Use of Microwave Radiation to Process Cereal-Based Products

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1. Introduction

Within the electromagnetic spectrum, microwave radiation is characterized by being situated in the frequency interval between 300 MHz and 300 GHz, with those normally used for the industrial processing of foods being between 915 and 2450 MHz and, for domestic use, of 2450 MHz (Pei, 1982).

Microwave ovens can be built for industrial (continuous or batch processes), laboratory or domestic use. Industrial equipments present greater process control, but are costly and designed for large scale, which limits their use in research. Those developed for laboratory use are also costly, due to the need of heating, pressure and time control mechanisms to increase the reproducibility of the results. Therefore, many researchers end up adapting domestic microwave ovens, which results in lower cost equipments. Domestic microwave ovens do not have a uniform distribution of microwave radiation, as they were not designed for such. They produce interference between the microwaves and, thus, some parts of the oven receive a greater incidence than others. Therefore, it is necessary to map the distribution of microwave radiation for a more effective use of the energy generated (Pecoraro et al. 1997; Marsaioli Jr., 1991; Loewen & Gandolfi, 2004; Breslin, 1990).

A typical microwave apparatus consists of:

- Feed source: supplies tensions and currents for the functioning of the microwave generator;
- Microwave generator: is an oscillator that converts electric energy supplied by the feed source in microwave energy;
- Transmission section: propagates, irradiates or transfers the energy radiated by the oscillator to the applicator;
- Coupling: permits a more efficient transfer of microwave energy to the applicator;
- Microwave application cavity: is a volume limited by metallic walls in which the interaction material/microwaves occurs;
- Field agitator: rotating metallic reflector inside the cavity that modifies contour conditions periodically, with the objective of uniformizing energy distribution;
- Door or opening with electromagnetic blindage: permits an easy access to the interior of the applicator and must limit electromagnetic emissions to the surroundings to the maximum level permitted.

- Operation and safety control: permit the selection of heating conditions, the interruption of the potency flow and also indicate, through a sound and/or visual signal, the end of the processing cycle (Confort et al., 1991; Rocha, 2002).

Senise & Jermolovicius (2004) reported that the technically possible applications of microwaves, at the industrial level in the food industry are the drying of pasta products, dehydration, blanching, sterilization, pasteurization, cooking and thawing. However, nowadays these applications have increased with the use of microwaves for chemical reactions, insect and germination control, production of expanded cereals or tubers, etc.

The heating of foods using microwaves results of the coupling of electric energy from and electromagnetic field in a microwave cavity and of its dissipation within the product. This results in an instant temperature increase inside the product, in contrast to conventional heating processes that transfer energy from the surface, with high thermal time constants and a slow heat penetration (Goldblith, 1966).

The advantages of the use of microwaves, in comparison to conventional processing techniques, are a shorter processing time, higher yield and better quality of the final product (Decareau & Peterson, 1986), both sensory and nutritional (Sacharow & Schiffmann, 1992; Hoffman & Zabik, 1985).

The development of food processes and products with the use of microwaves should try to determine the interaction mechanisms between the food and the electromagnetic energy in the microwave frequencies. The main aspects that should be considered are:

- dielectric properties of foods;
- quantity of energy coupled by a food product and distribution within the product;

microwave time and frequency necessary to heat the food product; and

- temperature, pressure and electric field parameters (Mudgett, 1982; Rocha, 2002).

The proposal of this chapter is to show the state-of-the-art of the use of microwaves in cereal products, with the aim of presenting the main results found in this promising area for research and industrial application.

2. Principles of the use of microwaves and main technological applications in cereal-based products

The basic phenomena involved in microwave heating are: the coupling of the energy from an electromagnetic field by the product and the attenuation of energy absorption within it. The most important intrinsic property of this form of energy for food technology is volumetric absorption by dielectric materials, in the form of heat (Engelder & Buffler, 1991).

In microwave processing, intermolecular friction caused mainly by bipolar rotation of polar molecules, generates heat internally in the material, with a lower heat gradient in the product and results in an instant temperature increase. Aqueous and polar ionic constituents in foods and their associated solid constituents have a direct influence on how the heating will be conducted (Buffler, 1992; Marsaioli Jr. 1991; Schiffmann, 1986).

Apart from the chemical composition of the product, its geometry, size and volume affect the distribution of microwave heating (Remmen et al., 1996; Khraisheh et al., 1997; Yang & Gunasekaran, 2004; Ohlsson & Risman, 1978).

In contrast to conventional methods, in microwave heating the production of heat is continuous and, therefore, there is a continuous and rapid temperature increase when the food is exposed to this radiation. During heating of a moist product, the heat will be used to evaporate water and the temperature will be maintained at 100ºC. As soon as the free water is evaporated, product temperature can increase rapidly, with the risk of it burning (Sale, 1976).

2.1 Grain drying

In cereals, grain drying is directly related to conservation and time and quality maintenance. Keeping moisture content of cereal grains at low levels, of 10-12%, makes safe storage of approximately 5 years possible, as damaging effects, such as the plague attack, microorganism growth and grain respiration, are reduced. Grain drying can be natural and artificial (Frisvad, 1995; Marini et al., 2007).

In natural drying, the product is dried by sunlight, spread in open areas, being exposed to the environmental conditions of the region for a long period of time and occupying large areas, once the grains must be moved and spread around for a greater efficiency of the process.

Artificial or mechanical drying consists in submitting a layer of grains to a heated air current, which can be through electric energy or the use of fuels such as gas, wood or coal. At the beginning of drying, free water is evaporated rapidly, but after this the process becomes slow to evaporate the water from the interior of the product to the surface. The main controls are temperature, to avoid the loss of grains due to high temperatures, and aeration, with the aim of reducing the temperature and moisture of the grains during storage, avoiding the deleterious effects of moisture migration to the surface of the grain. This drying process takes long and can damage grain quality (Frisvad, 1995; Marini et al., 2007).

Microwave drying is an alternative drying method for a wide variety of grains, as it avoids the effects of conventional air drying that can cause serious damage to flavor, color and nutrients and can reduce bulk density and rehydration capacity of dried food product (Loewen & Gandolfi, 2004; Park, 2001).

During microwave drying there must be transportation of water from the interior of the solid to its surface, for evaporation to occur. The most important mechanisms involved in this process are:

- Liquid diffusion that occurs due to the existence of the concentration gradient;
- Vapor diffusion that occurs due to the vapor pressure gradient, caused by the temperature gradient;
- Liquid and vapor flow caused by the difference in external pressure, concentration, high temperature and capillarity;
- Initial moisture content of the material;
- Final moisture content that the material can reach, that is, its equilibrium moisture content;
- Thus, the water is related to the structure of the solid; and
- How water transportation is carried out from the interior to the surface of the solid (Park et al, 2001).

However, one of the problems of microwave drying is related to the non-uniform distribution of the electromagnetic field inside the applicator, which can induce a non-uniform heating of the product (Kudra, 1989).

Some researchers have developed equipments that aim to solve this problem:

Marsaioli Jr.(1991) developed a microwave equipment with a cylindrical rotatable applicator, where the movement of the product inside the cavity permits a more uniform distribution of heating.

Loewen & Gandolfi (2004) developed an equipment to dry cereals using microwaves, with elements that carry out the heating of water inside the cereal grains themselves, vaporizing only small quantities of water from the surface at the beginning of the operation. With the advance of heating, an internal pressure is created inside the grain that, in turn, causes an unbalance between internal and external pressure, thus favoring homogeneity and speed of drying. Once the desired temperatures are reached, adequate for each cereal, water migrates to the surface, being removed by a dry air current.

Breslin (1990) built a pilot scale microwave-convection dryer. The dryer had a working length of 4.25 m, with a maximum power of 20 kW. The residence time used was approximately 120 seconds and the drying time required to reduce the moisture content from 28 to 21% wet basis was reduced by 450% compared to the conventional convection system. He concluded that the reduction in residence time can be used to decrease the length of the dryer from 10.1 to 3.1 m, or to increase the capacity of the production unit by 235%.

Doty & Baker (1977) conditioned wheat in a closed system with up to 450 seconds of microwave application (625 watts), with a temperature variation from 22 (0 seconds) to 105ºC (450 seconds). Flour analysis showed that the 90 second treatment maintained flour quality; however, quality was reduced after 270 seconds.

2.2 Enzyme inactivation

Cereals in the form of grains and wholegrain or refined flours, when raw, present variable enzymatic activity according to the type of enzyme, moisture content and storage temperature. Enzymatic inactivation of lipases and lipoxygenases in cereals and their flours increases stability during storage, by preventing lipid hydrolysis and oxidation that could lead to the formation of off-flavors (Saunders, 1990).

Brown rice has a higher nutritional value than polished (white) rice because it has more protein and B-complex vitamins, especially thiamin, riboflavin and niacin. Its production process results in greater yield with fewer broken grains (Juliano, 1985). However, brown rice is unstable during storage mainly due to the rapid decomposition of bran lipids, attributed to the action of the enzyme lipase also contained in rice bran (Takano, 1993). Brown rice lipids are readily hydrolyzed by lipase, releasing free fatty acids (FFAs), which contribute to the appearance of off-flavors.

Chang & El-Dash (1998) used microwave energy as a thermal treatment to inactivate lipase in brown rice, consequently improving its long term storage stability. The parameters studied were: (i) microwave energy level (maximum and medium); (ii) initial moisture content (13.4, 14.6 and 17.3%) and time of treatment (20 to 140 s). Microwave energy treatment was considered effective in the control of lipase activity in brown rice with the maximum inactivation rate at the maximum power/level of microwave energy, a treatment time of 80 s and initial moisture content of 14.6%. Moisture content of treated brown rice was reduced. During storage, a decrease in the production of free fatty acids (FFAs) was observed.

Vetrimani et al. (1992) used microwave energy to inactivate lipase and lipoxygenase in rice bran, germ and soybean. This treatment led to considerable inactivation of the lipase and complete inactivation of the lipoxygenase present in these materials.

Jiaxun-Tao et al. (1993) reported stabilization of rice bran by microwave heating at 2450 MHz for 3 minutes, for up to 4 weeks storage.

Wennermark (1993) verified that heat-inactivation of lipid-degrading enzymes with low-moisture processes, such as steam-flaking and microwave cooking, improved vitamin E retention during subsequent processing in the presence of water.

The feasibility of microwave energy for the inactivation of α-amylase in wheat and wheat flour has been successfully tested by Edwards (1964) and Aref et al. (1969). They showed that the levels of enzyme activity decreased without damaging the flour with respect to its capacity to form dough, maintaining its viscoelastic properties.

2.3 Insect control

When grain storage conditions are precarious, there can be damage to cereals and by-products through the action of biological agents such as insects, acarus, rodents and fungi. The factors that negatively affect grain storage are: moisture, temperature, storage period, initial contamination level, impurities, insects, intergranular CO_2 concentration, grain physical and sanitary conditions (Prado et al., 1991; Scudamore et al., 1999).

Grain damage causes economic losses by reducing quality and altering nutritional value. Sanitation measures must be taken in storage, production, maintenance and distribution practices, including steps such as cleaning and disinfection of the storage structures, grain expurgation, rodent control, among others.

Warchalewski & Gralik (2010) verified that microwave heating of wheat grains within the temperature range of 28-98°C, using microwaves, caused a decrease in water-extractable proteins, statistically significant when grain temperature reached 79 and 98°C. A statistically significant increase in reducing sugars content was noted in grain samples heated only to 48°C; a decrease was noted above this temperature. Above 48°C, inactivation of the enzyme α-amylase occurs. All biological activities studied (amylolytic and inhibition activities against α-amylases from insects (*Sithophilus granarius L., Tribolium confusum Duv., Ephestia kuehniella Zell.*)), human saliva, hog pancreas, antitryptic activity) were distinctly diminished in grain samples heated to 79°C. At the highest grain temperature of 98°C, the loss of all biological activities was even more pronounced due to denaturation of 45% of extractable proteins.

Microwave heating was evaluated to reduce the incidence of mycoflora on rice (Oryza sativa L.) grains without adversely affecting the aroma and cooking quality of the grains. The duration of exposure of microwave heat directly correlated with grain temperature and inversely correlated with grain moisture and mycoflora. The exposure of rice grains to microwave heat at 100% power level up to 2 min retained the moisture and cooking-quality attributes of rice grains but reduced the mycoflora incidence by > 50% (Gupta & Kumar, 2003).

2.4 Grain germination

Germination is an ample and complex phenomenon and can be characterized when, under appropriate conditions, the embryo axis of the seed continues its development, which was interrupted by physiological maturity (Carvalho & Nakagawa, 1988).

In this process, catabolic reactions, such as the degradation of storage substances, and anabolic reactions, in the production of new cells and organelles of the embryo, occur (Metivier, 1979).

Cereal grains are susceptible to post-harvest germination (Bushuk, 2001), especially when temperature and humidity conditions are favorable, which can lead to great losses during grain storage. Few studies have been carried out to evaluate the effect of microwave radiation on cereal grains.

Vadivambal et al. (2009) used a pilot-scale industrial microwave drier operating at 2450 MHz to heat grains and oilseed. An infra-red thermal camera was used to determine the temperature distribution in bulk rye and oats at 14, 16, and 18% moisture content (wet basis) and sunflower seeds at 8, 10, and 12% moisture content after being heated in the microwave drier. Fifty grams of grain were placed in a sample holder and allowed to pass on a conveyor belt under the applicator at 0, 200, 300, 400, and 500 W for 28 or 56 s. There were hot and cool regions in the samples. The temperature difference between hot and cool regions in a given sample varied between 23 and 62°C for rye, 7 and 25°C for oats and 7 and 29°C for sunflower seeds. The preliminary results of this study suggest that while using microwave as a heat treatment, the maximum temperature that can affect seed viability (potential to germinate under favorable conditions) should be taken into consideration, when developing microwave processing systems for grains and oilseeds.

2.5 Pre-cooking

The objective of pre-cooking operations is to reduce preparation time for the consumer. In the case of cereals, these operations consist basically of treating starch to reduce its gelatinization time during the final preparation of the food product.

By toasting cereal flours, Wang et al. (1993) obtained pre-cooked rice flour (with 13.4% moisture) after 11 min in a microwave oven (2450 MHz) and Caballero-Córdoba et al. (1994) obtained pre-cooked wheat flour (with 14% moisture) after 11 min in a microwave oven (2450 MHz), with good sensory and nutritional evaluations, which were used in combination with defatted soy flour with additional microwave treatment for 8 min, for porridge and soup products.

Martinez-Bustos et al. (2000) produced nixtamalized maize flours (NMF) for the production of masa and tortillas, with the use of microwaves, operating frequency 2450 MHz, high-power setting, heating for 10, 15 and 20 min during alkaline cooking with the objective of accelerating the conventional alkaline cooking process. The results showed that microwave heating reduced processing time (approximately 50%) and liquid waste discharges (cooking liquor) during NMF production. Samples of NMF from whole maize microwave heated for 20 min with 70 $g.kg^{-1}$ water and 2.0 $g.kg^{-1}$ $Ca(OH)_2$ were statistically similar to the control with respect to masa firmness.

Roberts (1977) obtained rice similar to conventional parboiled rice by processing at 30-35% moisture for 2 to 5 min with microwaves.

Velupillai et al. (1989) developed a process for parboiling rough rice, which includes: (1) soaking the rough rice; (2) subjecting the soaked rough rice to a first value of microwave energy to partially gelatinize the starch in the rice and raise its water content; (3) draining free water, if any, from the treated soaked rough rice; and (4) subjecting the drained rough rice from (3) to a second level of microwave energy to effect substantially complete gelatinization and to lower the rough rice water content.

2.6 Cooking

Cooking and thawing operations in microwave ovens are already well documented. Some authors reported that the cooked and/or thawed product presents sensory changes in flavor, color and texture. According to Li (1995), flavor loss due to steam distillation is a major problem when microwave foods are cooked or reheated and this results in a unbalanced flavor profile in the final product.

With respect to color, the promotion of browning in a microwave oven is a difficult problem. According to Domingues et al. (1992), the solutions to microwave browning can be divided into the following categories: packaging aided, cosmetic and reactive coating approaches, and they developed a browning system that includes Maillard browning reactants for developing the desired browning effect during microwave irradiation, and a carrier system which contains the Maillard browning reactants.

Regarding texture, Clarke & Farrell (2000) studied the impact of water-binding agents (potato starch, pea fibre, oat fibre, locust bean gum), emulsifiers, ingredient blends and a proteolytic enzyme (fungal protease) on the textural characteristics of frozen five-inch pizza bases topped with tomato and cheese, reheated for 120, 150 and 180 s in a domestic microwave oven. The textural characteristics of the microwave-reheated pizza base samples were influenced by the presence of the selected agents.

2.7 Baking

Baking using microwave energy has been limited due to poor product quality compared to products baked by using conventional energy sources, which can be a reflection of the differences in the mechanism of heat and mass transfer (Sakonidou et al., 2003).

In products such as breads, cakes and cookies, microwave baking can affect texture, moisture content and color of the final product, which represents a great challenge for research. Some researchers suggest adjustments in formulation and alterations in the baking process, while others study the interactions between microwave energy and the ingredients of the formulation.

2.7.1 Breads

The producton of bread with the requisite quality attributes presumes a carefully controlled baking process. Thus, the rate of heat application and the amount of heat supplied, the humidity level within the baking chamber, and the duration of the bake all exert a vital influence on the final quality of the bread (Pyler, 1988).

In the conventional baking process, heat is transmitted to the dough piece in three different ways: radiation, convection and conduction. In the transformation of dough to bread, different phases occur: oven-rise (rapid expansion of carbon dioxide), oven-spring (expansion of the dough by about one-third of its original volume), moisture evaporation, starch gelatinization and protein coagulation; finally, cell walls become firm and crust color is developed (Pyler, 1988; Young & Cauvain, 2007).

In studies with bread during microwave heating, there was a rapid loss of moisture and, after microwaving, the mechanical strength of bread was increased greatly (Jahnke, 2003; Chavan & Chavan, 2010). According to Yin & Walker (1995), the heat and mass transfer patterns, insufficient starch gelatinization due to very short microwave baking times, microwave-induced gluten changes, and rapidly generated gas and steam could be reasons for the poor quality of microwave-baked breads. The work of Umbach et al. (1990) reported differences in bagel structure by using microscopy following conventional or microwave baking.

Park (2000) studied microwave (MW) – water interaction in a bread system and verified that:

- there was a linear relationship between moisture losses and energy input within the range of experiment conditions.
- the creep compliance value of MW heated bread was significantly lower than those of non-MW heated bread although both had the same moisture content level, suggesting the collapse of the aerated structure during microwaving by losing water molecules.

- MW heated breads absorbed less water than non-MW heated breads (they were less hygroscopic).

Jahnke (2003) developed a microwave baking dough additive that has a gelling component, a gum component and an enzyme component, as a means of controlling moisture migration or starch recrystallization in yeast-leavened bakery products that are baked by microwave energy.

2.7.2 Cakes

During cake production, after the mixing process, the cake must be deposited into cake pans and rapidly conveyed to the oven. Baking time is inversely related to baking temperature and the optimum baking conditions for cake baking are determined by the sweetener level of the formula, amount of milk used in the batter, fluidity of the batter, pan size and others (Young & Cauvain, 2007; Bennion & Bamford, 1998).

Stinson (1986) verified that yellow cakes baked in microwave/convection (MW/C) and conventional (CON) ovens showed slight sensory differences, however were acceptable, indicating that high quality cakes can be baked 15–25% faster in a MW/C oven than in a CON oven.

The effect of modifications in cake ingredients was studied by Tsoubeci (1994). Sucrose substitution with a blend of WPI (whey protein isolate) and maltodextrin and fat substitution with a special fiber were evaluated in a model cake system during baking by conventional and microwave methods. Substitution of sucrose with WPI and maltodextrin affected the dielectric properties of the batters. Power absorption predictions indicated that the power absorbed by microwave heated cakes increased when sucrose was substituted. Removal of fat influenced the dielectric behavior of batters whereas substitution with the special fiber compensated for fat in both microwave and conventionally heated cakes.

Şummu et al. (2000) used the response surface methodology to optimize the formulation of microwave-baked cakes and found that cakes formulated with wheat starch, containing 0.3% polysorbate 60, 133.7% water and 45.2% shortening (flour substitute basis), baked for 6 min at 100% power yielded acceptable cakes that can compete with conventionally baked cakes.

Takashima (2005) patented a process to obtain a sponge cake free from bake shrinkage and good-looking voluminous appearance, through a batter prepared by adding a thermocoagulation protein to a sponge cake premix containing as main ingredient a cereal powder consisting of starch and a pregelatinized starch cooked under heat with a microwave oven.

2.7.3 Cookies

There is a wide variety of cookies and their formulations, weight, diameter and other factors directly influence the baking process. In general, when cookies are baked using conventional methods, in conveyor belt ovens of 80 to 110 m, with cyclothermal heating, and universal conveyor belts, after approximately 3.5 to 4 minutes, they exit the oven with 5 e 8% moisture content and are cooled so as to lose moisture, to a final content of 3.5 to 4%. If the moisture gradient between the border and the center of the cookie is too high (greater than 1.5%), it can present fissures and cracks (checking) during storage, due to expansion and contraction of the cookie. Other factors are involved in checking, such as formulation, oven temperature, air relative humidity, etc. (Bernussi et al., 1998; Manley, 2000).

Shiffmann (1992) used microwave heating for final baking of cookies and obtained a more uniform moisture distribution than with forced convection.

Bernussi et al. (1998) studied the effects of microwave heating after conventional baking on moisture gradient and product quality of cookies and showed that cookies prebaked in a conventional oven at 140°C for 4 min and subsequently baked with a microwave oven set at 2450 MHz and magnetron power output of 617.27 W for 29 s showed significant reductions in moisture gradient, from 2.16 to 0.88% (central disk-outer rim), and incidence of cracking, from 41.7 to 0%. So the association of conventional and microwave heating processes for baking cookies minimized cookie cracking by reducing the moisture gradient and preserved the normal characteristics of the product (color, texture, flavor and linear dimensions).

Lorenz et al. (1973) verified that the baking time of cookies with microwaves was 30-45 seconds, however without crust color formation, so they suggested small modifications in the formulation, such as the use of molasses, chocolate or cocoa.

Lou et al. (1990) patented the production of prebaked cookie dough pieces, containing gluten, pregelatinized starch and high fructose corn syrup, to be baked in a microwave oven.

2.8 Pasta products

In dry pasta products, drying is the most critical step, as product moisture content must be reduced from approximately 30% to 12-13%. The greatest quality defects in pasta products are due to problems in this step: if drying is too fast, fissures or ruptures can occur; if drying is too slow, microbiological and enzymatic deterioration of the product is accelerated (Banasik, 1981; Kruger et al., 1996).

Pasta products are difficult to dry because moisture slowly migrates to the surface. Hot air is, by itself, relatively efficient at removing free water at or near the surface, whereas the internal moisture takes time to move to the surface. Microwave energy can solve this problem by providing a positive moisture flow towards the surface, and studies show pasta drying through combined processes (hot air + microwave drying) in a unique way (Decareau, 1986).

Maurer et al. (1971) obtained pasta drying speeds 20 times greater using microwaves when compared to conventional drying, therefore pasta dried by microwaves required lower drying process times.

Altan and Maskan (2005) studied the effect of conventional and microwave drying on the quality parameters of cooked and uncooked macaroni. Macaroni samples were dried by conventional hot air, microwave alone and hot air followed by microwave drying methods. Drying only with microwave energy (70 and 210 W) or hot air–microwave energy (70 and 210 W) resulted in substantial shortening of the drying time, but starch was not completely gelatinized during drying.

Goksu et al. (2005) studied microwave assisted fluidized bed drying of macaroni beads using a household microwave oven. They found that the increase in microwave power and air temperature significantly reduced (at 50%) the drying time of the macaroni beads when compared with fluidized bed only.

Berteli & Marsaioli Jr. (2005) evaluated the efficiency of air drying of Penne-type short cut pasta with the assistance of microwave energy and observed that the average drying time was reduced by more than ten times when compared to conventional air drying, without negatively affecting the appearance of the final product. The greatest benefits of drying pasta products using microwaves are the reduction of drying time and the maintenance of product quality.

2.9 Expansion

Besides heating, cooking or baking, it is possible to use microwave energy for expansion of foods.

2.9.1 Popcorn

Freshly popped popcorn, with its characteristic aroma and taste, has long been a popular snack product, particularly when flavored (Chedid et al., 1998). Popcorn is a whole-grain product obtained from a special variety of corn and its consumption increased with the development of microwave popcorn, this being one of the most popular applications of microwave heating, especially in the United States (Lin & Anatheswaran, 1988; Zhuang, 1998; Dofing et al., 1990; Pordesimo et al., 1990, 1991; Mohamed et al., 1993; Singh & Singh, 1999a, 1999b; Allred-Coyle et al., 2000, 2001; Chedid et al., 1998; Moraru & Kolkini, 2003).
Schwartzberg et al. (1995) considered that starch is the major polymer responsible for popcorn expansion.
Singh & Singh (1999b) reported that >75% popped kernels can be obtained by using 10% hydrogenated oil, 2% butter, and 0.5% sodium chloride, and expanding it in a 2450 MHz, 660 W microwave oven, at 70% power.
Chedid et al. (1998) prepared flavored and/or colored unpopped popcorn by use of an amylase-treated low viscosity starch, to be popped in a microwave oven without the use of added fat or oil, thus having a decreased caloric content.

2.9.2 Pellets or third-generation snacks

Manufacturing of 3rd-generation snacks is one of the newest applications of microwave heating. Third-generation snacks bring tremendous extension to popcorn expansion as it becomes possible to use food polymers to form snacks of various biological origins, in any desirable shape. They are obtained from half-products (pellets) that can be further expanded by baking, deep-fat frying, or microwave heating (Boischot et al., 2003; Ernoult et al., 2002; Suknark et al., 1999; Van Lengerich et al., 1992; Van Hulle et al., 1981, 1983; Willoughby, 2001).
Microwave expandable snack food products have been developed using cereal-based formulations with additives prepared as pellets in extruders (van Lengerich et al., 1992; Boehmer et al., 1992).
The non-expanded pellets are formed by extruding cereal flours at high moisture contents (30 to 35%), moderate shear and temperature, and die temperatures below 100°C, followed by cooling and drying to 5 to 10% moisture (Suknark et al., 1999; Boischot et al., 2003; Ernoult et al., 2002).
Other processes were also developed, as that of Willoughby et al. (1999), who prepared pellets from starchy compositions such as cooked farinaceous dough or dehulled popcorn with an outer methylcellulose skin or casing of sufficient tensile strength to allow build-up of internally generated steam pressure upon microwave heating. Upon sufficient build-up of steam pressure, the skin fails suddenly, allowing the pellet to puff explosively, thereby simultaneously causing an audible popping sound.
During microwave heating, glassy cereal pellets simultaneously lose moisture and expand (Boischot et al., 2003; Ernoult et al., 2002). This was demonstrated by the study of Ernoult et al. (2002), who obtained no expansion for totally dehydrated pellets, and maximum expansion was observed at 10.8% moisture content (weight/weight), and collapse was visible at 11.9% moisture content (weight/weight).

During microwave expansion of cereal pellets, the microwave energy heats the product through the vibrational energy imparted on moisture. Upon heating, moisture generates the superheated steam necessary for expansion, which accumulates at nuclei in the glassy matrix, creating a locally high pressure (Boischot et al., 2002). As the cereal matrix undergoes a phase transition from the glassy to the rubbery state, it starts to yield under the high superheated steam pressure and expansion takes place. As moisture is lost from the matrix, and upon cessation of microwave heating, the matrix cools down and reverts to the glassy state and the final structure sets. When the matrix is too soft (that is, at high moisture), collapse occurs (Moraru & Kokini, 2003).

Chen & Yeh (2000) observed that the high moisture pellets resulted in expanded products with a coarse structure, a small number of relatively large cells, and thick cell walls. At a lower moisture content of the pellets, a much finer structure was obtained.

When used for the manufacturing of snacks from half-products (pellets), starch is usually pregelatinized, as the limited amount of moisture and heat available in the expansion stage as well as the short residence times in microwave expansion, would not allow it to gelatinize and form a network that can be expanded by superheated steam (Schiffmann, 1993; Wang, 1997).

The study of Lee et al. (2000) indicated a nonlinear correlation between the degree of gelatinization and the expansion bulk volume of extruded cornstarch pellets and an optimum level of starch gelatinization (50%) for maximum product expansion.

Ernoult et al. (2002) obtained maximum expansion ratio (of about 10) for amylopectin pellets containing 6% solid fat, while at 10% solid fat expansion decreased due to a slight collapse of the expanded structure.

Gimeno et al. (2003) added 1% xanthan gum or carboxymethylcellulose to glassy cereal pellets and significantly improved the uniformity of the expanded matrix. The authors assumed that the large hydrocolloid molecules disrupted the alignment of the starch chains and promoted a uniform distribution of moisture in the matrix.

Weisz (2007) developed a process to produce a snack product from an extruded dough to be prepared by expansion in a microwave oven before consumption, or through any cooking method that permits expansion, such as conventional or electric ovens or frying.

2.10 Nutrient and ingredient modifications in cereal products

The main modifications in cereals and their respective products during microwave applications have been related to protein and starch.

With respect to proteins, research indicates a reduction in available lysine, independent of the type of heating and, in the case of wheat, studies indicate damage to gluten (Campana et al., 1993). Monks et al. (2003) studied the effect of microwave drying of soft wheat on the rheological behavior of the flour and the alveographic analysis of wheat flour showed that the P/L relationship and the gluten strength (W) increased ($p<0.05$) with the increase of microwave conditioning time, producing doughs that were inadequate for bread making.

There are various studies of the behavior of starch submitted to heating by microwave radiation and they are based mainly on gelatinization properties. However, other studies of chemical and physical modifications have been carried out and will be described below.

2.10.1 Pre-gelatinized starch

The production of pre-gelatinized starches has been investigated and developed industrially, as the products can be easily used in various food preparations, once they present rapid swelling in cold water and an increase in viscosity. The gelatinization process promotes the rupture of the starch granule and, consequently, an increase in the linkage sites of starch hydroxyl groups with water and other nutrients in an aqueous medium. The most studied cooking processes are:

- Conventional cooking: a suspension of starch in water is heated above gelatinization temperature (>65ºC), using a combination of time, agitation, water and temperature until complete cooking of the starch, which can be used after cooling or drying as pre-gelatinized starch;
- Drum-drier cooking: a suspension of starch in water is cooked and dried on heated rotating drums; and
- Thermoplastic extrusion cooking at high temperature and pressure: the starch, conditioned to moisture contents that vary from 20 to 30%, is transported through an extruder with heating and high pressure zones. When cooked starch exits the extruder, it must go through drying and pulverization processes (Leach, 1965; Chiang & Johnson, 1977; Harper, 1979).

Microwaves have been used to obtain pre-gelatinized starches, due to rapid cooking, however the published literature with respect to microwave heating of starch suspensions is limited and focuses primarily on the differences in the swelling of the starch granule during conduction and microwave heating (Palav & Seetharaman, 2007). A comprehensive investigation addressing the changes occurring in starch–water systems during microwave heating at molecular and macroscopic level is still necessary.

Various authors have shown that gels formed by heating starch slurries using microwave energy had significantly different properties than those heated by using conduction heat. The lack of granule swelling and the resulting soft gel are two key observations that highlight the differences in the two modes of heating. The significant differences in the other molecular properties, including enzyme susceptibility and amylopectin recrystallization, suggest a different mechanism of gelatinization during microwave heating (Goebel et al., 1984; Zylema et al., 1985, Palav & Seetharaman (2007).

Palav & Seetharaman (2007) proposed that during microwave heating starch granules lose their birefringence much earlier than gelatinization temperature due to the vibrational motion of the polar water molecules. The vibrational motion and the rapid increase in temperature also result in granule rupture and formation of film polymers coating the granule surface. This results in a soft gel even in the absence of a continuous network of amylose chains.

Goebel et al. (1984) and Zylema et al. (1985) compared the properties of starch–water systems at granular level following microwave heating. Zylema et al. (1985) found no differences in the swelling of granules when heated using microwave or conduction at the same heating rate. Goebel et al. (1984) worked with 1:1, 1:2, 1:4 and 5:95 starch/water ratios while Zylema et al. (1985) worked with 1:1, 1:2, 1:4 and 1:8 starch/water ratios. Despite the different sample sizes both studies found that their most dilute suspensions needed about 40% more time to heat-up compared to the most concentrated ones, an observation opposite to what might be intuitively expected (Buffler, 1993).

Ndife et al. (1998) reported the rates of gelatinization for different starches as influenced by microwave heating and also developed a quantitative model describing the relationship between water content and rate of gelatinization for corn, wheat and rice starches during microwave heating.

A relatively large volume of maize starch suspension (2.5–20% w/w solids) was heated to above its gelatinization temperature by two means: a microwave oven meant to provide a uniform global thermalization of the sample, and a conventional local electrical heater which, depending on agitation, yields different heating patterns on the sample. Contrary to what was observed in the conventionally heated samples, gelatinization was not completed in the microwave irradiated samples, although the temperatures reached were as high as with conventional heating. This was attributed to poor mass transfer of water molecules during microwave irradiation as a result of the short processing period and the absence of mixing of water with starch components (Sakonidou et al., 2003).

Niba (2003) tested autoclave, parboiling and microwave processes to gelatinize and enzymatically stabilize starches from various sources and, after storage under freezing conditions for 10 days, he verified that autoclaved and parboiled starch presented higher rapidly digestible starch (RDS) content that microwave processed starch.

Thed & Phillip (1995) studied domestic cooking methods comparatively to prepare potato products: microwave-heating and deep fat frying reduced an appreciable amount of in-vitro digestible starch and significantly increased both the resistant starch (RS) and water-insoluble dietary fiber (IDF), while boiling and baking had less effect. Water-soluble dietary content was not affected by any of the domestic cooking methods studied. The significant correlation between IDF and RS supported the idea that some of the starch in cooked potato had become indigestible by amylolytic enzymes, and this RS might contribute to the observed increment in the IDF fraction.

Roberts (1977) tested the effect of microwave energy on the gelatinization of hulled, whole or polished rice grains and verified that rice containing 30-35% moisture presented promising gelatinization results with microwave heating at atmospheric pressure.

Wadsworth & Koltun (1986) verified that there were no significant differences between rice dried in air (control) and rice dried under vacuum with microwaves, when peak viscosity and starch retrogradation were evaluated. The sensory evaluation team did not distinguish the samples with respect to differences in taste and texture.

2.10.2 Interactions between starch and other nutrients

Understanding the interactions between sugar, starch, protein and water, which are the main components of a baked product, will advance the development of high quality, microwaveable products (Sumnu et al. (1999); Chavan & Chavan, 2010), as less satisfactory results have been obtained for starch-based products.

Sumnu et al. (1999) evaluated the quantitative relationships between water, sugar and protein on the gelatinization of wheat starch following 20 s of microwave heat as determined by differential scanning calorimetry. They verified that the addition of sugar decreased the degree of gelatinization of starch due to microwave heating significantly. Water and protein were not found to be as significant as sugar in delaying gelatinization. The effects of sugar and protein on the gelatinization of starch were pronounced in water-limited systems.

The dielectric properties of hydrated whey protein isolate (WPI), Ca-caseinate, wheat starch and their mixtures were measured at ambient temperature and during heating to 90°C. WPI exhibited higher dielectric properties than starch at lower moisture contents and ambient temperature. At most moisture contents WPI showed increasing microwave absorption properties with increasing temperature. Addition of WPI in the starch:water system affected the dielectric loss and absorptivity of starch during heating (Tsoubeci, 1994).

2.10.3. Modified starches

Annealing and heat/moisture-treatment both cause a physical modification of starches without any gelatinization, or any other damage of the starch granules with respect to size, shape or birefringence only via a controlled application of heat/moisture (Stute, 1992).

Gupta et al (2003) investigated the effect of microwave heat-moisture and annealing processes on buckwheat starch that had been dried to three moisture levels: 30.3, 40.0, and 50.4 kg/100kg. DSC data indicated that moisture levels had a significant effect on onset melting temperature, peak melting temperature and enthalpy. In addition, heat treatment and interaction of moisture with heat treatment both had a significant effect on amylose leaching results. Resistance to amylose leaching and melting at higher temperatures for higher moisture level buckwheat starch samples was attributed to increased networking among the amylose and amylopectin components in the buckwheat starch.

Wheat, corn and waxy corn starches of intermediate moisture content (30%) were subjected to microwave processing and the effect of microwave radiation on physico-chemical properties and structure of cereal starches was studied. Microwave radiation was evidenced to cause a shift in the gelatinization range to higher temperatures, and a drop in solubility and crystallinity. The extent and type of these changes depended on the variety of starch. Normal corn and wheat starches suffered pronounced changes, whereas under the same conditions waxy corn starch was almost unchanged. It was concluded that susceptibility of different starches to changes due to microwave irradiation depended not only on their crystal structure, but also on their amylose content (Lewandowicz et al., 2000).

Shogren & Biswas (2006) prepared starch acetates of 0.1-1.5 substitution through microwave heating of corn starch, acetic acid and acetic anhydride in sealed, stirred, teflon vessels. They found that starch acetates of high cold water solubility with DS (degree of substitution) values of 0.3-1.1 were prepared quickly and efficiently by microwave heating of starch, acetic acid and acetic anhydride. Molecular weights of starch acetates were much lower than the native starch. This study contributed to increase the efficiency of the reaction and to economize reagents when compared to the conventional method to prepare starch acetates.

Resistant starches (RS), in other words, those that are not digested in the small intestine, have been used to substitute fiber in food products, because although both have the same physiological functions, RS does not interfere in the palatability of foods.

Oliveira et al. (2007) studied the cooking of starches in a microwave oven using different starch:water ratios (1:5 to 1:8) and cooking/cooling cycles (1 to 3). They evaluated the content of resistant starch (%RS) after each process, as well as water absorption index (WAI) and water solubility index (WSI) and verified that the %RS increased with the increase in the number of cooking/cooling cycles and the starch:water ratio, while WAI and WSI were higher with a reduced number of cycles and starch:water ratio.

3. Future perspectives

In applications involving cereal products, the use of microwaves is promising in pre-processing operations, such as the drying of cereal grains or flours, the production of starches and the control of moisture and germination during grain storage, once the results presented in the various studies show the efficiency of the process, which economizes time and energy.

One of the greatest successes of the use of microwaves is in the preparation of expanded products and research and development of new products in this area is growing, with an unlimited number of processes being patented. Future indicates the development of healthier expanded products, with the reduction of fat and the inclusion of nutrients that are more beneficial to health.

Cooking and baking processes to obtain cakes, breads, cookies and pasta show that when microwaves are use associated to the conventional process results are more satisfactory for final product quality, but the isolated use of microwaves to obtain these products requires changes in formulation and process conditions.

Effects on different food constituents have been studied. In cereal-based products, the most studied constituent is starch, as it is present in greatest proportion in grains, followed by protein. These two constituents directly influence the quality of the final product, both bakery products and pasta. There is a lack of information on the evaluation of the effect of microwaves on lipids, fibers, vitamins and antioxidant compounds in cereal grains. These constituents are present in smaller quantities, but due to the daily consumption of cereals, are of nutritional importance in the diet.

The use of microwaves as catalysts of chemical reactions is starting to be studied in the area of modified starches and tends to develop more, once the advantages shown are promising, such as speed of the reaction, lower quantity of reagents and final products with the desired physical-chemical characteristics.

4. Conclusions

The use of microwave radiation to process cereal-based products has progressed in a promising way, improving process efficiency with respect to economy of time and energy. While many processes are already considered of high efficiency, such as grain drying, moisture control in cookies, starch modifications and pop-corn and expanded snack production, others such as bread and cake baking still need greater investments in research and development to improve quality.

5. References

Allred-Coyle, T.A.; Toma, R.B.; Reiboldt, W. & Thakur, M. (2001). Effects of bag capacity, storage time and temperature, and salt on the expansion volume of microwave popcorn. *Journal of the Science of Food and Agriculture, Vol.* 81, No. 1, 121-5, *ISSN*-1097-0010.

Allred-Coyle, T.A.; Toma, R.B.; Reiboldt, W. & Thakur, M. (2000). Effects of moisture content, hybrid variety, kernel size, and microwave wattage on the expansion volume of microwave popcorn. *International Journal of Food Sciences and Nutrition, Vol.* 51, No. 5, 389-94, ISSN-1465-3478.

Altan, A. & Maskan, M. (2005). Microwave assisted drying of short-cut (ditalini) macaroni: Drying characteristics and effect of drying processes on starch properties. *Food Research International,* Vol. 38, No.7, 787–796, ISSN-0963-9969.

Aref, M. M.; Brach, E. I.; Tape, N. M. (1969). A pilot-plant continuous-process microwave oven. *Canadian Institute of Food Technology*, Vol. 2, No.1, 37-41, ISSN-*0315-5463*.

Banasik, O.J. (1981). Pasta processing. *Cereal Foods World,* Vol. 26, No. 4, 166-169, ISSN-0146-6283.

Bennion, E.B. & Bamford, G.S.T. (1997). *The Technology of Cake Making,* Chapman & Hall, 6ª ed., ISBN-10-0751403490, London.

Bernussi, A. L. M.; Chang, Y. K. & Martinez-Bustos, F. (1998). Effect of Production by Microwave Heating After Conventional Baking on Moisture Gradient and Product Quality of Biscuits (cookies). *Cereal Chemistry*, Vol. 75, No. 5, 606-611, ISSN- 0009-0352.

Berteli, M. N. & Marsaioli Jr., A. (2005). Evaluation of short cut pasta air dehydration assisted by microwaves as compared to the conventional drying process. *Journal of Food Engineering*, vol. 68, No. 2, 175–183, *ISSN – 0260-8774.*

Boehmer, E. W.; Bennet, W. L.; Guanella, T. J. & Levine, L. (1992). *Microwave expandable half product and process for its manufacture*. United States Patent 5,165,950.

Boischot C.; Moraru C. I.; Kokini J.L. (2003). Expansion of glassy amylopectin extrudates by microwave heating. *Cereal Chemistry*, Vol. 80, No.1, 56-61, ISSN- 0009-0352.

Breslin, J. C. (1990). *Microwave--convection drying of ready-to-eat cereals*. M.S. dissertation, Michigan State University, United States -- Michigan. Retrieved June 24, 2010, from Dissertations & Theses: A&I.(Publication No. AAT 1341402).

Buffler, C. R. (1992). *Microwave cooking and processing.* New York Van Nostrand Reinhold, ISBN-10- 0442008678, New York.

Bushuk, W.(2001). Rye production and uses worldwide. *Cereal Foods World,* Vol. 46, No.2, 70-73, ISSN- 0146-6283.

Caballero-Córdoba, G. M.; Wang, S. H. & Sgarbieri, V. C. (1994). Características nutricionais e sensoriais de sopa cremosa semi-instantânea à base de farinhas de trigo e soja desengordurada. *Pesquisa Agropecuária Brasileira*, Vol. 29, No. 7, 1137-1143, ISSN- 0100-204X.

Campaña, L.E.; Sempé, M.E. & Filgueira, R. R. (1993). Physical, chemical, and baking properties of wheat dried with microwave energy. *Cereal Chemistry*, Vol. 70, No. 6, 760-762, ISSN- 0009-0352.

Carvalho, N.H. & Nakagawa, J. (1988). *Sementes: ciência, tecnologia e produção*. Fundação Cargill, 3 ed., *ISBN- 85-87632-01-9,* Campinas.

Chang, Y. K. & El-Dash, A. A. (1998). Effect of microwave energy on lipase inactivation and storage stability of brown rice. *Acta Alimentaria*, Vol. 27, No.2, 193-202, ISSN-0139-3006.

Chavan, R.S. & Chavan, S.R. (2010). Microwave baking in food industry: A review. *International Journal of Dairy Science*, Vol. 5, No. 3, 113-127, ISSN (on Line)-*1811-9751.*

Chedid, L.; Huang, D. P. & Baytan, P. (1998). *Flavored popping corn with low or no fat*. United States Patent 5,753,287.

Chen, C.M. & Yeh, A.L. (2000). Expansion of rice pellets: examination of glass transition and expansion temperature. *Journal of Cereal Science*, Vol.32, No.2, 137-45, ISSN- 0733-5210.

Chiang, B-Y. & Johnson, J.A. (1977). Gelatinization of starch in extruded products. *Cereal Chemistry*, Vol.54, No.3, 436-443, ISSN- 0009-0352.

Clarke, C.I. & Farrell, G.M. (2000). The effects of recipe formulation on the textural characteristics of microwave-reheated pizza bases. *Journal of the Science of Food and Agriculture*, Vol. 80, No.8, 1237-1244, ISSN-0022-5142.

Conforti, E.; Kieckbusch, T.G. & Marsaioli Jr., A. (1990). A prototype of a combined hot air and microwave rotary cylindrical oven for continuous drying of granular products. In: *Engineering and Food, Preservation Processes and Related Techniques*. Spiess, W.E.L. & Schubert, H. (ed). 679-685, Elsevier Sci. Publ., *ISBN-10- 1851664661,* London & New York.

Decareau, R.V.; Peterson, R.A. (1986). *Microwave processing and engineering.* Ed. Wiley-VCH, 224 p.ISBN-10- 3527262105, Weinheim.

Dofing , S.M.; Thomas-Compton, M.A. & Buck, J.S. (1990). Genotype X popping method interaction for expansion volume in popcorn. *Crop Science* , Vol.30, No. 1, 62-5, *ISSN* 1435-0653.

Domingues, D.J.; Atwell, W. A.; Beckmann, P. J.; Panama, J. R.; Conn, R. E.; Matson, K. L.; Graf, E.; Feather, M. S.; Fahrenholtz, S. K. & Huang, V. T. (1992). *Process for microwave browning*. United States Patent 5,108,770.

Doty, N.C. & Baker, C.W. (1997). Microwave conditioning of hard red spring wheat. I. Effects of wide power range on flour and bread quality. *Cereal Chemistry*, Vol. 54, No. 4, 717- 727, ISSN- 0009-0352.

Edwards, G. H. (1964). Effects of microwave radiation on wheat and flour: the viscosity of the flour pastes. *Journal of the Science of Food and Agriculture*, Vol.15, No.1, 108-114, ISSN-0022-5142.

Engelder, D. S. & Buffler, C. R. (1991). Measuring dielectric properties of food products at microwave frequencies. *Microwave World,* Vol. 12, No.2, 6-15, ISSN-1759-0787.

Ernoult ,V.; Moraru, C.I. & Kokini, J.L. (2002). Influence of fat on the expansion of glassy amylopectin extrudates by microwave heating. *Cereal Chemistry*, Vol. 79, No.2, 265-273, ISSN- 0009-0352.

Frisvad, J.C. (1995). Mycotoxins and mycotoxigenic fungi in storage. In: *Stored –grain ecosystems*, Jayas, D.S. & White, W.E.M. M. Dekker, 251-288, ISBN - 0824789830, New York.

Gimeno, E.; Moraru, C.I.; Kokini, J.L. (2003). Effect of Xanthan Gum and CMC on the texture and microstructure of glassy corn flour extrudates expanded by microwave heating. *Cereal Chemistry*, Vol. 81, No.1, 100-107, ISSN- 0009-0352.

Goebel, N. K.; Grider, J.; Davis, E. A. & Gordon, J. (1984). The effects of microwave energy and convection heating on wheat starch granule transformations. *Food Microstructure*, Vol.3, No.1, 73–82, ISSN-1046-705X.

Goksu, E. I.; Summu, G. & Esin, A. (2005). Effect of microwave on fluidized bed drying of macaroni beads *Journal of Food Engineering*, Vol. 66, No. 4, 463 – 468, *ISSN – 0260-8774.*

Goldblith, S.A. (1966). Basic principles of microwaves and recent developments. *Advances Food Research*, Vol.15, p. 277-301. ISSN- 0065-2628

González Galán, A.; Wang, S. H.; Sgarbieri, V. C. & Moraes, M. A. C. (1991). Sensory and nutritional properties of cookies based on wheat-rice-soybean flours baked in a microwave oven. *Journal of Food Science*, Vol. 56, No. 6, 1699-1701, ISSN 0022-1147.

Gupta, A. & Kumar, P. (2003). Effect of microwave heating on rice (Oryza sativa) grain quality. *Indian Journal of Agricultural Sciences*, Vol. 73, No. 1, 41-43, ISSN- 0019-5022.

Gupta, M.; Gill, B. S.; Baw, A. S. (2008). Gelatinization and X-ray Crystallography of Buckwheat Starch: Effect of Microwave and Annealing Treatments. *International Journal of Food Properties*, Vol. 11, No. 1, 173 – 185, ISSN (electronic)- 1532-2386.

Harper, J.M. (1979). Food extrusion. *CRC - Critical Reviews in Food Science and Nutrition*, Vol.11, n.2, p.155-215, ISSN 1040-8398.

Hoffman, C.J. & Zabik, M.E. (1985). Effects of microwave cooking/reheating on nutrients and food systems: a review of recent studies. *Journal of the American Dietetic Association*, Vol. 85, No.8, 922-6, ISSN- 0002-8223.

Jahnke, M. (2003). *Method of making microwavable yeast-leavended bakery product containing dough additive*. United States Patent 6,579,546.

Jermolovicius, L. A.; Schneiderman, B. & Senise, J. T. (2006). Alteration of Esterification Kinetics Under Microwave Irradiation. In: *Advances in Microwave and Radio-Frequency Processing,*Willert-Porada, M. *(ed),* Springer, Germany, ISBN978- 3-540-43252-4.

Jiaxun-Tao; Rao, R. & Liuuzo, J. (1993). Microwave heating for Rice bran stabilization. *Journal of Microwave, Power and Electromagnetic Energy,* Vol. 28, No.3, 156-164, ISSN-0832-7823.

Juliano, B. O. (1985). Criteria and tests for rice grain quality. In: *Rice Chemistry and Technology,* The American Association of Cereal Chemists (Ed.), pages 443-513. ISBN-10- 0913250414, St.Paul.

Khraisheh, M. A.; Cooper, T. J. R. & Magee, T. R. A. (1997). Microwave and air drying I. Fundamental considerations and assumptions for the simplified thermal calculations of volumetric power absorption. *Journal of Food Engineering,* Vol.33, No.1, 207–219. *ISSN – 0260-8774.*

Kruger, J.E.; Matsuo, R.B. & Dick, J.W. (1996). *Pasta and Noodle Technology.* American Association of Cereal Chemists, ISBN-10- 0913250899, St.Paul.

Kudra, T. (1989). Dielectric drying of particulate materials in a Fluidized in a fluidized state. *Drying Technology,* Vol. 1. No.7, 17-34. *ISSN – 0737-3937*

Leach, H.W. (1965). Gelatinization of starch. In: Starch Chemistry and Technology, vol I, ed. Whistler, R.L. & Paschalle.F. *Academic Press*, New York,. ISBN-10- 0127462759

Lee, E.Y.; Lim. K.I.; Lim, J.; Lim, S.T. (2000). Effects of gelatinization and moisture content of extruded starch pellets on morphology and physical properties of microwave expanded products. *Cereal Chemistry*, Vol.77, No.6, 769-73. ISSN-0009-0352

Lewandowicz, G.; Jankowski, T. & Fornal, J. (2000).Effect of microwave radiation on physico-chemical properties and structure of cereal starches. *Carbohydrate Polymers* vol. 42, No. 2, 193-199, *ISSN – 0144-8617.*

Li, H.-C. (1995). *Identification of aroma compounds and evaluation of volatile losses during the frying and microwave reheating of a flour-based batter system (pancake)*. Ph.D. dissertation, University of Minnesota, United States -- Minnesota. Retrieved June 24, 2010, from Dissertations & Theses: A&I.(Publication No. AAT 9534129).

Lin ,Y.E. & Anantheswaran, R.C. (1988). Studies in popping of popcorn in a microwave oven. *Journal of Food Science*, Vol. 53, No.6,1746-9, ISSN 0022-1147.

Lin, Y. E.; Anantheswaran, R. C. & Puri, V. M. (1995). Finite element analysis of microwave heating of solid foods. *Journal of Food Engineering*, Vol.25, No.1, 85–112. ISSN – 0260-8774.

Loewen, R. H. & Gandolfi, O. (2004). *Equipamento para secagem de cereais por microondas*. PI0402177-0 A2, Brasil.

Lorenz, K.; Charman, E. & Dilsaver, W. (1973). Baking with microwave energy. *Food Technology,* Vol. 27, No.12, 28-36, ISSN- 0015-6639.

Lou, W. C. & Fazzolare, R. D. (1990). *Shelf-stable microwavable cookie dough*. United States Patent 4,911,939.

Manley, D. J. R. (2000). *Technology of biscuits, crackers and cookies* - Third Edition. CRC Woodhead Publishing Limited, ISBN- 1855735326, Abington.

Marini, L. J.; Gutkoski, L.C.; Elias, M. C. & Santin, J. A. (2007). Qualidade de grãos de aveia sob secagem intermitente em altas temperaturas. *Ciência Rural* [online], Vol.37, No.5, 1268-1273, ISSN (On line) 1678-4596.

Marotti Neto, A. S. (2007). *Secador por microondas modular com turbilhonamento em caracol por fluxo de ar sobre esteira.* MU8700836-0 U2, Brasil.
Marsaioli Jr., A. (1991). *Desenvolvimento de um protótipo de secador cilíndrico – rotativo a microondas e a ar quente para a secagem contínua de produtos sólidos granulados*. 197p. Tese (Doutor em Engenharia de Alimentos) – Faculdade de Engenharia de Alimentos, Universidade Estadual de Campinas.
Marsaioli Jr., A.; Berteli, M. N. & Pereira, N. R. (2009). Applications of microwave energy to postharvest technology of fruits and vegetables. *Stewart Postharvest Review*, Vol. 5, No.1, 1-5, ISSN- 1745-9656.
Martinez-Bustos, F. M.; Garcia, M.; Chang, Y. K.; Sanchezsinencio, F. & Figueroa, C. (2000). Characteristics of nixtamalised maize flours produced with the use of microwave heating during alkaline cooking. *Journal of the Science of Food and Agriculture*, vol. 80, No.6, 651-656, ISSN-0022-5142.
Maurer, R.L.; Trembly, M.R. & P.E. Chadwick, P.E. (1971). Microwave processing of pasta. *Food Technology* , Vol.25, 1240-1245, ISSN- 15574571.
Metivier, J.R. (1979).Dormência e germinação. In: *Fisiologia Vegetal*. FERRI, M.G. (Ed.).: EPU:EDUSP, 343-392 (Cap.12), ISBN-10: 8512119101, São Paulo.
Mohamed, A.A.; Ashman, R.B. & Kirleis, A.W. (1993). Pericarp thickness and other kernel physical characteristics relate to microwave popping quality of popcorn. *Journal of Food Science*, Vol. 58, No.2, 342-6, ISSN- 0022-1147.
Monks, L.F.; Costa, C.S. , & Soares, G.J.D. (2003). Microwave effects on wheat drying (T. aestivum, L.) and flour quality. *Alimentos e Nutrição,* Vol.14, No.2, 219-224, ISSN- 0103-4235.
Moraru, C.I. & Kokini, J.L. (2003). Nucleation and expansion during extrusion and microwave heating of cereal foods, *Comprehensive reviews in Food Science and Food Safety*, Vol. 2, No.3, 120-138, ISSN-1541-4337.
Mudgett, R. E. (1982). Electrical properties of foods in microwave processing. *Food Technology,* Vol.36. No. 2, 109-115, ISSN- 15574571.
Ndife, M.; Sumnu, G. & Bayındırlı, L. (1998). Differential scanning calorimetry determination of gelatinization rates in different starches due to microwave heating. *Lebensmittel-Wissenschaft Untersuchung-Technoology*, Vol. 31, No.5, 484–488. ISSN (Online) 1532-1738.
Niba, L. L. (2003). Processing effects on susceptibility of starch to digestion in some dietary starch sources**.** *International Journal of Food Sciences and Nutrition*, Vol.54, No.1, 97-109, ISSN (electronic) - 1465-3478.
Ohlsson, T., & Risman, P. O. (1978). Temperature distribution of microwave heating-spheres and cylinders. *Journal of Microwave Power*, Vol. 13, No.4, 303–310, ISSN- 0022-2739.
Oliveira, M.; Clerici, M. T.; Pompeu, F.; Chang, Y. K. & Martinez-Bustos, F. M. (2007). Physicochemical and technological properties of resistant starch obtained using microwave oven. In: 2007 IFT Annual Meeting, Chicago, 275-275.
Palav, T. & Seetharaman, K. (2007). Impact of microwave heating on the physico-chemical properties of a starch–water model system. *Carbohydrate Polymers*, Vol.67, No. 4, 596–604. ISSN — 0144-8617.
Park , J. K.; Bin, A. & Brod, F. P. R. (2001). Obtenção das isotermas de sorção e modelagem matemática para a pêra bartelett (*Pyrus sp.*) com e sem desidratação osmótica. *Ciência e Tecnologia de Alimentos*, Vol.21, No.1, 73-78, ISSN- 0101-2061.
Park, T. (2001). *A study of microwave-water interactions in bread system*. Ph.D. dissertation, Rutgers. The State University of New Jersey - New Brunswick, United States --

New Jersey. Retrieved June 24, 2010, from Dissertations & Theses: A&I.(Publication No. AAT 9973982).

Pecoraro, E. ; Davolos, M. R.; Jafelicci Jr., M. (1997). Adaptações em forno de microondas doméstico para utilização em laboratório. *Química Nova*, Vol. 20, No. 1, ISSN (On-Line) 1678-7064.

Pei, D.C.T. (1982). Microwave baking-new developments. *Baker's Digest,* Vol. 56, No.1, 8-10.

Pordesimo, L.O.; Anantheswaran, R.C.; Fleischmann, A.M.; Lin , Y.E.& Hanna, M.A. (1990). Physical properties as indicators of popping characteristics of microwave popcorn. *Journal of Food Science*, Vol. 55, No.5, 1352-5, ISSN- 0022-1147.

Pordesimo, L.O.; Anantheswaran, R.C. & Mattern, P.J. (1991). Quantification of horny and floury endosperm in popcorn and their effects on popping performance in a microwave oven. *Journal of Cereal Science*, Vol. 14, No.2, 189-98, ISSN- 0733-5210.

Prado, G.; Mattos, S. V. M. & Pereira, E. C. (1991). Efeito da umidade relativa na contaminação microbiana e produção de aflatoxinas em amendoim em grão. *Ciência e Tecnologia de Alimentos*, Vol.11, No. 2, 264-273, ISSN-0101-2061.

Pyler, E.J. (1988). *Baking Science and Technology. Sosland Publishing Company*. v.1 e 2. ISBN-0929005007, Chicago.

Remmen, H. H. J.; Ponne, C. T.; Nijhuis, H. H.; Bartels, P. V. & Kerkhof, P. J. A. M. (1996). Microwave heating distribution in slabs, spheres and cylinders with relation to food processing. *Journal of Food Science*, Vol. 61, n. 6, p. 1105-1113, ISSN- 0022-1147.

Roberts, R.L.(1977). Effect of microwave treatment of pre-soaked paddy, brown and white rice. *Journal of Food Science*, Vol. 42, No. 3, 804–806, ISSN- 0022-1147.

Rocha, C. R. (2002). *Efeitos do Tratamento por Microondas do Arroz Recém Colhido no Rendimento de Grãos Inteiros, na Qualidade de Cozimento e na Estabilização do Farelo*. 207 p. Tese (Doutorado em Engenharia de Alimentos) - Universidade Estadual de Campinas.

Sacharow, S. & Schiffmann, R. (1992). *Microwave Packaging*. Pira International, *Leatherhead* UK, 155p, ISBN 0-902799-70-3

Sakonidoua, E.P., Karapantsiosa, T.D. & Raphaelides, S.N. (2003). Mass transfer limitations during starch gelatinization. *Carbohydrate Polymers,* Vol. 53, No.1, 53–61, ISSN— 0144-8617.

Sale, A. J. H. (1976). A review of microwave for food processing. *International Journal of Food Science & Technology,* Vol. 11, No.4, 319–329, ISSN 0950-5423.

Saunders, R. M. (1990). The properties of rice bran as a foodstuff. *Cereal Foods World*, Vol.35, No. 7, 632-636, ISSN- 0146-6283.

Schiffmann, R.F. (1993). Understanding microwave reactions and interactions. *Food Product Design* (April), 72-88, ISSN - 1065-772X.

Schiffmann, R. F. (1986). Food product development for microwave processing. *Food Technology*, vol. 40, 94–98, ISSN- 15574571

Schiffmann, R. F. (1992). Microwave processing in the US food industry. *Food Technology*, Vol.56, No.1 50-52, ISSN- 15574571.

Scudamore, K. A.; Patel, S. & Breeze, V. (1999). Surveillance of stored grain from the 1997 harvest in the United Kingdom for ochratoxin A. *Food Additives and Contaminants*, Vol.16, No. 7, 81-290, ISSN- Online-1464-5122.

Senise, J. T. & Jermolovicius, L. A. (2004). Microwave Chemistry - A Fertile Field For Scientific Research And Industrial Applications. *Journal of Microwaves and Optoelectronics*, Vol.3, No.5, 97-112, ISSN- 1516-7399.

Shogren, R.L. & Biswas, A. (2006). Preparation of water-soluble and water-swellable starch acetates using microwave heating. *Carbohydrate Polymers*, Vol.64, No.1, 16-21, ISSN — 0144-8617.

Singh, J. & Singh, N. (1999a). *Effect of different ingredients and microwave power on snacks upon microwave heating*. U.S. Patent 4,409,250.

Singh, J. & Singh, N. (1999b). Effect of different ingredients and microwave power on popping characteristics of popcorn. *Journal of Food Engineering,* Vol. 42, No.3, 161-5. *ISSN — 0260-8774.*

Stinson, C. T. (1986). A Quality Comparison of Devil's Food and Yellow Cakes Baked in a Microwave/Convection Versus a Conventional Oven. *Journal of Food Science*, Vol. 51, No. 6, 1578–1579, ISSN- 0022-1147.

Stute, R. (1992). Hydrothermal Modification of Starches: The Difference between Annealing and Heat/Moisture –Treatment. *Starch – Stärke,* Vol. *44*, No.6, 205-214, ISSN-0038-9056.

Suknark, K.; Phillips, R.D. & Huang, Y.W. (1999). Tapioca-fish and tapioca-peanut snacks by twin-screw extrusion and deep-fat frying. *Journal of Food Science, Vol.* 64, No.2, 303-8, ISSN- 0022-1147.

Şummu, G.; Ndife, M.K. & Bayindirli, L. (2000). Optimization of microwave baking of model layer cakes. *European Food Research and Technology*, Vol. 211, No. 3, 169-174, ISSN-(electronic)- 1438-2385.

Şummu, G. (2001). A review on microwave baking of foods. *International Journal of Food Science and Technology,* Vol. 36, No.2, 117-127, ISSN-0950-5423.

Şummu, G.; Ndife, M.K & Bayındırlı, L. (1999) . Effects of sugar, protein and water content on wheat starch gelatinization due to microwave heating. *European Food Research and Technology,* Vol. 209, No.1, 68–71, ISSN (electronic version) 1438-2385.

Takano, K.(1993).Mechanism of lipid hydrolysis in rice bran. *Cereal Foods World*, Vol.38, No.2, 95-698, ISSN- 0146-6283.

Takashima, H. (2005). Sponge cake premix and method of manufacturing sponge cake by using said premix. United States Patent 6,884,448.

Thed, S. T. & Phillip, R. D. (1995)**.** Changes of dietary fiber and starch composition of processed potato products during domestic cooking. *Food Chemistry* ,Vol. 52, No.3, 301-3.

Tsoubeci, M. N. (1994). Molecular interactions and ingredient substitution in cereal based model systems during conventional and microwave heating. Ph.D. dissertation, University of Minnesota, United States -- Minnesota. Retrieved June 24, 2010, from *Dissertations , & Theses*: A&I.(Publication No. AAT 9514682).

Umbach, S.L.; Davis, E.A. & Gordon, J. (1990). Effects of heat and water transport on the bagel-making process: Conventional and microwave baking. *Cereal Chemistry*, Vol. 67, 355-360, ISSN- 0009-0352.

Vadivambal, R.; Jayas, D.S.; Chelladurai, V. & White, N.D.G. (2009). Preliminary study of surface temperature distribution during microwave heating of cereals and oilseed. *Canadian Biosystems Engineering / Le Genie des biosystems au Canada*, Vol. 51, 3.45 - 3.52.

Van Hulle, G.J.; Anker, C.A. & Franssell, D.E. (1983). *Method for preparing sugar-coated, puffed snacks upon microwave heating*. U.S. Patent 4,409,250.

Van Lengerich, B. H. & Lou, W.C.(1992). *Filled, microwave expandable snack food product and method and apparatus for its production*. United States Patent 5,124,161.

Van Remmen, H.H.J.; Ponne, C.T.; Nijhuis, H.H.; Bartelis, P.V. & Kerkhof, P.J.A.M. (1996). Microwave heating distributions in slabs, spheres and cylinders with relation to food processing. *Journal of Food Science*, Vol. 61, No.6, 1105-13, *ISSN- 0022-1147.*

Velupillai, L.; Verma, L. R. & Tsangmuichung, M. (1989). *Process for parboiling rice*. United States Patent 4,810,511

Vetrimani, R.; Jyothirmayi, N.; Rao, H. P. & Ramadoss, C. S. (1992). Inactivation of lipase and lipoxygenase in cereal bran, germ and soybean by microwave treatment. *Lebensmittel Wissenshaft und Technologie*, Vol.6, No. 6, 532-535, ISSN (printed) - 0023-6438.

Wadsworth, J. I. & Koltun, S. P. (1986). Physicochemical properties and cooking quality of microwave dried rice. *Cereal Chemistry*, Vol.63, No. 4, 346-348, ISSN- 0009-0352.

Wang, S.W. (1997). Starches and starch derivatives in expanded snacks. *Cereal Foods World*, Vol.42, No.9, 743-5, ISSN- 0146-6283.

Wang, S. H.; Caballero-Córdoba, G. M. & Sgarbieri, V. C. (1992). Propriedades funcionais de misturas de farinhas de trigo e soja desengordurada, pré-tratadas por micRoondas. *Ciência e Tecnologia de Alimentos*, Vol. 12, No. 1, 14-25, ISSN- 0101-2061.

Wang, S. H.; Clerici, M. T. P. S. & Sgarbieri, V. C. (1993). Características sensoriais e nutricionais de mingau de preparo rápido à base de farinhas de arroz e soja desengordurada e leite em pó. *Alimentos e Nutrição*, Vol. 5, No.1, 77-86, ISSN- 0103-4235.

Warchalewski, J.R. & Gralik, J. (2010). Influence of microwave heating on biological activities and electrophoretic pattern of albumin fraction of wheat grain. *Cereal Chemistry*, Vol. 87, No. 1, 35-41, ISSN- 0009-0352.

Weisz, M. A. Co. 2007. *Processo de produção de salgadinho, snack ou pellet elaborado a partir de massa extrusada.* MU8701618-4 U2, Brasil.

Wennermark, B. (1993). *Vitamin E retention during processing of cereals*. Fil.Dr. dissertation, Lunds Universitet (Sweden), Sweden. Retrieved June 24, 2010, from *Dissertations & Theses*: A&I.(Publication No. AAT C299434).

Willoughby; C. L. & Engle, T. L. (2001). *Expandable food products and methods of preparing same* . United States Patent 6,171,631.

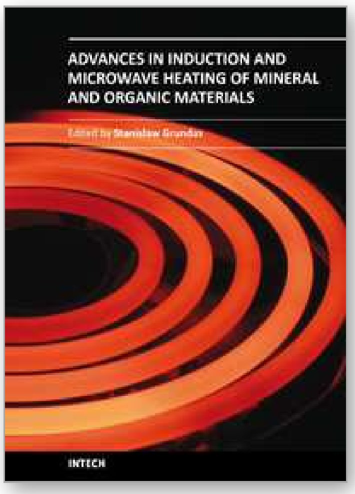
Yang, H. W. & Gunasekaran, S. (2004). Comparison of temperature distribution in model food cylinders based on Maxwell's equations and Lambert's law during pulsed microwave heating. *Journal of Food Engineering*, Vol.64, No.4, 445–453, *ISSN – 0260-8774.*

Yin, Y. & Walker, C.E. (1995). A quality comparison of breads baked by conventional versus non conventional ovens: a review. *Journal of the Science of Food and Agriculture*, Vol.67, No.3, 283-91, *ISSN* (Online) 1097-0010.

Young, L.; Cauvain, S.P. (2007). *Technology of Breadmaking*. Springer; 2 ed., ISBN-10-0751403458, Germany.

Zhuang, M. (1998). Microwave popcorn, waiting to explode. *Agexporter, Vol.* 10, No.3,10-1. ISSN- 1047-4781.

Zylema, B. J.; Grider, J. A.; Gordon, J. & Davis, E. A. (1985). Model wheat starch systems heated by microwave irradiation and conduction with equalized heating times. *Cereal Chemistry*, Vol.62, No.6 , 447–453, ISSN- 0009-0352.



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