absorbed microwave energy at relatively slower rate and the average temperature of the rice grains did not reached up to the glass transition temperature (Tg) after 30 s of heating. The hard rice starch polymer must change to soft rubbery state before puffing expansion. The thermal transition of rice starch from hard glassy state to soft rubbery state occurs at the glass transition temperature of starch over a temperature range (368–388 K) (Chung et al., 2002). The most of the rice grain placed in these puffing zones was unable to puff and the absorbed energy resulted in drying of the rice grains.

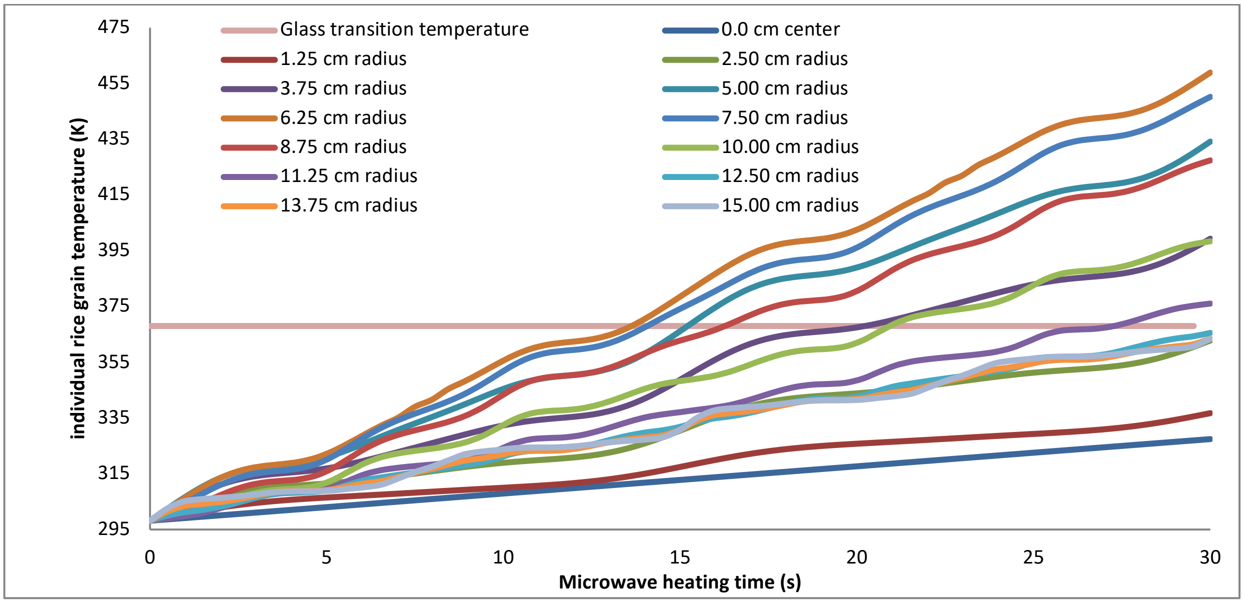

**Figure 4: The change in average temperature of rice grains placed at the different radial distance from the center of the turntable**

The rice grains placed in the puffing zone of 3.75-6.25 cm absorbed microwave energy at relatively faster rate and the average temperature of the rice grains reached up to the glass transition temperature (Tg) after 30 s of heating. The average temperature of the rice grains reached up to the glass transition temperature after 21, 14 and 13 s for puffing zones of 3.75, 5.0 and 6.25 respectively. Hence, most of grains placed in these puffing zones puffed completely.

The rice grains placed in the puffing zone of 8.75-11.25 cm absorbed microwave energy at relatively slow rate but the average temperature of the rice grains reached up to the glass transition temperature (Tg) after 30 s of heating. The average temperature of the rice grains reached up to the glass transition temperature after 16, 21 and 13 s for puffing zones of 8.75, 10.0 and 11.25 respectively. Delay in glassy to rubbery state transition of rice starch and generation of water vapour pressure was not favourable for puffing process. Hence, most of grains placed in these puffing zones resulted into semi-puffed rice.

## CONCLUSION

The placement of rice grain on the turntable of microwave oven influenced the heating pattern of the rice grain because the distribution of electromagnetic field and hence the microwave power absorption inside rice grains were influenced by the design of the microwave oven and dielectric properties of rice and together with other factors. Rice grain, placed in the radial zones of 0 - 2.5 cm, 12.5-15 cm and 8.75-11.25 cm, did not absorb sufficient of microwave energy and this resulted in mainly evaporative loss of moisture from the grain and no puffing or incomplete puffing process. Rice grains placed in the puffing zone of 3.75 to 6.25 cm was absorbed sufficient energy and crossed glass transition temperature in 13-14 s which resulted in mostly puffed rice. Apart from the location of puffing zone and heating time, revolution of rice grain on the turn table and distribution of electromagnetic field also influenced the heating pattern. The non-uniform rate of microwave power absorption in case of microwave puffing was the main reason for achieving puffing temperature.

## REFERENCES

Buffler, C. 1993. Microwave Cooking and Processing. Engineering Fundamentals for the food Scientist. New York: Avi Book, pp 6-7

Campañone, L. A., Paola, C. A., and Mascheroni, R. H. 2012. Modeling and simulation of microwave heating of foods under different process schedules. Food and Bioprocess Technology, 5(2): 738–749.

Chandrasekaran, S., Ramanathan, S., and Basak, T. 2013. Microwave food processing: A review. Food Research International, 52: 243–261.

Chandrasekhar, P.R. and Chattopadhyay, P.K. 1988. Heat transfer during fluidized bed puffing of rice grains. Journal of Food Process Engineering, 11(2): 147-157.

Chung, H. J., Lee, E. J., and Lim, S. T. 2002. Comparison in glass transition and enthalpy relaxation between native and gelatinized rice starches. Carbohydrate Polymers, 48(3): 287–298.

Datta, A. K., Sumnu, G., and Raghavan, G. S. V. 2005. Dielectric properties of foods. In M. A. Rao, S. S. H. Rizvi, and A. K. Datta (Eds.), Engineering properties of foods (Vol. 3, pp. 501–557). Boca Raton, FL: CRC Press.

Dibben, D. 2001. Electromagnetics: Fundamental Aspects and Numerical Modeling. In A. K. Datta and R. C. Anantheswaran (Eds.), Handbook of microwave technology for food applications (pp. 33–68). Marcel Dekker.

Geedipalli, S. S. R., Rakesh, V., and Datta, A. K. 2007. Modeling the heating uniformity contributed by a rotating turntable in microwave ovens. Journal of Food Engineering, 82(3): 359-368.

Gulati, T., and Datta, A. K. 2016. Coupled multiphase transport, large deformation and phase transition during rice puffing. Chemical Engineering Science, 139: 75-98.

Kumar, A., and Shrivastava, S. L. 2019. Temperature, concentration, and frequency dependent dielectric properties of pineapple juice relevant to its concentration by microwave energy. Journal of Food Process Engineering, 42(3): e13013.

Lata, S., Swarnakar, A. K., Kumar, A., and Das, S. K. 2023. Effects of mode of heat transfer on puffing quality of rice grain: A modeling and simulation analysis. Journal of Food Process Engineering, e14323.

Mohapatra, M., Kumar, A., and Das, S. K. 2012. Mixing characteristics of rice by tracer technique in an agitated cylindrical preconditioner developed for puffed rice production system. Journal of Food Process Engineering, 35(5): 1–8.

Murugesan, G. and Bhattacharya, K. R. 1986. Studies on puffed rice. I. Effect of processing conditions. Journal of Food Science and Technology, 23(4): 97-202.

Rajha, H. N., Debs, E., Abi Rached, R., El Khoury, K., Al-Kazzi, M., Mrad, R., and Louka, N. 2021. Innovation in cannon puffing technology for the homogenization of bulk treatment: Half-popped purple corn, a new healthy snack. Journal of Food Process Engineering, 44(6): e13695.

Salvi, D., Boldor, D., Aita, G. M., and Sabliov, C. M. 2011. COMSOL multiphysics model for continuous flow microwave heating of liquids. Journal of Food Engineering, 104: 422–429.

Sumnu, G., and Sahin, S. 2005. Recent development in microwave heating. In D.-W. Sun (Ed.), Emerging technology for food processing (Vol. 16, pp. 419–444). London: Elsevier Academic Press.

Swarnakar, A. K., Devi, M. K., and Das, S. K. 2014. Popping characteristics of paddy using microwave energy and optimization of process parameters. International Journal of Food Studies, 3(1).

Zhang, H., and Datta, A. K. 2001. Electromagnetics of microwave heating: Magnitude and uniformity of energy absorption in an oven. In A. K. Datta and R. C. Anantheswaran (Eds.), Handbook of microwave technology for food applications (pp. 33–68). Marcel Dekker.

Zheng, X., Wang, Y., Liu, C., Sun, J., Liu, B., Zhang, B., Lin, Z., Sun, Y., and Liu, H. 2013. Microwave energy absorption behavior of foamed berry puree under microwave drying conditions. Drying Technology, 31(7): 785–794.

.

© The Author(s)

This is an Open Access article licensed under a Creative Commons license: Attribution 4.0 International (CC-BY).