DISINFESTATION OF STORED GRAIN INSECTS USING MICROWAVE ENERGY

BY

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ABSTRACT

Infestation of grain by insects is usually controlled using insecticides. Use of insecticides can result in chemical residues in the food which may have adverse effects on humans and animals. Disinfestation of grains using microwaves can be an alternate to chemical methods of killing insects in grain. A pilot-scale industrial microwave dryer operating at 2.45 GHz was used in this study to determine the mortality of different life stages of three common stored-grain insects namely *Tribolium castaneum* (Herbst), *Cryptolestes ferrugineus* (Stephens) and *Sitophilus granarius* (L.) in wheat, barley and rye. Grain samples of 50 g each at 14, 16, and 18% moisture content (wet basis) were infested with stored-grain insects. The samples were then exposed to microwave energy at four different power levels 200, 300, 400, and 500 W for two exposure times of 28 and 56 s. Complete (100%) mortality was achieved for adults of all three insect species at 500 W for an exposure time of 28 s and at 400 W for an exposure time of 56 s in barley and wheat. In rye, complete mortality of adult *T. castaneum* and *S. granarius* was achieved at 400 W, 28 s and at 300 W, 56 s whereas for *C. ferrugineus*, complete mortality was achieved at 500 W, 28 s and at 400 W, 56 s. The average temperature of wheat, barley, and rye at 500 W and 28 s was around 80, 71 and 82°C, respectively. Among the life stages of *T. castaneum* in wheat, eggs were the most susceptible followed by larvae, and the least susceptible were the pupae and adults. Among the life stages of *T. castaneum* in barley and rye, eggs were the most susceptible and adults were the least susceptible with no significant difference between pupae and larvae. There was no significant difference in the mortality of adult insect species at 14, 16, and 18%

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moisture content barley and rye and the life stages of *T. castaneum* and *S. granarius* in rye.

Germination tests were conducted for wheat, barley and rye and the germination of seeds decreased with an increase in power level or exposure time or both. The quality characteristics tested for barley were grain protein, alpha amylase, diastatic power, soluble protein, density and viscosity of the malt. The quality characteristics tested for rye were flour protein, flour yield, falling number, Sodium dodecyl sulphate sedimentation, dough mixing properties and loaf volume of the bread. The quality of the barley treated at 500 W for 28 s was the same as the control, whereas, there was significant decrease in the quality of barley and barley malt when treated at 400 W for 56 s. There was no significant difference in the quality of microwave-treated rye except for a decrease in the flour yield. There was no significant difference in the quality characteristics of microwave-treated and control wheat.

The surface temperature distribution on barley, rye, oats, and sunflower seeds were determined with the microwave dryer and an infrared thermal camera. The thermal images showed that, there was a wide variation in the temperature distribution during microwave heating with hot and cold spots within a sample. The average temperature of the rye was the highest followed by barley, oats and sunflower seeds. The moisture loss corresponding to one hundred percent mortality in barley, rye and wheat at 500 W and 28 s exposure time was 1.9, 2.5, and 2.0 percentage points, respectively.

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It is an impossible task to include everyone who assisted in the preparation of this thesis. Countless friends from the Department of Biosystems Engineering and associates have made their contributions, a fact that is acknowledged with sincere thanks.

Dedicated to my Dad
…who lives in my memory

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LIST OF ABBREVIATIONS

AMP	-	Absorbed Microwave Power
ANOVA	-	Analysis of Variance
CWB	-	Canadian Wheat Board
CGC	-	Canadian Grain Commission
DP	-	Diastatic power
DU	-	Dextrinizing units
EB	-	Electron Beam
FAB	-	Farinograph Absorption
FDDT	-	Farinograph Dough Development Time
FFA	-	Free Fatty Acid
FLY	-	Flour Yield
FN	-	Falling Number
HDPE	-	High Density Polyethylene
ISM	-	Industrial, Scientific and Medical applications
LV	-	Loaf Volume
MC	-	Moisture Content
MDDT	-	Mixograph Dough Development Time
MPL	-	Mean Plumule Length
MW	-	Microwave
PDU	-	Power Density Unit
PKH	-	Peak to Height
PPO	-	Polyphenol Oxidase

RH   -   Relative humidity

SDSS   -   Sodium Dodecyl Sulfate Sedimentation

SE   -   Standard Error

VMD   -   Vacuum Microwave Dried

SEM   -   Scanning Electron Micrographs

WEAX   -   Water Extractable Arabinoxylan

w.b.   -   Wet Basis

LIST OF SYMBOLS

P = power absorbed (W/m^3)

σ = dielectric conductivity

E = electric field strength (V/m)

f = frequency of energy source (Hz)

ε_o = dielectric constant of vacuum or permittivity of free space (F/m)

ε'' = the relative dielectric loss factor of the substance.

1. INTRODUCTION

1.1   Canadian Grain Storage

Harvested crops are stored on-farm or in commercial grain handling facilities, like primary and terminal elevators. In Canada, grain is mainly stored on-farm in galvanized steel bins, varying in size from 25 to 250 t (Sode et al. 1995). Maintaining quality and quantity are the main criteria for safe storage of grain. Canada has a legally defined zero tolerance for insects in stored grain for human consumption. If a stored-product insect is detected in a grain sample, the grain is termed infested and the grain must be treated to kill the insects (Canada Grain Act 1975).

1.1.1   Canadian grain handling

In Canada, the farmers transfer the grain from field to storage bins and then to the primary elevators located along the railways; sometimes farmers deliver grain directly from field to primary elevators. The main functions of a primary elevator are to receive grain delivered by truck, measure the mass and dockage, assign a grade, mix it with grain of the same grade, store it temporarily, and ship it out by rail when sold. Terminal elevators receive grain, weigh, process (clean, blend, dry, and fumigate) and store grain in readiness for shipment to domestic or export markets (CGC 1998). The total capacity of primary and terminal elevators is 12 Mt which is equivalent to about 20% of Canadian annual grain production. The Canadian grain industry is regulated by the Canadian Grain Commission (CGC). The CGC establishes and maintains standards for the quality of grain and is responsible for monitoring the quality of grain. The CGC regulates the

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operation of primary, terminal and process elevators and the commercial grain handling system in Canada. The Canadian Wheat Board (CWB) is the marketing agency for the wheat and malting barley produced in Canada. The CWB was set up to provide price stability and equal market sharing for individual farmers by developing a quota system based on the seeded area of each farmer. The CWB is responsible for controlling grain transportation by rail and works in cooperation with the railways and elevator companies to match the export demands (Muir 2001).

1.1.2   Losses during storage

The losses during storage could be classified as quantity losses and quality losses. Quantity losses occur when the grain is consumed by insects, rodents, mites, birds and microorganisms. Quality losses are reflected as reduced economic value of the crop. In Canada, quality of the grain is determined by the grading system.

1.1.2.1 Quantity losses   It is estimated that annual losses of cereal grains due to insects and rodents are about 10% in North America and 30% in Africa and Asia, but higher losses and contamination often occur locally (Hill 1990). Economic losses due to insects and microorganisms in grain have been estimated to be around one billion dollars per year in the United States (Brader et al. 2000). Post harvest losses of grains due to insects are estimated to be around 5 to 10% or about 1.4 to 2.8 billion dollars in 2006 in the United States. Losses due to processed commodities may be much higher than the losses due to raw material because of their greater economic value (USDA 2006). Grains harvested and stored in the hottest part of the year have a great chance of becoming infested and hence winter wheat, rye, barley or oats are more likely to have insect

problems than spring corn or soybeans which are harvested during the cooler, autumn months of the year (Chappell et al. 2000). Since losses of grain due to insect infestation are high, disinfestation of grain is very important for the safe storage of grain.

1.1.2.2 Quality losses   The stored-grain insects affect not only the quantity of grain but also the quality of grain. Insects consume grain and also contaminate it with their metabolic by-products and body parts (Venkatrao et al. 1960). Edwards et al. (1991) has stated that the grain quality decreased with time with increasing levels of infestation. The major quality factors affected by storage are soundness and color of the kernels. The quality of grain to be used for malting or seed is dependent on the rate and consistency of germination and vigor. Other quality characteristics of grain that are affected during storage are milling and baking qualities of wheat, oil quality for oil seeds, odor and taste. The quality of grain is also affected due to contamination by mycotoxins, insects or rodents, and chemical residues from insecticides (Muir 2001). Insect infestation causes changes in chemical compositions such as increase in moisture, free fatty acid levels, non protein nitrogen content, and a decrease in pH and protein contents in wheat (Venkatrao et al. 1960; Sanchez-Marinez et al. 1997).

1.2   Barley Facts

Barley (*Hordeum vulgare* L.), a major world crop, ranks among the top ten crops and it is the fourth most widely produced among the cereal crops. Barley contributes significantly to the world's food supply as human food, malt products and livestock feed. Barley is the second ranking cereal for production after wheat in Canada and is grown

mainly in the Prairie Provinces (Nilan and Ullrich 1993). Barley is relatively cold-tolerant and is considered as the most drought, alkali and salt tolerant among the small-grain cereal crop species. Barley's relatively early maturity and low water use are major factors in its adaptation to drought and temperature extremes (Poehlman 1985). The total barley production in 2005-2006 was about 138 Mt around the world (USDA 2007). Canada is the second largest barley producer in the world with a production close to 13 Mt annually (Growing Alberta, 2007). The chemical composition of barley is; protein (11-13%), starch (55-74%), fibre (5%), fat (2%), ash (2-3%) (Geddes 1944 cited from Briggs 1978; Kennelly et al. 1995). Barley can be classified by the number of rows of grains on the head as two, four or six row barley. Two-row barley produces 25-30 grains while six row barley produces 25-60 grains. Four row barley is actually loose six row barley and most cultivated barley is of six row type (Gramene *Hordeum* 2007).

1.2.1   Food uses of barley and barley malt

Barley flour can be used as a food thickener or additive to wheat flour, for making flat or dense breads and in many other non-bread bakery products, but it is less suited for making yeast-leavened bread because of its weak and non-elastic gluten. However 5-10% barley flour can be added to wheat flour without affecting the loaf volume and bread appearance (Bhatty 1986 cited from Bhatty 1993).

Malt is germinated barley. Barley malt is used to impart distinctive flavor and color to a variety of foodstuff. Malt is used in various food processes such as brewing, distilling and vinegar production. The most extensive use for barley malt is a source of fermentable sugars for beer and whisky. The characteristic properties of many beers

(color, foam) are a direct consequence of the major complement of malted barley used in their production (Bamforth and Barclay 1993).

Malt extracts enhance soluble sugars, protein, and α-amylase in the dough; promote yeast activity, bread texture, and loaf volume and impart flavor, color and aroma to the finished product. Non-fermented applications include: use in soda crackers, cookies, rolls, muffins and dark variety breads. The hull content of barley is a limiting factor for use of barley malt in food applications. Hence hull-less barley is ideally suited for making specialized food-grade malt (Bhatty 1993). Barley is an emerging health food, as it is an excellent source of dietary fibre, B- vitamins such as thiamin, riboflavin and niacin and protein (Growing Alberta 2007). The soluble fibre component in barley, beta glucan, has proven to reduce cholesterol and regulate blood glucose levels in humans. Barley has a low glycemic index that makes it useful in maintaining blood sugar levels for diabetes (ACIDF 2002). Barley is also a natural antioxidant that helps to neutralize free radicals, which may reduce the risk of cancer and heart disease (Growing Alberta 2007).

1.2.2   Feed uses of barley

Barley, one of the major feed grains of the world, is widely used as a livestock feed. The grain can be used as a major source of energy, protein and fibre (Munck 1981; Newman et al. 1981). It is estimated that 65% of Western Canadian production is utilized by the Canadian livestock industry. Barley is primarily used as an energy source for animals, however, the protein content and quality give barley an advantage over corn and wheat (AFRD 2005). Barley is a traditional feed for swine in many countries, particularly

in northern countries where corn cannot be grown successfully. It may supply 80-90% of the animal's energy and 50-80% of its protein requirements (Munck 1981; Newman et al. 1981).

1.3   Rye Facts

Rye (*Secale cereale* L.), a member of the grass family, is second to wheat among the grains most commonly used in the production of bread. Rye is extremely winter hardy and can grow in sandy soils with low fertility. It can be cultivated in areas that are generally not suitable for other cereal crops (Bushuk 2001). The world rye production for the year 2005-2006 was 14.5 Mt and Canada produced around 0.35 Mt of rye (USDA 2007). The European Union produces 25-30 % of the global rye and the Russian federation produces another 25-30% (Agriculture Statistics Canada 2001). Rye production has diminished by more than half from 1961 to 2005 (Gramene *Secale* 2007).

1.3.1   Food and feed uses of rye

Rye is the only cereal grain other than wheat to have the necessary qualities to make bread. Rye flour is inferior to wheat in production of high volume pan breads, because it lacks essential elasticity and gas-retention properties. Rye flour can be used to produce "black" bread and "light rye" bread is made from rye and wheat flour mixed in varying proportions. Rye is also used in the production of alcoholic beverages and rye is the acknowledged trademark of Canadian Whiskey (Bushuk 2001). The chemical composition of rye is protein (8-13%), fat (2-3%), starch (56-70%), ash (2%), total

dietary fibre (15-17%) of which soluble fibre is (3-4%) (Clydesdale 1994; Lasztity 1998; Härkönen et al. 1997; Nilsaon et al. 1997; Welch 1995; Vollendroff and Marlet 1991). Rye flour contains many essential and non-essential dietary components and is an important source of fibre (Knudsen et al. 1995; Feldheim and Wisker 1995 cited from Kruger et al. 1998). The dietary fibre content of typical rye bread is about three times higher than that of white bread. Rye is a good source of several minerals, including manganese, iron, copper, zinc, selenium, magnesium and fluoride (Clydesdale 1994). Studies have shown that it is possible to produce noodles of acceptable color and texture from wheat flour containing up to 30% rye flour (Kruger et al. 1998).

Rye has a feeding value of about 85-90% that of corn and has more digestible protein and nutrients than oat or barley (Oelke et al. 1990). Rye straw is fibrous and tough and hence it is not extensively used in livestock feed but is highly used as livestock bedding. In the growth stage before heading, rye is extensively used as a pasture crop (Bushuk 2001).

1.4   Various Methods of Insect Control

The various methods of insect control can be grouped as physical, biological and chemical methods.

1.4.1   Physical methods

Insects in stored grain can be controlled by manipulating the physical environment or by applying physical treatments to the grain and insect species. Physical methods to control insects include different types of traps (probe traps, pheromone traps),

manipulation of physical environment (Sinha and Watters 1985), mechanical impact, physical removal, abrasive and inert dusts and ionizing radiation (Muir and Fields 2001). The physical variables that are usually manipulated are: temperature, relative humidity or grain moisture content, and composition of atmospheric gases in the intergranular air spaces. Low temperatures are usually obtained by aeration with cold ambient air. Methods to obtain high grain temperatures are more diverse, including: microwaves, infrared, hot air and dielectric heating (Banks and Fields 1995). Physical control methods tend to be slow and some may not give high levels of mortality even when well managed. They can be used where the infestation is low. Microwave disinfestation is a physical method to control insects in stored grain (Muir and Fields 2001).

1.4.2 Biological methods

The biological method is to use living beneficial organisms, as natural enemies, to control pests. There are many approaches to biological control of pests in stored products, including the use of predatory insects and mites, parasitoids and species-specific pathogens. Unlike chemicals that need to be applied to a wide area, natural enemies can be released at a single location and they find and attack the pests in a grain mass. There are no chemicals involved and these methods do not pose serious risk to the consumers or to the environment (Subramanyam and Hagstrum 2000).

Biological control agents are usually species-specific. Since most infestations comprise multiple species, several different isolates or species of biological control agents may be needed. Biological control methods act slowly and consequently much

damage may occur before control is effective. It is not usually suitable for dealing with heavy infestations (Subramanyam and Hagstrum 2000).

1.4.3 Chemical methods

The chemical method uses insecticides to kill the insects. Pesticides are among the most commonly used chemicals in the world, and among the most dangerous to human health. The chemicals used to control insects in the bulk stored grains and cereal processing industries comprise two classes namely, contact insecticides and fumigants. Contact insecticides kill insects when they contact treated surfaces. Some of the commonly used insecticides are malathion, pirimiphos-methyl, chlorpyrifos-methyl (Sinha and Watters 1985). Fumigants are gaseous insecticides applied to control insects in grains and processed foods that are inaccessible by contact insecticide. Some of the commonly used fumigants are methyl bromide and phosphine (Sinha and Watters 1985). Methyl bromide is involved in the depletion of the atmospheric ozone layer. Hence it has been banned effective 2005 in developed countries, except for quarantine purposes (Fields and White 2002). Many alternatives have been tested as replacements for methyl bromide, from physical control methods such as heat, cold and sanitation to fumigant replacements such as phosphine, sulfuryl fluoride and carbonyl sulfide (Fields and White 2002).

Among the physical, chemical and biological control methods, the chemical method is widely used to control insects (Sinha and Watters 1985). Chemical control methods are essential for efficient production and preservation of food products. For the past three decades, efforts have been devoted to the study of possible alternative insect

control methods that might be helpful in minimizing the environmental hazards associated with chemical insecticides (Nelson and Stetson 1974a).

1.4.3.1 Drawbacks of chemical control methods A major limiting factor for using insecticide is that insects develop resistance to insecticides. A world-wide survey of stored-product insects revealed that 87% of 505 strains of the red flour beetle, *Tribolium castaneum*, collected from 78 countries were resistant to malathion (Sinha and Watters 1985). In several countries, where malathion resistance is a severe problem, other control methods such as alternative insecticides, fumigants or physical control methods have to be substituted. Even though insecticides and fumigants are applied with care and in limited quantity, there is a possibility of these chemicals remaining in the food grains and having adverse effects on humans. These chemicals also have a hazardous effect on the environment. Phosphine is increasingly used as a treatment to replace methyl bromide but the major drawback is the rapid increase in resistance of insects to phosphine (Taylor 1994, Fields and White 2002). Fumigation often only kills live larvae or adult insects but does not incapacitate or sterilize the eggs which are still alive in the grain kernels and which can incubate in a period of 3-7 weeks at fumigant levels that kill other life stages (Langlinais 1989). Hence, there is an ongoing search for an alternative method for controlling insects in stored grain.

1.5   Objectives

1. To determine the mortality of life stages (egg, larva, pupa and adult) of *Tribolium castaneum* (Herbst), red flour beetle, in barley and rye at 14, 16, and 18%

moisture content, at four microwave power levels: 200, 300, 400, and 500 W and at two exposure times: 28 and 56 s.

2. To determine the mortality of egg, larval and adult stages of *Sitophilus granarius* (L.), granary weevil, and adult stage of *Cryptolestes ferrugineus* (Stephens), rusty grain beetle in barley and rye at the above mentioned variables.

3. To conduct germination test and analyze the quality characteristics such as grain protein, malting, alpha amylase, diastatic power, soluble protein and viscosity on barley treated with microwave energy.

4. To conduct germination test and analyze the quality characteristics such as flour protein, flour yield, falling number, sodium dodecyl sulfate sedimentation (SDSS), dough mixing properties and baking test on rye treated with microwave energy.

5. To study the surface temperature distribution in microwave heated grains and oilseed using a thermal camera and to determine the moisture loss during microwave treatment.

2. LITERATURE REVIEW

2.1 Stored-Grain Insects

The most common stored-grain insects in Western Canada are *Tribolium castaneum* (Herbst), red flour beetle and *Cryptolestes ferrugineus* (Stephens), rusty grain beetle. *Sitophilus oryzae* (L.), rice weevil, *Sitophilus granarius* (L.), granary weevil and *Rhyzopertha dominica* (Fabricius), lesser grain borer also occur occasionally (Sinha and Watters 1985; Fields et al. 1993). Most stored-product insects have a wide range of food habits and they can feed on several different dry food products. This wide range allows them to move from one food product to another during storage and transportation leading to cross-infestations and residual infestations. The distribution of insects in bulk grain is typically non-uniform and is determined by gradients of temperature and moisture, distribution of dockage and broken grain, and inter and intra-species interactions of insects (Muir and White 2001).

Tribolium castaneum, a secondary grain feeder, feeds on grain germ, broken kernels, grain products, and grain flour (Lhaloui et al. 1988). The red flour beetle is found across Canada, mainly in bins where grain is stored for long periods, such as farm silos and country elevators. It prefers damaged grain, but attacks whole cereals, feeding first on the germ and then on the endosperm. The adult is a small reddish brown beetle about 4 mm long. Each female lays about 300-400 eggs and development from egg to adult takes 15-20 days under optimum conditions of $35^{o}C$ and relative humidity (RH) between 70-90%, but they can also develop under dry conditions such as 10% RH. The red flour beetle will fly when the temperature is $25^{o}C$ or higher, so infestations can spread quickly (Agriculture Canada 1981a). The red flour beetle is an omnivorous and

cannibalistic insect and the larvae and adults feed on the embryo of the seed, grain dust, broken grain and dockage. Some of its foods are wheat, corn, barley, rye, millet, flax, and sunflower. Because of the destruction of the grain germ by insect feeding, infested grain undergoes rapid germination loss (Sinha and Watters 1985).

Cryptolestes ferrugineus, is a common pest in farm granaries and storage elevators in Canada. In the prairies, it is rated as the most troublesome pest that attacks stored grain. They are secondary grain feeders and cannot penetrate sound grain kernels. They feed on exposed germ, broken and damaged seeds. The adult is a shiny reddish brown beetle about 2 mm long. Each female lays about 200-500 eggs which are deposited loosely on the grain kernels and hatch in 3 to 5 days in a temperature of about $30^{o}C$ (Agriculture Canada 1981b). Acclimated rusty grain beetles can tolerate very cold temperatures ($-15^{o}C$) for 2 weeks and low relative humidity (Sinha and Watters 1985). Rusty grain beetle feeds mostly on the germ. Whole seed of rye, wheat, and millet are more favorable food for rusty grain beetles but they also can consume and develop on cocoa, rice, corn, barley, and sunflower. Typical damage caused by rusty grain beetle could be identified by the presence of distinct burrowing hole in the germ area made by the emerging adult (Sinha and Watters 1985).

Sitophilus granarius, attacks small grains and hard cereal products. The insects feed on the kernels leaving only the hulls, and a severe infestation can reduce stored grain to a mass of hulls and frass. The adult is a brown or blackish beetle about 5 mm long, with a head that is prolonged into a long slender snout. The female drills a small hole in the kernel, deposits an egg and seals the hole with a gelatinous secretion. The legless larva completes its growth, pupates and develops into an adult weevil inside the

kernel. Infestation can start at temperatures around 15°C but optimum development takes place at 30°C and 70% RH (Agriculture Canada 1981c). The granary weevil feeds on whole cereals such as wheat, barley, rye, corn, sorghum, rice, cowpeas, chestnuts and sunflower seeds. The damages done by granary weevil could be recognized by small circular holes in seeds through which the adult emerges from inside the seed, where it spends its immature life stages. *Sitophilus granarius* is a dominant primary species which can create hot spots in stored grain, increasing the grain temperature to 40°C and facilitating invasion of other secondary grain insects, post-harvest fungi and bacteria (Sinha and Watters 1985).

2.2 Microwaves

2.2.1 Properties of microwaves

Microwaves are electromagnetic waves with frequencies ranging from about 300 MHz to 300 GHz and corresponding wavelength from 1 to 0.001 m (Decareau 1985). Figure 1 shows the electromagnetic spectrum with frequency and wavelength of various electromagnetic radiations (Wikipedia 2008). Microwaves are invisible waves of energy that travel at the speed of light, 3×10^{8} m/s. In the electromagnetic spectrum, microwaves lie between radio frequencies and infrared radiation. From the broad range of microwave frequencies available, a few are designated for industrial, scientific and medical applications (ISM). As a result, utilization of specific microwave frequencies comes under the regulations of the Federal Communications Commission (Copson 1962). For all practical purposes, industrial applications are carried out at 915 MHz in the USA, 896 MHz in the UK, and 2450 MHz worldwide (Mullin 1995). Since early 2002, a higher

frequency of 5800 MHz is available for industrial purposes (Linn and Moller 2003; Suhm et al. 2003). Microwaves are reflected by metals, transmitted through electrically neutral materials such as glass, most plastics, ceramics and paper, and absorbed by electrically charged materials (Decareau 1972; Mullin 1995).
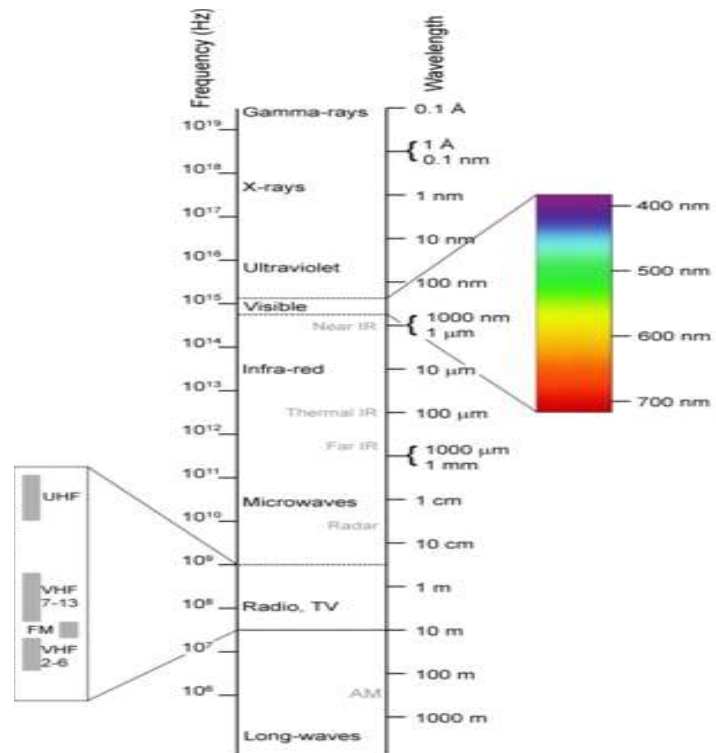
Figure 1. Electromagnetic spectrum (Wikipedia 2008)

2.2.2 Principle of microwave heating

Microwave heating is based on the transformation of alternating electromagnetic field energy into thermal energy by affecting polar molecules of a material. All matter is made up of atoms and molecules and some of these molecules are electrically neutral but many are bipolar. When an electric field is applied, the bipolar molecules tend to behave like microscopic magnets and attempt to align themselves with the field. When the

electrical field is changing millions of times per second (e.g. 915 or 2450 million times per second), these molecular magnets are unable to withstand the forces acting to slow them. This resistance to the rapid movement of the bipolar molecules creates friction and results in heat dissipation in the material exposed to the microwave radiation. Biological material placed in such radiation absorbs an amount of energy which depends on the dielectric characteristics of the material and heat is produced (Mullin 1995).

Microwaves are not heat. Microwave fields are a form of energy and microwaves are converted to heat by their interaction with charged particles and polar molecules, their agitation is defined as heat (Buffler 1993). The most important characteristic of microwave heating is volumetric heating which is different from conventional heating. Conventional heating occurs by convection or conduction where heat must diffuse from the surface of the material. Volumetric heating means that materials can absorb microwave energy directly and internally and convert it into heat. The conversion of microwave energy to heat is expressed by the following equation (Mullin 1995; Linn and Moller 2003):

$$P = 2\pi\, E^2 f \varepsilon_o\, \varepsilon''V \qquad\qquad\qquad (1)$$

where P = power, W

$\quad$ E = the electric field strength, V/m

$\quad$ f = the frequency, Hz

$\quad$ ε_o = the permittivity of free space, F/m

$\quad$ ε'' = the dielectric loss factor

$\quad$ V = volume of the material, m^3.

2.2.3 Dielectric properties of insects

Dielectric properties are the electrical characteristics of materials that are poor conductors of electricity (dielectrics). The dielectric properties of the materials depend on the frequency of the applied electric field and the temperature of the material (Nelson 1973a, 1991). If the material is hygroscopic, dielectric properties also depend on the amount of water in the material (Nelson 2001). The first reported measurements of insect dielectric properties were for bulk samples (insect and air space) of rice weevil and confused flour beetle, *Tribolium confusum* (J. duVal) at 40 MHz frequency. The dielectric constants were 6.6 and 7.8 for rice weevil and confused flour beetle, respectively, and loss factor was 2.2 for both the species (Nelson and Whitney 1960; Nelson et al. 1966; Nelson 1967). The insect permittivity data at 25°C for 2.47 GHz frequency reported by Nelson et al. (1998) are shown in Table 1.

Table 1. Dielectric properties of insects at 20-25°C (Nelson et al. 1998).

Adult insect species	Frequency (GHz)								References
	0.2		2.4		9.4		20		
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	
S. oryzae	28	12	17	3	17	3	-	-	Nelson 1972b
L. decemlineata	53	81	38	12	30	16	19	17	Colpitts et al. 1992
S. oryzae	42	28	32	9	25	12	18	13	Nelson et al. 1997
S. oryzae	55	48	42	13	31	16	23	16	Nelson et al. 1998
T. castaneum	61	56	47	15	34	19	25	19	
O. surinamensis	70	68	53	17	40	21	28	22	
R. dominica	63	55	43	15	34	19	25	18	

ε'- Dielectric constant; ε''- Dielectric loss

The dielectric properties obtained by measuring bulk samples containing insects were different from the dielectric properties of whole insect body (Nelson et al. 1998; Nelson 2001). The dielectric properties of whole insect bodies of various insect species are shown in Table 2.

Table 2. Adult body dielectric constant and loss factor for stored grain insects (Nelson et al. 1998).

Adult insect species	Temperature (°C)	Frequency (GHz)							
		0.2		0.5		1.08		2.47	
		ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
S. oryzae	10	54	40	49	20	45	14	42	13
	70	59	92	50	43	45	24	42	15
T. castaneum	10	59	43	54	22	50	16	46	15
	70	66	108	54	50	48	27	44	17
O. surinamensis	10	69	53	62	27	58	19	53	17
	70	81	125	67	59	59	34	53	22
R. dominica	10	59	41	54	22	50	16	45	15
	70	80	128	66	60	59	34	52	22

The dielectric properties of insect larvae were measured by Wang et al. (2003a) using an open ended coaxial probe method. The larvae of Indian meal moth, *Plodia interpunctella* (Hubner), Navel orangemworm, *Amyelois transitella* (Walker), Codling moth, *Cydia pomenella* (L.) and Mexican fruit-fly, *Anastrepha ludens* (Loew) were made into slurry and the initial moisture content of insect slurry was about 74% w.b. The dielectric properties of the four insect larvae are shown in Table 3. Ikediala et al. (2000) has shown that dielectric constant and loss factor of compacted codling moth has no significant difference from that of live larvae.

Table 3. Dielectric properties of four types of insect larvae at different frequencies (Wang et al. 2003a).

Insect species	Temperature (°C)	Frequency (MHz)					
		40		915		1800	
		ε'	ε''	ε'	ε''	ε'	ε''
C. pomonella	20	65 ± 0.9	163 ± 0.4	48 ± 0.2	12 ± 0.1	45 ± 0.1	12 ± 0.2
	40	72 ± 2.9	349±18.3	45 ± 2.4	19 ± 1	42 ± 2.2	14 ± 0.7
P. interpunctella	20	69 ± 0.9	149 ± 3.7	40 ± 0.4	13 ± 1.4	38 ± 0.5	11 ± 0.6
	40	90 ± 2.2	281 ±37.9	38 ± 1.6	20 ± 2.8	36 ± 1.7	13 ± 1.7
A. ludens	20	71 ± 0.3	231 ± 5.9	49 ± 3.4	18 ± 2.0	47 ± 0.7	13 ± 1.7
	40	112± 22	415 ± 31.7	45 ± 2	29 ± 5.9	43 ± 1.6	17 ± 2.7
A. transitella	20	69 ± 0.4	213 ± 3.1	45 ± 1.3	16 ± 0.1	42 ± 1.4	13 ± 0
	40	80 ± 0	387 ± 2.2	42 ± 0.1	24 ± 0.1	40 ± 0	16 ± 0

Dielectric properties of insects are affected by the frequency and temperature. The dielectric constant decreases with increasing frequency and generally increases with increasing temperature. The loss factor of insects decreases rapidly as frequency increases from 200 MHz to about 2 to 3 GHz and then they change little up to 20 GHz. Loss factors are highly dependent on temperature at the lower frequencies, but show little dependence above 2 or 3 GHz (Nelson et al. 1998).

2.2.4 Dielectric properties of grains

The dielectric properties of grain became very important as there was an increase in the interest for using microwave energy for grain drying, insect control, seed treatment to improve germination and moisture measurement (Chugh et al. 1973; Nelson 1992). At radio and microwave frequencies, dielectric properties of moist granular materials (grain)

depend on frequency, moisture content, bulk density and temperature (Nelson 1981; Chugh et al. 1973). Various methods have been developed and utilized for measurement of dielectric properties of grains. The three most popular methods for measuring dielectric properties of foods are: open ended coaxial probe, transmission line and resonant cavity method (Ohlsson 1980). The probe method is based on a coaxial line ending abruptly at the tip which is in contact with the test material. The probe method is the easiest to use because it does not require a particular sample shape or special containers. The transmission line method involves placing a sample inside an enclosed transmission line. This is more accurate than the probe method but it is difficult to use and is time consuming. The resonant cavity method uses a single-mode cavity. A sample of known geometry is placed in the cavity and the changes in the reflected power of the cavity and the frequency of resonance are used to determine the dielectric property of the sample (Wang et al. 2003a).

The dielectric constant for wheat varies between 2.7-2.98 and dielectric loss factor between 0.25-0.59 for frequencies 5-17 MHz and moisture content varying between 10.2-17.8% (Trabelsi and Nelson 2003). The dielectric constant and loss factor of grain types at 24°C are listed in Table 4.

The moisture content has the greatest influence on the dielectric properties of grain at any frequency. The dielectric constant increases with increasing moisture content at any given frequency and the dielectric constant decreases with increasing frequency. The dielectric loss factor is less predictable than the dielectric constant and may either increase or decrease with frequency or with moisture content, depending upon the particular range of frequency or moisture content (Nelson 1981). Grain bulk density is

the next important factor, followed by temperature. Other factors such as chemical composition may also have smaller influence on the dielectric properties of grain (Nelson 1981).

Table 4. Dielectric constant and loss factor of grains at 24°C and different moisture contents (w.b).

| Grain | MC (%) | Frequency (GHz) | | | | | | | | References |
| | | 10 | | 40 | | 1 | | 5.36 | | |
		ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	
Barley, spring	12.9	3.2	0.25	3.0	.038					ASAE (2006)
Rye, winter	12.7	-	-	4.0	0.52					ASAE (2006)
Oats, spring	10.7	2.8	0.2	-	-	2.2	0.18	-	-	ASAE (2006)
Sorghum	11.4	4.2	0.38	-	-	2.9	0.29	-	-	ASAE (2006)
Wheat	12.5	-	-	-	-	2.89	0.35	2.66	0.28	Nelson (1973c)
Oats	10.7	-	-	-	-	2.12	0.16	1.97	0.14	Nelson (1973c)
Sorghum	11.4	-	-	-	-	2.81	0.34	2.63	0.32	Nelson (1973c)

2.3   Principle of Microwave Disinfestation

The use of microwaves for killing insects is based on the dielectric heating of insects present in grain, which is a relatively poor conductor of electricity. Since dielectric heating depends upon the electrical properties of the material, there is a possibility of advantageous selective heating in mixtures of different substances (Hamid et al. 1968; Nelson 1972a; Ikediala et al. 1999; Wang et al. 2003b; Antic and Hill 2003). In a mixture of dry food stuffs and insects, it is possible to heat the insects to a lethal temperature because they have high moisture content while leaving the drier foodstuff unaffected or slightly warm (Hurlock et al. 1979; Wang and Tang 2001). Insects that infest grain, cereal products, seed and other stored products, can be controlled through dielectric heating by microwave or lower radio frequency energy. Raising the temperature of infested materials by any means can be used to control insects if the infested product can tolerate the temperature levels that are necessary to kill the insects (Hurlock et al. 1979).

2.3.1   Experiments on microwave disinfestation of grain

Hamid et al. (1968) conducted experiments for detection and control of *T. confusum, S. granarius* and *C. ferrugineus* in samples of wheat and flour. The required exposure times to microwaves for 90% mortality of the three species in wheat were approximately 30, 30 and 18 s, respectively. The corresponding exposure time for 90% mortality of *T. confusum* in wheat flour was 37 s. They concluded that bulk heating is not feasible when the depth is greater than 0.1 m. However, if wheat is passed in thin

layers on a conveyor belt, then a satisfactory mortality of insects can be achieved in a reasonable time and at a reasonable cost.

Hamid and Boulanger (1969) presented a method for the control of *T. confusum* by microwave heating with an output power of 1.2 kW at 2.45 GHz. Samples of insects were scattered in small plastic containers filled with wheat and allowed to pass through the wave guide. Temperature measurements were made inside the container of bulk wheat. For *T. confusum*, 70% mortality was obtained when the grain temperature was 55°C and 100% at 65°C. To determine the effects of high frequency radiation on the milling and baking qualities of wheat, three samples were heated to 55, 65, and 80°C and compared with the control samples. There was no effect on the milling quality or protein content of the wheat. But the bread making quality was affected deleteriously and progressively, as the treatment temperature was increased. The effects were similar to those produced by improper drying of grain. They suggested the use of lower-frequency power source to improve the efficiency of drying and disinfestation of grain.

Boulanger et al. (1969) compared the design, operation and cost of a microwave and a dielectric heating system for the control of moisture content and insect infestations of grain. Due to the highly effective penetration of high frequency and microwave energy, more uniform drying as well as efficient insect control was simultaneously achieved with the electrical drying technique. They concluded that microwave and dielectric heating systems are highly efficient and have significant advantages over conventional hot air dryers.

Kirkpatrick and Roberts (1970) studied the control of *Sitotroga cerealella* (Olivier), (Angoumois grain moth), *Rhyzopertha dominica*, and *Sitophilus oryzae,* in

wheat using microwave energy. The experiments were conducted in 2450 MHz frequency microwave oven at 2000 W power output with open and closed glass containers. Lower mortalities were obtained when insects were exposed in closed glass containers than the open containers. Also, lesser time was required to obtain 97% or more control of either angoumois grain moths and lesser grain borer than that of the rice weevil.

Kirkpatrick et al. (1972) compared the efficiency of microwave and infrared radiation to control *S. oryzae* in soft winter wheat. They concluded that both microwave and infrared treatments can control insects but the temperature required to give 100% mortality was higher for microwave energy and hence they suggested that infrared heating was preferable to microwave heating.

Kirkpatrick et al. (1973) studied the gamma, infra-red and microwave radiation combinations for control of *R. dominica* in wheat. Wheat samples containing eggs, larvae, pupae, and adults were given one of the following treatments: gamma radiation, infrared, microwave, gamma radiation plus infra-red or gamma radiation plus microwave. The gamma radiation source was a CO-60 irradiator at a dose rate of 2.1 krad/min. The infrared radiation source was an infra-red heater equipped with ceramic panels with a rated input of 14 kW. The microwave radiation source was a microwave oven operating at a frequency of 2.45 GHz and a 1.6 kW input magnetron. The average reduction in the emergence was 54, 55, 42, 99, and 96% for gamma, infrared, microwave, gamma plus infra-red and gamma plus microwave treatments, respectively. They concluded that combination treatment was more economical and effective for control of insects in wheat.

Nelson and Stetson (1974b) compared the effectiveness of 39 and 2450 MHz electric field for control of rice weevils in wheat. Their results indicated that complete mortality of adult weevils in wheat at radio frequency (39 MHz) resulted in a grain temperature of 40°C, whereas, treatments at microwave frequency (2450 MHz) resulted in grain temperatures of 80°C for achieving complete mortality. Their study also showed that delayed mortality in 39 MHz treated wheat was severe, whereas, very little additional mortality was observed in 2450 MHz treatments after 1 day mortality counts.

Watters (1976) studied the susceptibility of *T. confusum* to microwave energy by irradiating vials of infested wheat. Wheat samples at 8.5, 12.5, and 15.6% moisture content were infested with ten *T. confusum* adults. After irradiation, each block was removed from the radiation source and the wheat sample was allowed to cool to 32°C. The samples were then stored at 27.5^{o}C and 70% relative humidity for 2 d, when mortality was assessed. After 105 s, in wheat at 15.6, 12.5, and 8.5% moisture contents, mortality was 100, 90, and 68%, respectively. *Tribolium confusum* larvae were more tolerant than eggs or pupae. Complete mortality of eggs and pupae were obtained at 75°C, but 21% of the larvae completed development.

Hurlock et al. (1979) conducted experiments on bags of wheat at 13.7% moisture content containing 50 adult beetles of *Oryzaephilus surinamensis* (L.) (Saw-toothed grain beetle), *T. castaneum* or *S. granarius*. These insects were exposed to microwave generated from 896 MHz generator and subjected to a variety of exposure times and power settings. Another test was conducted on coca crumbs of 18% moisture content containing ten larvae of *Ephestia cautella* (Walker) (Warehouse moth), or fifty adult *T. castaneum*. When the samples from cocoa crumbs were examined, there were more

survivors in samples that comprised predominantly powdery material than those that contained a large proportion of lumps (irregular shaped mass). Samples of treated coca beans examined in the laboratory showed no change in fat or moisture content. But exposure to microwave radiation progressively lowered the peroxide level, indicating that some chemical changes occur due to microwave radiation and no food should be treated without first ensuring that its quality is not impaired.

Tilton and Vardell (1982) studied the control of stored-product insects using combination of microwave and partial vacuum in rye, corn, and wheat. The four insects selected were *Rhyzopertha dominica*, *Sitophilus oryzae*, *Sitophilus zeamais* Motschulsky (Maize weevil), and *Sitotroga cerealella* (Olivier). The infested grains were treated at three rates, high rate of 0.238 power density unit (PDU) for 10 min at 4.66 kPa, 0.083 PDU for 30 min at 4.66 kPa, and low rate of 0.028 PDU for 90 min at 4.66 kPa. They concluded that low rate of treatment was ineffective and produced only small reductions in the emerging adults whereas high rate of treatment was the most effective method and complete control of insects could be achieved.

Tilton and Brower (1987) conducted insect control experiments using a combination of gamma rays and infrared or microwave radiation. *Sitotroga cerealella*, *Rhyzopertha dominica*, and *Sitophilus oryzae* in wheat were treated with microwave and infrared radiations before and after gamma radiation. Each individual type of treatment produced a certain mortality and the expected mortality for combined treatments was calculated using individual mortalities. However, actual mortalities for the combined treatments were greater than the calculated mortalities. Average increases in mortality for combined treatments were 16 and 11% greater for the infrared and microwave

treatments, respectively. Hence, they suggested that the dose of gamma radiation could be reduced without reduction in the actual mortality of the insects, if a supplemental treatment is used.

Bedi and Singh (1992) studied the effect of microwaves on control of three stored-grain insect species: larvae of *Corcyra cephalonica* St. (Rice moth), adults of *Callosobruchus chinenesis* L. (Gram dhora) and *Rhyzopertha dominica*. The experiments were conducted at varying frequency between 12 to 18 GHz and exposure times of 2, 5, and 10 min. Their results suggested that mortality of insects increased significantly with an increase in both the frequency and the exposure times.

Shayesteh and Barthakur (1996) studied the mortality of life stages of *T. confusum* (J. du Val) in wheat flour and *Plodia interpunctella* in wheat by exposing to continuous or intermittent microwave radiation at 2450 MHz. The effect of microwave radiation on *T. confusum* eggs was higher followed by pupae, adults and larvae. Their results showed that use of intermittent power supply was more effective in killing insects and the operational cost of microwave generator could also be minimized. The survival of insects decreased at 6 or 9% MC compared to 12% MC. Higher mortality was observed in *P. interpunctella* than *T. confusum*. The larger size of *P. interpunctella* would favor a higher probability of direct microwave absorption and heat transfer from the medium than the smaller insects.

Halverson et al. (2003) conducted experiments to determine the species and age (life stage) that was most susceptible to microwave energy at 28 GHz frequency. The species tested were *S. granarius*, *T. castaneum* and *R. dominica* and the life stages tested were egg, young larva and pupa. Their results showed that eggs of the *R. dominica* were

the most susceptible to microwave energy. Their results also suggested that egg and young larva of all the three species were more susceptible than the pupa.

2.3.2 Microwave disinfestation of other food materials

Wang et al. (2003b) conducted experiments to determine whether the insects are preferentially heated in dry nuts and fruits using one radio frequency (27 MHz) and one microwave frequency (2450 MHz). They selected codling moth larvae and determined the dielectric properties of walnut kernels and codling moth larvae. They developed model insects using gel having dielectric properties similar to those of codling moth larvae because inserting temperature probes into a live insect caused loss of body fluid, which would affect the accuracy of the insect temperature measurement. Temperature measurements with model insects revealed 1.4-1.7 times greater heating of insects than walnuts at 27 MHz but no preferential heating of insects was detected at 915 MHz.

Ikediala et al. (1999) studied the mortality of codling moth larvae in infested cherries using microwave heating at 915 MHz. They also compared the quality parameters of the microwave treated berries with those subjected to methyl bromide fumigation. The mortality was more than doubled when the microwave treatment was combined with cold storage. With a 2 min holding and 5 min hydro-cooling after microwave treatments, mortalities ranged from 5 to 62% and 39 to 98% without and with 1-2 days of cold storage, respectively. Quality parameters such as firmness, percentage soluble solids content, acidity, fruit weight and objective fruit color of microwave treated fruit were comparable with those of methyl bromide fumigated cherries.

Wang and Tang (2001) reported a review on the use of radio frequency and microwave treatments as alternatives for control of insects in nuts. They suggested that radio frequency and microwave treatment seem attractive as a quarantine treatment because they are quick, safe and do not damage the product quality.

2.3.3 Microwave disinfestation of other materials

Hirose et al. (1975) conducted experiments to study the use of microwave heating to control insects in tobacco shreds used in cigarette manufacture. Control of all stages of tobacco moth and cigarette beetle in tobacco shreds were studied with a domestic microwave oven operating at 2450 MHz. The tobacco leaves at 18% MC are dried to 12% MC in a large rotary drier. When the tobacco shreds were heated by microwave, immediately following the rotary drier, sufficient temperature to kill the insects were achieved in a short exposure time without any detrimental effects on aroma and taste of tobacco.

Andreuccetti et al. (1994) studied the woodworm (*Hylotrupes bajulus* L.) disinfestation of wooden articles (painted boards, picture frames, and other objects of artistic interest) using microwave energy at 2450 MHz. Several holes were drilled in a test block of wood to measure the temperature at various locations in the wood and in the woodworm which were inserted in the holes. Power was turned on and the temperature was measured in the wood and the woodworms. The temperature of the woodworm was 57°C, whereas, the temperature of the wood was only 45°C. This shows that there is a feasibility to kill woodworms by microwave heating and the temperature of wood was

maintained below 50°C and hence no damage was observed on the wood or to the painting on its surface.

Control of insects using microwaves in woolen textiles was studied by Reagan (1982). The experiments were carried to determine the lowest level of microwave radiation lethal to egg, larval and adult stages of *Tineola bisselliella* (Humm.) (Webbing clothes moth). The wool was tested for fabric shrinkage, color change, moisture regain, alkali solubility, tensile properties and visual fibre characteristics as viewed by scanning electron microscopy. It was concluded that 3 min of microwave exposure was sufficient to obtain 100% mortality of egg, larval, and adult stages of the clothes moth with minimal effects on the chemical and physical properties of wool. Prolonged microwave irradiation for 10 min produced internal fabric temperatures of 149°C and caused an increase in alkali solubility, shrinkage and color change when compared with the unexposed samples and those treated for 3 min.

Mavrogianopoulos et al. (2000) studied the energy efficient soil disinfestation by microwaves. In agriculture and greenhouse management, efficient control of weed seeds, nematodes and various pests and pathogens is very essential. Fumigation and steaming of the soil is mostly used, but due to environmental issues, alternative methods are being explored. The major advantages of using microwaves for soil disinfestation are rapid heat transfer, selective heating, compactness of the equipment, speed of switching on and off and pollution free environment as there are no products of combustion. The experiments were carried out using a 900 W microwave generator with the magnetron tube channeled through a metal wave guide. The output opening of the waveguide was placed directly on the soil surface. Their results showed that energy demand for soil disinfestation was

determined by two critical parameters: initial soil temperature and moisture content of the soil. They concluded that in a relatively dry soil, increase of the initial soil temperature using low cost and environmental friendly renewable energies would decrease the energy demand and could make microwave soil disinfestation economically feasible.

2.3.4 Advantages of microwave disinfestation

The major advantage of using microwave energy is that no chemical residues are left in the food and hence no adverse effects on human beings (Hurlock et al.1979; Ikediala et al. 1999; Wang and Tang 2001; Wang et al. 2003b). Microwave energy has no adverse effect on the environment as chemical methods do (Watters 1976; Ikediala et al. 1999; Wang and Tang 2001). Insects are unlikely to develop resistance to this treatment (Watters 1976). High frequency radiation may not only kill insects by the dielectric heat induced within them but may also affect the reproduction of the survivors (Hamid et al. 1968).

2.4 Microwave Drying

Drying is one of the oldest methods of food preservation and it is a difficult food processing operation because of undesirable changes in the quality of the dried product. High temperature and long drying times required to remove the water in conventional air drying, may cause serious damage to the flavor, color, and nutrients, and a reduction in bulk density and rehydration capacity of the dried product (Lin et al.1998; Drouzas et al.

1999). Other disadvantages of hot air drying of foods are low energy efficiency and lengthy drying time during the falling rate period (Maskan 2000).

In recent years, microwave drying has gained popularity as an alternative drying method for a wide variety of food products such as fruits, vegetables, snack foods and dairy products. Several food products have been successfully dried by the microwave-vacuum application or by a combined microwave assisted-convection process: cranberries (Yongsawatdigul and Gunasekaran 1996a), carrot slices (Lin et al. 1998), model fruit gels (Drouzas et al. 1999), potato slices (Bouraout et al. 1994), carrots (Prabhanjan et al.1995), grapes (Tulasidas et al. 1996), apple and mushroom (Funebo and Ohlsson 1998), and banana (Maskan 2000). Several experiments have reported microwave-assisted hot-air drying, where considerable improvements in the drying process have been evident: apple and potato (Huxsoll and Morgan 1968), banana (Garcia et al. 1988), carrot (Torringa et al. 1993 cited by Funebo and Ohlsson 1998).

2.4.1 Advantages of microwave drying

Microwave drying results in a high thermal efficiency, shorter drying time and improved product quality compared to conventional hot air drying. Microwave drying helps to remove the moisture from the food products without the problem of case hardening (Prabhanjan et al. 1995). Compared with hot air drying, combined microwave hot air could greatly reduce the drying time of biological materials without damaging the quality attributes of the finished products (Ren and Chen 1998). Microwave drying requires a smaller floor space compared to conventional driers because the increase in processing rate makes it possible to design more compact equipment and hence plant

capacity can be increased without additional building space. In microwave drying, operational cost is lower because energy is not consumed in heating the walls of the apparatus or the environment (Mullin 1995; Thuery 1992). Heat generated by microwave energy occurs principally in the product, not in the oven walls or atmosphere. Therefore, heat losses from the oven to the surroundings are much lower, making for more comfortable working temperatures. Fast start-up and shut-down and precise process control are possible in microwave heating (Mullin 1995). Microwave drying has been reported to improve product quality such as better aroma, faster and better rehydration, considerable savings in energy and much shorter drying times compared with hot air drying alone (Maskan 2001). Nijhuis et al. (1998) compared the advantages and disadvantages of various technologies like freeze drying, microwave and radio frequency drying. Microwave drying has positive ratings for drying rate, flexibility, color, flavor, nutritional value, microbial stability, enzyme inactivation, rehydration capacity, crispiness and fresh-like appearance.

However microwave drying is known to result in a poor quality product if not properly applied (Yongsawatdigul and Gunasekaran 1996a; Adu and Otten 1996). It has also been suggested that microwave energy should be applied in the falling rate period or at low moisture content for finish drying (Prabhanjan et al. 1995; Funebo and Ohlsson 1998). The reason for this is essentially economic. Due to high cost, microwave cannot compete with conventional air drying. However, microwaves may be advantageous in the latter stages of air drying.

2.4.2 Microwave grain drying

Campana et al. (1986, 1993) studied the effect of microwave energy on wheat and the physical, chemical and baking properties of dried wheat. They reported that the total protein content was not affected even by heating to $91^{o}C$ in a microwave dryer, but germination and wet gluten content were progressively affected by temperatures above 60 and $66^{o}C$, respectively. They concluded that protein content was not affected, but the functionality of gluten was altered gradually with increasing exposure time.

Walde et al. (2002) studied the microwave drying and grinding characteristics of wheat. The microwave dried samples were ground in a domestic grinder and Bond's work index (gross energy requirement in kilowatt hour per tonne of feed needed to reduce a very large feed to such a size that 80% of the product passes through 100 μm screen) was calculated. The results showed that as the drying time increased the final moisture content was less and this resulted in a requirement of less grinding energy. As the final moisture content reduced, the product became brittle and less resistant to grinding forces. Also the total protein content of microwave-dried samples of wheat did not change and remained the same as that of the control (9.9%), but the structural and functional characteristics of wheat protein-gluten were changed. The functionality of gluten was altered which was observed by the absence of elasticity and stretchability of the dough.

Kaasova et al. (2002) studied the chemical and biochemical changes during microwave treatment of wheat and determined the effect of microwave heating on wet gluten content, gluten index, falling number and amylographic characteristics. Falling number and gluten index increased with increasing absorbed energy during microwave heating, whereas, gluten content decreased. The greatest changes occurred when the end

temperature was 80°C and the moisture content was 15%. The optimum values of gluten index for good quality wheat flour are approximately between 85-92%. The gluten index values obtained were above 95% and it is more than optimum quality. Amylographic maximum increased and the increase was caused by the α-amylase inactivation with increasing absorbed energy. As a result of an increase in amylographic maximum, improvement in the baking quality was observed. The negative effect of higher energy doses was the decrease in the wet gluten content.

The effect of microwave heating on endosperm microstructure and chemical changes of wheat grain was studied by Blaszczak et al. (2002). Microwave heating of grain up to 48°C did not influence kernel microstructure or the technological properties, but marked changes were observed when the temperature of the grain exceeded 64°C. Disruption of cell integrity with protein denaturation, as well as deformation of starch granules was observed under scanning electron microscopy or light microscopy. At temperatures above 79°C, there was a decrease in wet gluten content, sodium-dodecyl sulphate (SDS) sedimentation value, vitreosity of grain due to macroscopic changes of grain endosperm and significant changes in dough energy and bread quality were observed. They concluded that the microwave heating of wheat to 48°C did not cause any changes, whereas, heating to temperatures above 79°C causes significant decrease in grain vitreosity, SDS sedimentation values, wet gluten content, bread volume and quality.

Pinkrova et al. (2003) studied the changes of starch during the microwave treatment of rice. The properties of rice after microwave treatment were evaluated by means of determination of total and damaged starch. The microwave treatment does not affect the total content of starch in rice but the damaged starch content increased with

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absorbed microwave energy. Also, microwave treatment does not affect the cooking and processing quality of the milled rice.

Velu et al. (2006) studied the dry milling characteristics of microwave-dried maize (*Zea mays* L.). The microwave drying did not alter the protein content as measured by the Kjeldahl's method. However, some structural changes in the starch and protein were noticed.

Zhao et al. (2007) studied the effects of microwave treatment on the quality of rice immediately after treatment and after certain period of storage. Rice samples were kept on the microwave oven (2450 MHz) belt and exposed to microwaves with different energy consumption (energy consumption defined as the quotient of microwave power divided by the flow rate of the rice samples). The microwave treated rice was cooled to 38°C and stored in a chamber at 25°C and 75% RH. Free fatty acid content, blue value (ratio of amylase to amylopectin content), protein content and sensory quality of cooked rice were determined at 0, 30, 60, 120, 150, and 180 days of storage. As microwave energy consumption increased, free fatty acid and protein content decreased whereas blue value increased. The sensory qualities of the cooked rice increased as microwave consumption increased which may be due to increase in amylase content, which leads to better adhesiveness of cooked rice. The free fatty acid content of both microwave treated and untreated rice changed during storage but the changes were smaller in the microwave-treated rice probably because microflora on the kernels was killed. There was no difference in the amylose content of both microwave treated and untreated rice at the beginning and end of storage. The protein content of microwave treated rice was lower but there was no difference in the protein content between the two treatments after 120 days

of storage. The taste score of microwave treated rice was higher than the untreated rice during storage.

2.4.3 Microwave drying of fruits

Maskan (2000) studied the drying characteristic of 4.3 mm thick banana slices by using the following drying regime: convective (60°C at 1.45 m/s) until equilibrium was reached, microwave (350, 490, and 700 W) until the material reached a constant weight and convection until the point where drying slowed down followed by microwave (at 350 W) finish drying. The drying of banana slices took place in the falling rate drying period. Higher drying rates were observed with the higher power level. Microwave finish drying reduced the convection drying time by about 64.3%.

Hot air, microwave and hot air-microwave drying characteristics of kiwi fruits were studied by Maskan (2001). Drying rates, shrinkage and rehydration capacities for these drying regimes were compared. Shrinkage of kiwifruits during microwave drying was greater than during hot air drying. Less shrinkage was observed with hot-air microwave drying. Microwave-dried kiwifruit slices exhibited lower rehydration capacity and a faster water absorption rate than when the hot air and hot air-microwave drying methods were used.

Vacuum microwave drying offers an alternative way to improve the quality of dehydrated products. The low temperature and fast mass transfer conferred by vacuum (Yongsawatdigul and Gunasekaran 1996a), combined with rapid energy transfer conferred by microwave heating, generates very rapid, low temperature drying. Moreover, the absence of air during drying may inhibit oxidation, and therefore, color

and nutrient content of products can be largely preserved. Yongsawatdigul and Gunasekaran (1996b) reported that vacuum microwave dried (VMD) cranberries had redder color and softer texture as compared to the hot air dried cranberries. Petrucci and Clary (1989 cited by Lin et al. 1998) also indicated that the contents of vitamin A, vitamin C, thiamin, riboflavin, and niacin in dried grapes were largely preserved during vacuum microwave drying.

Funebo and Ohlsson (1998) studied dehydration of apple (*Malus domestica* L.) and the lightness (L), redness (a), yellowness (b) values were similar for hot air and microwave dried apples. Funebo et al. (2002) studied the microwave convective dehydration of apple slices. The firmness of dehydrated apple pieces increased linearly with temperature during dehydration and the apples were almost twice as firm when dehydrated at 70°C, compared with 50°C. These dehydrated samples were 5-9 times harder than fresh apples.

Askari et al. (2006) studied the effect of hot air and microwave drying on the rehydration characteristics of apple slices. The rehydration capacity of air dried, freeze dried and microwave dried apple slices were 404.6, 484.0 and 676.0%, respectively. The rehydration capacity of freeze dried samples was less than microwave treated samples. Their results showed that the intercellular gaps created by microwave energy could absorb large amounts of water during rehydration and give rise to an increased rehydration capacity.

Raw apples (*Malus domestica*) contain high concentration of phenolics and flavonoids which reduce the risk of cancer and cardiovascular heart disease and contribute to health (Knekt et al. 1996; Pearson et al. 1999; Eberhardt et al. 2000 cited by Gerard and

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Roberts 2004) but the concentration of phenolics and flavonoids in juice and cider are drastically reduced after juice processing. Heat treatment of fruit mash has proven effective for increasing the concentration of phenolic compounds in fruit juices as well as yield. But most heat treatments produce juice with unacceptable analytical and sensory properties. Microwave energy has the advantage of heating more rapidly thereby inactivating enzymes more quickly and minimizing browning. Gerard and Roberts (2004) evaluated the effect of microwave heat treatment of apple cultivars: Fuji and MacIntosh mash on juice yield, quality and total phenolics and flavonoids content in the juice. Microwave heat treatment increased the juice yield and the concentration of total phenolics and flavonoids. The juice from heated mash was of high quality and the sensory panelists were unable to detect differences between the cider produced at room temperature and that produced at 40 and 60°C. The results also showed that heating the apple mash to 60°C is the optimum temperature for improving the fruit yield. They concluded that apple mash heated to 60°C resulted in maximum yield with significant increases in phenolics and flavonoids content.

Karatas and Kamisli (2007) conducted a study to determine the variations of vitamins (A, C, and E) and malondialdehyde in apricots (*Prunus armeniaca* L.) using infrared and microwave driers. Vitamin A, C, and E of apricot samples dried in microwave drier are higher than those of infrared drier. Also the values of malondialdehyde are higher in microwave dried than in infrared dried apricot samples. Hence, they concluded that using a microwave drier for apricot is much more effective than infrared drier in terms of retention of vitamin A, C, and E and malondialdehyde values.

2.4.4 Microwave drying of vegetables

Prabhanjan et al. (1995) studied the thin layer drying of carrot (*Daucus carota* L.) and showed that product dried by conventional air drying and microwave drying at half the power level retained good color while those dried at maximum microwave power were dull. Lin et al. (1998) made a comparative study of vacuum microwave drying of carrot slices to air drying and freeze drying on the basis of rehydration potential, color, density, nutritional value, and textural properties. Vacuum microwave dried carrot slices had higher rehydration potential, higher alpha-carotene and vitamin C content, lower density, and softer texture than those prepared by air drying. Carrot slices that were air dried were darker, and had less red and yellow hues. Less color deterioration occurred when vacuum-microwave drying was applied. Although freeze drying of carrot slices yielded a product with improved rehydration potential, appearance, and nutrient retention, the vacuum microwave dried carrot slices were rated as equal to or better than freeze dried samples by a sensory panel for color, texture, flavor and overall preference, in both the dry and rehydrated state.

Oduro and Clarke (1999) performed quality assessment of gari (fermented form of cassava) (*Manihot esculenta* Crantz*)* produced using microwave energy and compared with the commercially available products. Values of *L* and *b* were measured which indicates lightness and yellowness but *a* values were not recorded as they measure levels of redness which is not relevant in this case. The *L* values increased slightly with time, producing pale colors and values of *b* also increased with time producing more yellowness. The acceptable range of color values is 80-85 for *L* and 17-21 for *b*. Cooking times greater than 15 min gave color properties which fell beyond the accepted range but

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the samples cooked between 12-15 min were regarded as high quality gari. The *L* and *b* values for gari purchased from commercial market ranged between 77.5-85.8 and 18-27.5, respectively. Hence, gari produced using microwave energy exhibited lower variation compared to that of commercial gari.

Sharma and Prasad (2001) conducted a study to explore the possibility of drying garlic by combined hot air microwave and hot air drying alone. The retention of volatile components responsible for flavor was more in hot air microwave drying compared to conventional hot air drying alone. The flavor strength of garlic dried by hot air alone was 3.27 mg/g dry matter, whereas, the flavor strength of the garlic dried by microwave drying was 4.06 mg/g dry matter. Cui et al. (2003) studied the dehydration of garlic slices by various drying methods. The cutting forces for garlic slices showed that freeze dried garlic slices were the softest followed by microwave vacuum dried slices which were softer than the air dried garlic slices. Both freeze drying and combined microwave vacuum and air drying created a very porous structure in the samples, however, freeze drying maintained the porous structure throughout the drying process, while the porous structure collapsed due to a high rate of water evaporation in the last stage of combined microwave vacuum and air drying. This shrinkage and collapse was also found during hot air drying resulting in a low transport rate of water, prolonged drying time and therefore tough texture.

Fathima et al. (2001) studied the effect of microwave drying on the shelf life and sensory attributes (appearance, color, odor and overall quality) of coriander (*Coriander sativum* L.), mint (*Mentha spicata* L.), fenugreek (*Trigonella foenum-graceum* L.), amaranth (*Amaranthus* sp.) and shepu (*Peucedanum graveolens* Benth). Amaranth had similar scores for fresh and dried ones; however, there was significant decrease for the

sensory attributes of other greens. They concluded that microwave drying was highly suitable for amaranth, moderately suitable for shepu and fenugreek and less suitable for coriander and mint.

The limiting factor for reduced consumption of legumes is the presence of α-galactooligosaccharides and other anti-nutritional factors. These may cause diarrhoea, flatus gas and other discomfort. Kadlec et al. (2001) conducted studies to determine the changes of soluble carbohydrates during germination and microwave heating and drying of pea (*Pisum sativum* L.) seeds. The sample peas were allowed to germinate and then treated with microwave at a frequency of 2450 MHz and dried in fan assisted dry air oven at 80°C to a final moisture content of 12-14%. Their results showed that there was a decrease of α-galactooligosaccharides during first three days of germination and the drying time was reduced significantly by microwave treatment.

Khraisheh et al. (2004) studied the quality and structural changes in potatoes (*Solanum tuberosum*) during microwave and convective drying. Their results indicated that potato samples dried in a microwave field exhibited less shrinkage than those of air dried samples. The rehydration of potato samples was quantified on the basis of coefficient of rehydration and rehydration ratio. The rehydration properties of the microwave dried samples were better than those of convective dried samples. The extent of rehydration also increased with increasing power level. However, at high power levels (38 W) starch gelatinization was observed and this reduced the degree of rehydration.

Shaw et al. (2007) studied the drying and color characteristics of coriander (*Coriandrum sativum* L.) foliage by convective and microwave drying. Approximately 60 g sample of coriander foliage (leaves and stem together) was placed on mesh trays in

the thin layer drying unit and the drying air temperature was set at 50°C and the air velocity was maintained at 1.1 m/s. The microwave dryer was operated at a power of 295 W which maintained the average product temperature close to 50°C. Microwave drying was able to reduce the moisture content to 12% w.b within 21 to 22 min whereas convective drying took about 236 to 267 min. Also, the convective dried coriander samples exhibited significantly greater color change than the microwave dried samples. The color index values for microwave dried sample ranged from 2.67 to 3.27 whereas those of convective dried samples ranged from 4.59 to 6.58.

2.5   Other Applications of Microwave Treatment

2.5.1   Seed germination enhancement

The germination capability of seeds is sometimes affected by impermeability of the shell, immaturity of the embryo, presence of inhibitors or lack of heat or light causing seeds to remain in a dormant state until favorable growth conditions are available. Exposure to 650 W, 2.45 GHz microwaves for about 30 s is sufficient to ensure a high rate of germination by some mechanism that is not as yet fully understood. The microwaves seem to act on the strophiola, a sensitive part located on the ventral side of the seed, which may thus become more water permeable. The effect of the radiation varies according to the species: clover, peas, beans, and spinach respond favorably whereas wheat, corn, and cotton are less sensitive (Thuery 1992). Extensive studies were conducted by Nelson (1976) on germination of alfalfa seeds at various frequencies. Tran and Cavanagh (1979) investigated the effect of microwave energy on the germination of clover, acacia, douglas fir, pine and spruce. Nelson (1992) in his review on application of

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microwave energy, states that, small seeded legumes such as alfalfa, red clover and arrowleaf clover, which has impermeable seedcoats, responded positively to dielectric heating and showed improved germination. Generally, seeds of grasses, woody plants, and tree species do not respond very favorably, whereas field crops such as corn, cotton and wheat showed acceleration of germination in some lots.

2.5.2 Soil treatment

Vegetable tissue is very sensitive to the thermal effect of microwaves. The use of microwaves instead of herbicides for the destruction of unwanted seeds and parasitic plants has been under investigation since the early 1970s by the USDA Agricultural Research Center (Welasco, Texas). The aim was to destroy, before sowing, all undesirable grain and shoots. The first prototype applicator for soils "Zapper", could be described as a four wheel trailer carrying four 1.5 kW generators operating at 2.45 GHz and connected by means of flexible guides to four antennas forming a square shaped assembly. The first trial with the zapper produced very good results for grass, parasitic fungi and nematodes (Thuery 1992).

Effect of microwave radiation on soil nitrification and respiration was studied by Wainwright et al. (1980). According to them, a 20 s exposure to 2.45 GHz microwave radiation had a marked differential effect on the viable count of soil micro-organisms, had little influence on numbers of heterotrophic bacteria, but reduced fungal colonies. The growth of fungi from soil particles was reduced following treatment. Microwave radiation was investigated as a controlled biocidal treatment which could selectively kill

microbial biomass. Fungi were more susceptible to irradiation than bacteria (Speir et al. 1986).

The advantages of using microwaves for soil disinfestation are rapid heat transfer, selective heating, compactness of the equipment, speed of switching on and off and a pollution-free environment as there are no products of combustion. A major obstacle prohibiting the use of microwaves for soil disinfestation is the large amount of energy required to obtain effective results. Mavrogianopoulos et al. (2000) conducted an experimental study on the effect of initial soil temperature and moisture on energy consumption by application of microwaves for soil disinfestation. It was concluded that humidity of the soil and the initial soil temperature are critical for a low-cost use of microwaves for soil disinfestations. A combination of solarization and microwaves was proposed as an energy efficient technique of using microwaves for soil disinfestation.

Velázquez-Marti et al. (2006) studied the use of microwave radiation for germination inhibition of unwanted weed seeds buried directly in the soil and weed seeds placed in flower pots in greenhouse. A microwave distribution system with waveguide fed by one 4 kW magnetron was used to treat large soil surface and the radiation of seeds buried in trays were tested with four lined magnetrons of 1 kW each and the seeds tested were ryegrass and rapeseed. The germination decreased as the microwave energy applied increased. The results of this study demonstrated that a negative relationship exists between the microwave energy absorbed by the seeds buried in the soil and the germination capacity. The extent of germination reduction depends on the temperature reached within the seed. When the water content in the seed is higher than the soil moisture content, a selective heating is produced which means the temperature reached

by the seed is higher than the soil temperature for the same energy and it is possible to reduce the power or exposure time by 25% to obtain the same reduction in germination. Hence, this study suggested that to improve the efficiency of microwave application to eliminate undesirable seeds, it is better to irrigate 4 or 5 days prior to microwave treatment.

2.5.3 Effect of microwaves on green algae

Hamid and Badour (1973) observed two types of thermal effects by exposing unicellular green algae (*Chlamydomonas segnis* Ettl) to microwave radiation. Exposure of algae to microwaves at 4900 MHz frequency and the rise in temperature beyond 50°C resulted in proteolysis and complete failure of the algae to photosynthesize and grow. But exposure of algal suspension to microwaves at 2450 MHz with a temperature rise of not more than 35-40°C resulted in a stimulating effect on photosynthesis and subsequent algal growth as compared to conventional heating within the same temperature range. Pretreatment of algae by microwaves to 10 s led to about 50% increase in the photosynthetic rate as compared to the untreated ones.

2.5.4 Eradication of *Fusarium* in melon using microwave

Soriano-Martin et al. (2005) studied the possibility of eradicating *Fusarium* wilt caused by the fungus *Fusarium oxysporum* Schlect in melon (*Cucumis melo* L.), because it is one of the most destructive diseases of melon. Melon seeds were placed in Petri dishes and allowed to germinate. When each plant developed its first true leaf, it was

inoculated by immersing the roots in conidial (spores of fungus) suspension and then irradiated in the 2.45 MHz microwave oven for 5-30 s with 5 s interval time. After irradiation, plants were kept in controlled environmental chamber for 22 days and disease level was determined after every two days. The study showed that high energy level can eradicate the fungus and at low levels of microwave energy, though fungus was not completely eliminated, the aggressiveness of the disease was reduced. Hence, the authors concluded that microwave treatment provides a rapid, economic, safe and non-destructive method for eradicating the *Fusarium* wilt.

Lozano et al. (1986) conducted experiments to eradicate seed-borne pathogens in cassava seed. A high percentage of cassava seed collected from different climatic zones were found to be infected with fungal and bacterial pathogens. The seeds to be treated were placed in Pyrex glass beakers containing water and the beaker was placed in the oven cavity and exposed to microwave (2450 MHz) for different periods of time (0, 30, 60, 90, 120, 150, 180, and 240 s). Temperature was the most important factor for microbial control and to obtain an optimum level of germination, a temperature of $77^{o}C$ (120 s exposure time) was found to be effective in eradicating microorganism as well as maintaining maximum germination percentage of 90%.

Cavalcante and Muchovej (1993) evaluated the use of microwave radiation for control of seed-borne pathogenic fungi in seeds of soybean (*Glycine max.* (L.) Merr.), peanut (*Arachis hypogaea* L.), bean (*Phaseolus vulgaris* L.) with either black, brown or white seed coats, wheat (*Triticum asestivum* L.) and pop corn (*Zea mays* L.). Healthy seeds and seeds naturally infected with fungi (*Cercospora kikuchii* Matsumoto and Tomoy in the soybean seed, *Bipolaris sorokiniana* (Sacc.) Shoemaker in the wheat seeds

and *Colletotrichum lindemuthianum* (Sacc. and Magnus) Briosi and Cavera in the bean seed, were used for the experiments. Seed lots of 50 g each were placed in cups and irradiated for 0, 0.5, 1, 1.5, 2, 3, 4, 5, 6, or 7 min with either full power or half power or 1/3 power of the microwave oven (1420 W, 2450 MHz). After treatment, seeds were divided into lots of 200 seeds and one lot was tested for germination. Other lot of seed was stained with tetrazolium to determine seed damage. When naturally infected seeds were treated with microwave radiation, pathogenic fungi were suppressed but the seed germination was reduced and increased tissue damage was observed. The germination of irradiated naturally infected seeds was affected by the dosage which did not affect vigorous seeds which was probably due to lack of resistance to the microwave radiation by the infected seeds. They concluded that use of lower dosages of radiation for a longer period of time could be helpful.

Banik et al. (2003) in their review on the bioeffects of microwave has stated that death rate of *Escherichia coli* (Migula) Castellani and Chalmers exposed to microwave radiation was higher than those obtained in conventional heat sterilization at the same temperature.

2.5.5   Use of microwave for control of post harvest diseases

Karabulut and Baykal (2002) studied the use of microwave power for the control of post harvest diseases in peaches (*Prunus persica* L). Fruits were wounded with dissecting needle and wound sites inoculated by adding 20 μl of *Botrytis cinerea* (De Bary) Whetzel and *Penicillium expansum* Link pathogens. Two fruits were placed in the 2450 MHz (Samsung, USA) microwave oven and heated for 2 min and the fruits were

left in the laboratory for 20 min to allow the heat to redistribute and to equilibrate with room temperature. The fruits were then placed in carton boxes and stored at 0°C for 45 days followed by 5 days at 24°C and the percentage of infected wounds were recorded. To evaluate the effect of microwave power on development of natural decay, fresh fruits were treated with microwaves and stored at the same conditions described above. Firmness, percentage soluble solids and fruit weight were determined at harvest, after storage and shelf life. The results showed that growth of both pathogens could be markedly inhibited by microwave heating for 2 min. Post harvest storage experiments also showed that the microwave heating was very effective in controlling natural infections and resulted in a very low decay incidence after 45 days of storage and 5 days of shelf life.

2.5.6 Thermal processing of waste using microwave energy

Casasnovas and Anantheswaran (1994) developed a method for thermal processing of food packaging waste using microwave energy. Simulated waste material consisting of high density polyethylene (HDPE), milk carton, polystyrene foam, napkin, plastic wrap and aluminum foil was shredded and the waste material was put into cylindrical containers transparent to microwaves. For lower power experiments, the waste was treated with 2.45 MHz microwave oven at 700 W and for high power, it was treated up to 2000 W at different density ratios (ratio of the density of the compressed dry waste material and density of the non-compressed dry waste material), moisture content and positions. They introduced spore strips containing 10^5 spores of *Bacillus stearothermophilus* Donk into the waste cylinder to evaluate the microbial destruction of

spores in wastes using microwave energy. They concluded that microwaves can be used in combination with size reduction and compaction to thermally process food packaging material.

Martin et al. (2006) studied the waste treatment such as food residuals and sewage sludge from a food industry using microwave (MW) (non-ionizing) and electron beam (EB) (ionizing) irradiation. The main idea was to combine the advantages of both high electron beam irradiation efficiency and high microwave selectivity and volumetric heating for biological waste processing. The treatment was carried out by various procedures such as EB alone, MW alone, first EB followed by MW, first MW followed by EB, and simultaneous irradiation of EB and MW. Their results showed that combined EB and MW irradiation produced the biggest reduction of microorganisms. The research has shown that some microorganisms exhibit more sensitivity to EB radiation while some to MW radiation. Hence by combined EB and MW irradiation, wide range of microorganism could be inactivated.

2.5.7 Rice bran stabilization by microwave heating

Tao et al. (1993) showed that microwave heating could be an effective method for the inactivation of lipase that is responsible for rice bran degradation and instability. One hundred and fifty grams of bran was heated with microwave energy at 340 ± 10 W for 3 min and the stabilized bran was stored in an incubator maintained at $33\pm2^{o}C$ and $75\pm5\%$ RH, to stimulate unfavorable storage conditions. Samples were withdrawn every week and free fatty acid (FFA) determination was carried out according to AACC method 02-01. The results showed that FFA of microwave stabilized bran increased from 4.0 to

4.9% in long grain rice and from 4.6 to 6.2% in medium grain rice, even after storage under unfavorable conditions. The FFA content of untreated bran ranged from 4.0 to 68.3% and 4.6 to 56.8% in long and medium grain rice, respectively.

2.5.8 Prevention of cotton seed from deterioration during storage

Deterioration of cottonseed during storage prior to processing for oil has been a major problem for cottonseed oil processing industry. As deterioration occurs, FFA level increases, which affects the quality and the economic value. Conkerton et al. (1991) evaluated the possibility of microwave heating to prevent cottonseed during storage. Three experiments were conducted with the first experiment comprised of 120 g seeds with 0.75% FFA and 11.4% MC, heated in 2450 MHz microwave oven for 1 and 2 min and stored for three and six weeks. Experiment two comprised of 200 g sample with 0.24% FFA and 13.8% MC., heated for 0.5, 1.0, and 2.0 min and stored for six and nine weeks. The third experiment comprised of 200 g sample with 0.83% FFA and 14.5% MC, heated for 1, 1.5, and 2 min and stored for six and nine weeks. The results showed that the total oil content of unheated cottonseed was 23% whereas microwave heated samples varied between 21-24%. There was no increase in the FFA content of unheated or microwave heated seeds after three weeks of storage. After nine weeks of storage, FFA content of unheated seeds increased to 2.29% whereas the FFA content of seed heated for 1 min increased 1% while that of the 1.5 and 2 min heated seeds increased to 0.23 and 0.13%, respectively. Also there was a significant deterioration of the protein quality of the unheated seed while 2 min microwave heated seeds maintained the integrity of the protein during storage. Microwave heat treatment reduced the moisture

content of the seed and destroyed the enzymes responsible for the formation of FFA, thereby resulting in prevention of deterioration during storage.

2.5.9 Improvement of oil extraction in rapeseed by microwave treatment

Irfan and Pawelzik (1999) studied the effect of microwave treatment on rapeseed (*Brassica napus* L.) oil extraction and oil quality. The seeds of rapeseed were heated in a laboratory type microwave oven operating at 2450 MHz and 1200 W power and the maximum temperature on the seed surface was limited to 100°C. The seeds were pressed for oil extraction and the oil quality was analyzed. There were no effects on the fatty acid composition and on the iodine value of the rapeseed oil, whereas acid and peroxide values were reduced. The reduction in the acid value was assumed to be as a result of successful inactivation of lipid esterase in the seeds. The peroxide value increased at 60 and 70°C but, as temperatures reached 80°C, there was a reduction in peroxide value which allows other lipid splitting enzymes to inactivate, which is very important in the storability and the further processing properties of oils. Oberndorfer and Lücke (1999) studied the effect of rapeseed treatment by microwave on the influence of mechanical oil extraction and concluded that microwave pretreatment resulted in an increase of the extraction rate in microwave treated samples compared to an untreated control. Light microscopy and electron microscopy showed clear differences in the microstructure of the oil bearing cells between the microwave treated and control samples.

Velentová et al. (2000) studied the microwave and γ-irradiation treatment to improve the oil extraction process in rapeseed. Thermal pretreatment is one of the important steps in the processing, which damages the oil bodies, improves the fluidity

and adjusts the optimal moisture content of the seeds for further processing. Twenty five gram samples of rapeseed were spread to 20 mm depth and treated in a microwave oven (2450 MHz) for treatment times of 1 to 7 min. The γ irradiation was given at a dose rate of 8 kGy/h using ^{60}CO γ-irradiator. The results of this study showed that oil extracted from microwave-treated seeds was comparable with the value obtained for flakes and was higher than those for untreated and γ-irradiated seeds. No changes in enzyme activity were observed for untreated and γ-irradiated seeds whereas activities of both the enzymes (phospholipase D and peroxidase) dropped to approximately 10% of the original value in microwave treated rapeseed. This study suggested that microwave treatment of rapeseed is recommended for processing operations due to improvement in the oil extraction process and quality.

2.5.10 Development of a microwave system for greenhouse heating

Greenhouse heating in cold climates is usually done by traditional hot-water or hot-air systems. In the conventional hot-water or hot-air heating methods, there is a wastage of energy due to the heating of greenhouse air and construction. Microwave heating could be an alternative because of its potential to rapidly heat the plants with less heat losses to the surrounding. Teitel et al. (2000) developed a microwave generator of 500 W power at 2450 MHz frequency to heat mature tomato and pepper plants in a green house. The results of the experiment showed that it was possible to heat the plants with microwaves without visible damage. Also, the energy required for microwave heating was about 55% of that required by hot air method.

2.5.11 Summary

Disinfestation of grain using microwaves is being studied by various researchers and a thorough review has been done. Studies conducted on the possibility of disinfestation of cigarette, wooden articles and woolen textiles using microwaves are also reviewed. Microwave drying of grains such as wheat, maize and rice and their quality parameters are also reviewed. The application of microwave for drying of various agricultural products is gaining popularity as an alternative drying method. The microwave drying is found to be efficient for many vegetables (carrot, potato, garlic) and fruits (banana, apple and kiwi fruits) and a thorough review of the potential applications of microwave energy has been discussed.

2.6   Major Problems with Microwave Heating

One of the major problems associated with microwave heating is the non-uniform temperature distribution. The non-uniform temperature distribution has been studied by several researchers (Fakhouri and Ramaswamy 1993; Mullin and Bows 1993; Goksoy et al. 1999; Ryynanen and Ohlsson 1996; Ryynanen et al. 2001; Lee et al. 2002; Sakai and Wang 2004; Manickavasagan et al. 2006; Gunasekaran and Yang 2007; Geedipalli et al. 2007). Researchers have tried to develop a model for the microwave heating to predict temperature distribution in the microwave heated food (Chen et al. 1993; Barringer et al. 1995; Lin et al. 1995; Zhou et al. 1995; Mallikarjunan et al. 1996; Ni and Datta 1999; Vilayannur et al. 1998; Raaholt and Ohlsson 2000; Yang and Gunasekaran 2004; Campanone and Zaritsky 2005). Microwave heating or drying sometimes results in poor quality of the end product (Gunasekaran 1990; Adu and Otten 1996; Warchalewski et al.

1998; Funebo and Ohlsson 1998; Krokida et al. 2001; Blaszczak et al. 2002). One of the serious concerns in heating food in a microwave is the incomplete kill of microbes due to uneven temperature distribution (Fung and Cunningham 1980; Carlin et al. 1982; Aleixo et al. 1985; Rosenberg and Bogl 1987). Moisture accumulation at the surface of food during microwave heating was studied by Datta and Ni (2002). Ohlsson and Thorsell (1984) observed a couple of problems in microwave reheating of chilled foods such as uneven heat distribution between different meal components, dehydration of thin meat and fish slices, and skin formation on boiled white potatoes.

Another issue with the microwave heating is the large number of factors that affect the microwave heat transfer behavior such as the thickness, the geometry, and the dielectric properties of the food. The heat capacity and the dielectric properties (dielectric constant ε', loss factor ε'') change with the moisture content and temperature which also complicates the microwave drying process (Funebo and Ohlsson 1998). In addition, several factors influence the uniformity of electromagnetic field. These factors can be divided into two groups: cavity effects; and workload or product interaction. Cavity effects are due to design limitation, location of the microwave inlet point, shape of the cavity, hanging parts such as mixer which are used for stirring of the product to assure more uniform electromagnetic field distribution. Workload interactions include loss factor, penetration depth, thickness, shape and size of the product that are different from product to product (Kelen et al. 2006).

2.7 Review on Temperature Distribution Studies during Microwave Heating

The temperature distribution studies have been conducted by several researchers in various types of food materials such as ready-to-eat meals, different kinds of meat, grains and food models. The non-uniform temperature distribution pattern and the results of the various studies are summarized in this section.

2.7.1 Ready-to-eat meals

Ryynanen et al. (1996) studied the effect of temperature on the pleasantness of microwave heated ready meals and meal components during microwave heating for 4 min. The food samples tested were four component chilled ready meal containing meat patties, sauce, mashed potato and carrot. Temperature measurements were made using two fiber optic measuring systems with copper constantan thermocouples, 30 s after microwave heating and after a cooling period of 5 min. The temperature difference between the hottest and the coldest spot in mashed potatoes was greater than $70^{o}C$, after 30 s of microwave heating. Mean component temperatures, 30 s after heating were $62.7\text{-}79.9^{o}C$ for mashed potatoes, $78.8\text{-}87.2^{o}C$ for meat patties, $82.1\text{-}90.0^{o}C$ for sauce and $61.3\text{-}94.3^{o}C$ for carrots. During cooling period of 5 min, mean temperatures decreased and the range became smaller as temperature distribution was more even due to heat conduction.

Microwave pasteurization of ready-to-eat meals was studied by Burfoot et al. (1988) using a domestic microwave oven (2450 MHz), a pilot-scale tunnel (2450 MHz, multi-mode) and another pilot scale tunnel of 896 MHz (single-mode). The ready-to-eat meal consisted of spaghetti in the base of the tray with a bolognaise meat sauce on top.

Temperatures were measured using thermocouples. The probes were inserted near the four corners of the product, at the centre and mid-way along each edge. Temperature differences measured in the sample heated for same duration using a domestic microwave oven and pilot-scale tunnel at 2450 MHz were 66 and 36°C, respectively. In experiments with a domestic oven, the temperatures at the corners were higher than at the edges while the temperature at the center was substantially lower. When heated using the multi-mode tunnel, the mean temperatures were higher than 77.5°C but the minimum temperature was as low as 50°C which is insufficient for pasteurization. In the 896 MHz tunnel, maximum temperature difference of 17°C was observed. Temperature distribution was different in the multi-mode and the single-mode tunnels. In the multi-mode tunnel, product temperatures were cooler at their center than the edges and the corners whereas in the single-mode tunnel, a more uniform temperature distribution was obtained with corners cooler than the edges.

Ramaswamy and Pillet-Will (1992) studied the temperature distribution in microwave heated laboratory formulated food products (spaghetti with meat sauce, rice with salmon and white sauce) similar to commercial products in small trays. The experiments were conducted in domestic microwave oven (2450 MHz) without a turntable. Temperatures were recorded using needle type copper-constantan thermocouples. The difference in the temperature between the hottest and the coldest spot was as high as 65°C for spaghetti and rice. Temperatures of prepared meals at various locations are given in Table 5. Based on the temperature distribution, it was concluded that reheating of food in a microwave oven may lead to some spots far from hot, while

certain parts may be close to the boiling point giving an illusion that the whole food may be steaming hot.

Table 5. Temperature distribution in microwave heated foods (Ramaswamy and Pillet-Will 1992).

Food product	Temperatures (^{o}C) at			
	Corner	Edge	Near center	Center
Spaghetti	92.9	58.0	37.2	27.4
Rice	96.8	65.4	44.2	33.6

Fakhouri and Ramaswamy (1993) studied the temperature distribution in frozen and refrigerated foods during microwave heating. The household microwave oven (2450 MHz) was used and the temperatures were measured using copper constantan thermocouples. The frozen and the refrigerated food studied were lasagna and shepherd's pie. The frozen food was heated as per the instructions, i.e., the frozen lasagna was heated for 4 min at full power, 4 min at 70% power level and held for 5 min before serving. This heating resulted in a center temperature of over 90°C with a maximum variability of 10°C. The frozen shepherd's pie was heated for 9 min at 50% power level and the temperature in the central region was only about 20°C whereas the corners were nearly boiling and the temperatures around the edges were close to 90°C, thereby resulting in a temperature variation of 70°C. The instruction for refrigerated lasagna and shepherd's pie was to heat for 5 min at full power. When heated as instructed, the center temperature of shepherd's pie reached 62°C while the edges and corners reached boiling temperature and the maximum variation was 42°C. The variation in the temperature after a holding time of 5

min was 18°C. The refrigerated lasagna when heated for 5 min, resulted in a centre temperature of 56.7°C and even after holding it for 5 min, increased to 67.5°C, which was still not the safe temperature for killing pathogenic bacteria. They concluded that precooked frozen and refrigerated foods showed non-uniformity in temperature, even when the manufacturer's instructions were followed.

James et al. (2002) studied the heating performance of domestic microwave ovens. The materials used for testing were liquid (water, sauce), solid (mashed potatoes) and multi-component food (mashed potato, sauce) and the temperatures were measured using T-type (copper-constantan) thermocouples. For the multi component food, the tray was divided into 12 compartments and the minimum, maximum temperatures were measured and the mean and the range of temperatures were calculated. The most uniform temperature distribution was found in trays containing water corresponding to 61.7°C and 83.9°C for mean temperatures at cold and hot spot, respectively. The least uniform temperatures were found in the multi component trays, with mean temperatures of 36.7°C and 91.8°C at cold and hot spot, respectively.

2.7.2   Meats

Goksoy et al. (1999) studied the non-uniformity of surface temperatures of poultry meat after microwave heating. Whole chilled chicken carcasses ranging in weight from 1063 to 1820 g and chicken breast portions 126-189 g were used in the study. The fiber optic probes were used to monitor the temperatures. Different trials were conducted by keeping the carcass breast up, breast down and breast portion alone. In carcass breast up position, the highest temperatures were measured on the vent, wing, and lower leg areas

and the lowest on the upper leg, upper back and breast. Placing the carcass breast down during heating, changed the temperature distribution but did not improve it. The vent, wing, lower leg and lower back parts of the carcasses reached high average temperatures of 88, 97, 90, and 96° C, respectively. However, the average temperature on the upper leg and breast muscle were 48 and 29°C, far below that required to destroy the pathogens. Their study revealed that an average temperature difference of up to 61°C was found between different parts on the carcass and a variability of up to 30°C in surface temperatures at defined positions on replicates was seen. The mean temperature and standard deviation of the chicken carcass heated by microwave is given in Table 6.

Table 6. Mean temperature and standard deviation at different locations of the chicken carcass during microwave heating (Goksoy et al. 1999).

Carcass position and treatments	Temperature (^{o}C) at different locations					
	Vent	Wing	Upper leg	Lower leg	Lower back	Breast
Breast up: 700 W, 20 s	97 ± 7.0	92 ± 9.0	61 ± 11.0	95 ± 10.0	78 ± 6.0	52 ± 6.0
Breast down: 700 W,15 s	88 ± 10.0	97 ± 7.5	48 ± 10.0	90 ± 17.0	96 ± 4.5	29 ± 5.0
Breast up: 500 W, 5 min	92 ± 11.0	91 ± 8.0	51 ± 6.0	81 ± 7.0	74 ± 6.0	36 ± 7.0
Breast up: 200 W,10 min	71 ± 11.0	73 ± 6.0	43 ± 14.0	44 ± 4.0	-	38 ± 15.0

They concluded that substantial cooking was achieved at some parts of the chicken, whereas some other surfaces had only reached a temperature that would support pathogenic growth rather than eliminate any pathogens present.

Jeong et al. (2007) studied the variability in temperature distribution of ground pork patties with and without salt cooked by microwave energy. Pork patties of 90 g each

were made with and without salt and at two fat levels of 10 and 20%. Patties were cooked in a domestic microwave oven (2450 MHz), until the center of the patty reached the designated testing temperature (76.7°C). The temperatures were measured using fiber optic sensors (Optical Slip Ring Systems, Fiso Technologies, Quebec, Canada) and measured at three locations: at the center, edge, and at mid-way between the center and the edge position. The results of the experiments showed that the temperatures at the edges of the patties increased more rapidly to above 90°C than those at the center position or the mid-way where the temperatures were only around 75°C. Patties with and without salt had similar range of temperatures at the center and mid-way, thus showing similar non-uniformity in temperature distribution.

Aleixo et al. (1985) evaluated the extent of destruction of food borne pathogenic bacteria in turkeys cooked in microwave ovens (2450 MHz). The turkeys were inoculated with *Salmonella typhimurium* (ex. Kauffmann and Edwards) LeMinor and Popoff, *Staphylococcus aureus* Rosenbach or *Clostridium perfringens* Veillon and Zuber. The turkeys were cooked until the temperature reached 76.6°C, the necessary temperature for development of desirable sensory attributes and tested for the presence of bacteria. The results showed that although there was a reduction in the number of cells containing bacteria, the cooking procedure did not completely eliminate any of the three pathogenic bacteria from the turkeys. The extent of survival was proportional to the number of spores in the initial inoculums. They concluded that any recommendations made to consumers on microwave roasting of turkeys should take into account the possibility of survival of pathogenic microorganisms in the product after cooking.

Carlin et al. (1982) studied the destruction of *Trichinella spiralis* larvae in beef-pork loaves cooked in microwave ovens. Ground chuck was purchased from supermarket and infected with *T. spiralis*. Meat loaves were made in three different shapes: 1) ring, (R), 2) oval (O) and 3) oblong (L) shapes. The meat loaves were then cooked for various periods of time at different power settings and the final temperatures were measured at five locations. The results of this study showed that infective *Trichina* was found in beef-pork loaves after cooking in microwave ovens. They recommended not to cook pork in microwave ovens. The temperature of beef pork loaves at various cooking times are given in Table 7.

Table 7. Temperature of ring, oval and oblong shaped beef-pork loaves (Carlin et al. 1982)

Power	Cooking time (min)	Temperature of ring shape (^{o}C)	Cooking time (min)	Temperature of oval shape (^{o}C)	Cooking time (min)	Temperature of oblong shape (^{o}C)
High	11	57.8-67.2	13	47.8-68.9	17	52.2-66.7
	13	65.0-68.9	17	63.3-76.1	22	63.3-68.9
Medium	17	53.9-59.4	20	58.3-60.6	26	55.6-60.0
	20	65.0-69.4	24	66.1-75.0	34	72.2-84.4

2.7.3 Food models

Ramaswamy and Pillet-Will (1992) studied the temperature distribution in microwave heated food models. The experiments were conducted in a domestic microwave oven (2450 MHz) without a turntable and the material tested was 10% starch

gel. Temperatures were recorded using needle type copper-constantan thermocouples. The difference in the temperature between the hottest and the coldest spot for the starch gel was 63.9^{o}C. Temperature distribution in starch gel decreased from the corners (68.8^{o}C) to the edges (63.6^{o}C), then near the center (45.0^{o}C) and finally at the center (37.7^{o}C). Based on the temperature distribution, it was concluded that uneven temperature distribution is found in all samples, with corners close to boiling temperatures while interior locations were still below 50°C.

Sakai and Wang (2004) studied the temperature distribution during microwave heating (2450 MHz) of food products having different dielectric properties. One percent agar gel (sample A) and 1% agar gel containing 1% NaCl (sample B) were prepared as pseudo foods having different dielectric properties. Temperatures were measured using infrared thermometers and from the results it was observed that the sample A was hot at the center and at the edges, while the sample B was hot at the edges. Their results confirmed that variation in dielectric properties, influence the temperature distribution during microwave heating.

Gunasekaran and Yang (2007) studied the effect of experimental parameters such as sample size, pulsing ratio and microwave processing time on sample temperature distribution. Two percent agar gel samples were prepared and poured into glass beakers and stored at 4°C for 16 h for uniform initial sample temperature. The samples were then heated individually in a laboratory microwave oven (2450 MHz) and the temperatures were measured. The samples were removed from the microwave oven after every minute of microwave heating and the temperatures were measured using a T-type thermocouple. When heated by continuous microwave power, the temperature distribution in 3.5 cm

radius sample was more uneven compared to the 4.0 cm radius sample. Since the depth of penetration and microwave power was the same in both cylinders, the absorbed power along the radial axis in 3.5 cm radius agar gel cylinder was greater than in 4.0 cm agar gel cylinder. They concluded that pulsed microwave heating resulted in more uniform temperature distribution in the samples than the continuous microwave heating.

2.7.4   Grain

Manickavasagan et al. (2006) studied the non-uniformity of surface temperatures of grain after heating in a pilot-scale industrial microwave dryer (2450 MHz). The grains studied were barley, canola, and wheat. Fifty grams of grain samples were heated in a pilot-scale microwave dryer at five power levels and two exposure times. The average surface temperatures after microwave treatment were between 72.5 to 117.5^{o}C, 65.9 to 97.5^{o} C, and 73.4 to 108.8^{o}C for barley, canola, and wheat, respectively. They reported that non-uniform heating patterns were observed for all three grain types and the difference between maximum and minimum temperatures ($\triangle$t) were in the range of 7.2-78.9^{o}C, $3.4-59.2^{o}$C, and $9.7-72.8^{o}$C for barley, canola, and wheat, respectively. Vadivambal et al. (2007a) has stated that there was a temperature difference of about 70°C between a hot and cool region, within a sample of barley treated with microwave energy.

2.8 Modeling of Temperature Distribution during Microwave Heating

Ho and Yam (1992) studied the effectiveness of using metal bands to improve the heating uniformity of a model food. The food model used was 3% agar gel in cylindrical

beakers and heated in a 2450 MHz microwave oven. Aluminum bands of 0.002 cm thickness were shielded in various patterns in the cylindrical beakers with different spacing and orientation. Fiber optic temperature probes were placed in the sample and the probes were connected to the fiber optic temperature acquisition systems to measure the temperature of the sample. Temperatures were also measured in unshielded cylinders containing food model. Since the temperature profile in a cylindrical sample was a function of both time and position, they defined two parameters to compare the heating uniformity in shielded and unshielded samples. The first one is relative uniformity (RU) defined as:

$$RU = \left(\frac{SD}{SD(open)} \right) \times 100 \qquad (2)$$

where SD and SD (open) are standard deviations of heating rates of shielded and unshielded samples, respectively. The second parameter is relative power absorption (RP) defined as:

$$RP = \left(\frac{P}{P(open)} \right) \times 100\% \qquad (3)$$

where P and P (open) are power absorption of shielded and unshielded samples, respectively. Their results indicated that the unshielded samples had the larger heating rate variation and the shielded samples had more uniform heating.

Zhou et al. (1995) developed a finite element model of heat and mass transfer in food material during microwave heating. Experiments were conducted using potato in two geometries: slab (64 mm x 48 mm x 30 mm) and cylinder (50 mm diameter and 40 mm height) as test material. The temperature distribution pattern was similar to those reported by Ramaswamy et al. (1991). In slab geometry, the temperature decreased away from the

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corners to the edges with a further decrease at the center. The temperature at the top surface was lower than the middle layer because of a large evaporation at the top surface. The moisture distribution pattern showed that moisture dropped rapidly at the corners and edges while relatively flat in the center portion. The temperature distribution in cylindrical geometry was different from that of slab geometry. In cylinder, hot spots were along the central axis of the cylinder and the lowest temperature was at the region between the center and the surface. Moisture distribution was flat in the central region with a rapid drop near the surface because of evaporation. They concluded that for cylindrical shaped food materials, during microwave heating, hot spots occurred along the central axis and for slab shaped materials, cold spot was located near the geometric center and hot spots occurred along the corners.

Vilayannur et al. (1998) studied the size and shape effect on non-uniformity of temperature distribution in microwave heated food materials using a finite element model (FEM). The key factors that influence the uniformity of temperature distribution are the dielectric and thermophysical properties of the product, frequency and power of the incident microwave energy and the shape and size of the product (Datta 1990). Hence they tried to predict the most desirable size and shape combination for a product of any given volume using finite element analysis. The model food selected was potato in three different shapes namely, brick, cylinder and hexagonal prism with three different volumes 75, 90, and 105 cm^3, respectively. Their results showed that for the brick shaped products, hot spots were at the corners while the cold spot was at the geometric center. For the cylinder, the hot spot was at the center confirming the focusing effect observed by the earlier researchers. In hexagonal prism shaped product, the center was cool whereas a hot

spot was found along the boundary. Comparing the temperature distribution in the three shapes, non-uniformity in temperature distribution was lower in hexagonal shaped products than the cylinder and brick shaped products.

Funawatashi and Suzuki (2003) studied the characteristics of microwave heating by a numerical analysis of electromagnetic and temperature fields in a microwave cavity. Their analysis has shown that electric field and the heating rate depends greatly on the position of the dielectric. They suggested that uneven heating in a microwave field is of two types. One is due to the standing wave and another is due to rapid decay of the microwave. In the case of uneven heating due to standing waves, the non-uniformity could be reduced by moving with time, the nodes of the standing wave which are done by metallic stirrers and turntables in domestic ovens.

Campanone and Zaritzky (2005) developed a mathematical model for different geometries to predict temperature profiles during the microwave heating process, as a result of which hot and cool spots could be determined and they also verified the numerical predictions with the experimental data obtained in the lab. According to their model, in case of spheres, a hot spot occurred at the center of the sphere. In cylinders, non-uniform radial distribution was observed with the highest temperatures at the surface and the center. In cubes and brick shaped products, microwave energy concentrated in the corners, resulting in hot spots in the corners.

2.9 Solutions Proposed to Reduce Non-uniform Temperature Distribution

Non-uniform heating is prevalent in microwave heating, irrespective of the food product. Wide temperature variations were observed within heated samples, during microwave heating of different kinds of meat, ready-to-eat meals, grains, vegetables and model foods. Researchers have suggested some ways to reduce the intensity of uneven heating. Fung and Cunningham (1980) suggested that microwave heating in combination with conventional heating would result in more uniform heating of foods and destruction of bacteria. Ohlsson and Thorsell (1984) recommended that large food components of above 25-30 mm thickness should not be placed on top of each other but should be placed side by side whereas thin slices should be stacked edge to edge and uniform thickness should be maintained whenever possible. By controlling the food geometry, heating uniformity could be improved substantially.

Ho and Yam (1992) studied the effectiveness of using metal bands to improve the microwave heating uniformity and concluded that shielding using metal bands was an effective way to improve the heating uniformity of the cylindrical samples under restricted conditions. They concluded that more experimental works are needed to describe the effect of metal shielding under conditions of food materials with various dielectric properties, sizes and geometries. Buffler (1993), Ryynanen and Ohlsson (1996), and Vilayannur et al. (1998) suggested some means for controlling the uneven heating, such as design of the microwave oven, manipulation of the heat cycle, ingredient formulation, design of the package and a combination of the above.

Fakhouri and Ramaswamy (1993) suggested that uniform temperatures could be achieved by a combination of heating at high power for a short time and subsequent holding of the product or heating at low power for a longer period of time. Boyes et al. (1997) studied microwave and water blanching of corn kernels and suggested that non-uniformity could be overcome by over-blanching, but the product viability may be commercially lowered compared to a water or steam blanched product. Goksoy et al. (1999) suggested that heating on reduced power for longer times and shielding the over-heated portion with aluminum foil resulted in improved surface temperature distributions. Funawatashi and Suzuki (2003) suggested that in the case of uneven heating due to standing waves, the non- uniformity could be reduced by moving with time the nodes of the standing wave which are done by metallic stirrers and turntables in domestic ovens.

A device and method for uniform heating of food in microwaves was designed by Zhang et al. (2004) (US patent No: 6,777,655 B2) to reduce the problems of cold spot, uneven heating, and splattering of food. Datta et al. (2005) suggested that microwave heating in combination with air-jet impingement or infrared heating decreases the non-uniformity of temperature distribution.

Gunasekaran and Yang (2007) concluded that pulsed microwave heating resulted in more uniform temperature distribution in the samples than the continuous microwave heating. Although researchers have given some solutions based on their studies, the results are confined to specific conditions and cannot be generalized.

3. MATERIALS AND METHODS

3.1 Mortality Experiments

3.1.1 Grain samples

The barley cultivar "Stander" and rye cultivar "Musketeer" was used for the experimental study. Initial moisture content was determined by drying 10 g of unground barley at $130 \pm 2^{o}C$ for 20 h and rye for 16 h (ASAE 2003) and was expressed on a wet mass basis. After determining the initial moisture content of the sample, the grain was then conditioned to 14, 16, and 18% MC by adding a calculated quantity of distilled water and rotating the grain and water mixture for about 1 h. The samples were then kept in polythene bags and stored in a refrigerator for 72 h for uniform moisture distribution. Samples were mixed within the bag every 4 h during the day to ensure uniform distribution of moisture. The moisture content was then verified by drying 10 g samples, in triplicate, and the moisturized grain was then kept in air-tight plastic bags in a refrigerator until used for the experiments.

3.1.2 Insects

The *T. castaneum* culture originated with individuals obtained from a farm in Landmark, MB in 1998 and maintained in the laboratory on whole wheat flour and brewers yeast at $30^{o}C$ and 70% RH. The *C. ferrugineus* culture was started with individuals obtained from a farm in Argyle, MB in 1994 and grown on whole wheat and wheat germ at $30^{o}C$ and 70% RH. The *S. granarius* culture was started with individuals

obtained from a farm in Oak Bank, MB in 1995 and grown on whole wheat at 30°C and 70% RH.

3.1.2.1 Life stages of *Tribolium castaneum* To obtain different life stages of *T. castaneum*, adults were mixed with wheat flour and brewer's yeast and kept for three to four days at 30°C and 70% RH. The flour was then sieved using sieve no.40 and the eggs were then collected using a soft bristle brush by looking through a Nikon SMZ 1000 microscope. To obtain larval and pupal stage, adults mixed with wheat flour and brewer's yeast were left for two and three weeks, respectively, and larvae and pupae were collected manually using a soft bristle brush.

3.1.2.2 Life stages of *Sitophilus granarius* *Sitophilus granarius* drill a hole in the kernel, deposits an egg and seals the hole with a gelatinous secretion and there will be only one larva in each infested kernel (Agriculture Canada 1981c). To obtain the kernels infested with *S. granarius*, 10 adult insects were kept in a vial with 10 grains and left in an environmental chamber for 48 h. The adults were then removed and the kernels checked under a microscope to find an egg plug. Initially it was difficult to determine the egg plugs in the kernels. So, the kernels were dipped in acid-fuchsin to stain the egg plugs in order to determine the infested kernels, following the method described by Frankenfield (1950 cited from Gudrups 2001). The grains were dipped in acid-fuchsin for 5 s, rinsed with tap water for 5 s and dried using tissue paper to remove excess water. Acid fuchsin strains the egg plug a pink color, which was then identified. The kernels infested with egg plugs were identified with the use of a microscope. The infested kernels were then treated with microwave energy and kept in the environmental chamber for 5 weeks (Sinha and Watters 1985) for the adults to emerge. For the larval stage, when

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the kernels with eggs were identified, they were kept in the environment chamber for 22 days. By this time the eggs would have developed into a late larval stage. The kernels were then treated with microwave energy and kept in the chamber for 15 days for adults to emerge.

3.1.3   Industrial microwave system

All the experiments were conducted in a continuous, pilot-scale, industrial microwave system having a rated capacity of approximately 40 kg/h (Model No: P24YKA03, Industrial Microwave Systems, Morrisville, NC). The microwave dryer shown in Fig. 2 consists of a belt assembly, an applicator, fan and heater assembly and control panel. The maximum speed of the conveyor was 3 m/min. The power output of the generator was adjustable from 0 – 2000 W. A polystyrene, microwavable rectangular box 30 cm x 3 cm x 1 cm was made to hold a 50 g sample (Fig. 3). All the experiments were conducted by placing the sample in this box and allowing it to pass on the conveyor belt.

3.1.4   Experimental design

The experiments were conducted with grain samples at 14, 16, and 18% moisture content (one moisture each in straight, damp and tough grade) and at two infestation levels of five and ten insects per 50 g of sample. The experiments were carried out at two different exposure times. At the maximum speed (3 m/min) of the conveyor it takes 28 s for the sample to pass the applicator and at the speed of 1.5 m/min the sample is exposed

to microwave energy for 56 s. The power levels selected were 200, 300, 400, and 500 W

based on the preliminary tests.
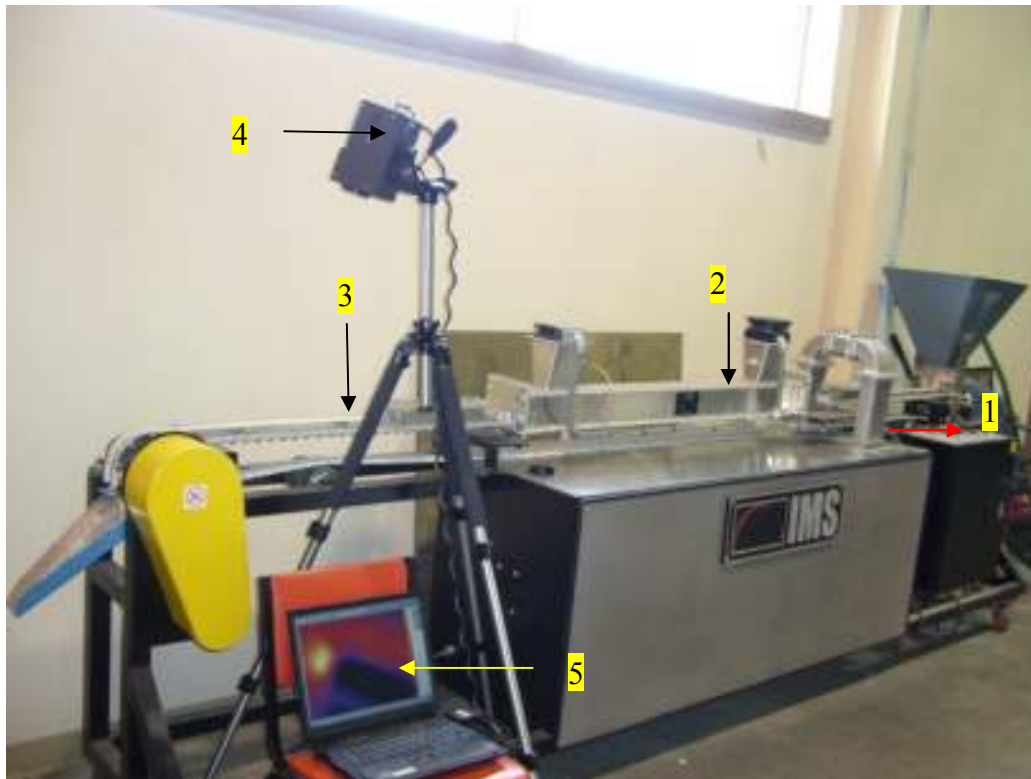
Figure 2. Industrial microwave system

1. Control panel   2. Microwave applicator   3. Conveyor belt 4. Thermal camera
5. Image acquisition system
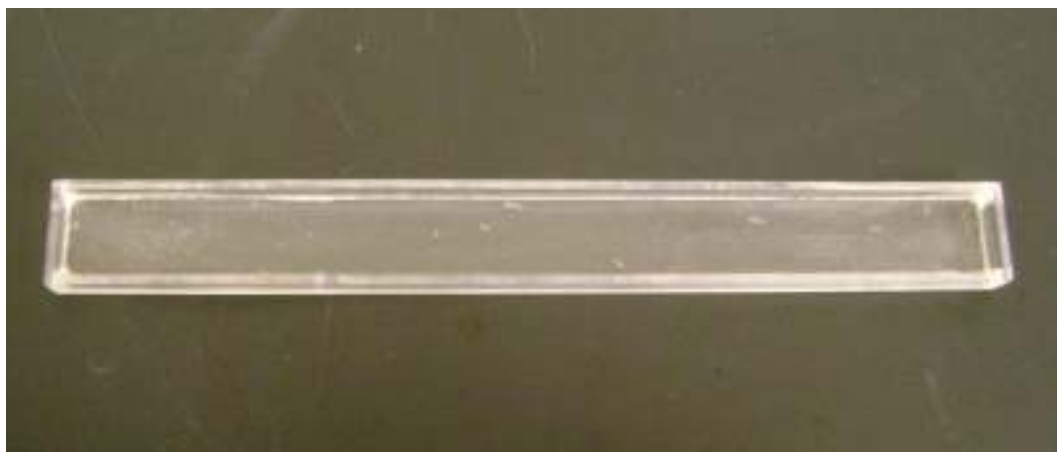
Figure 3. Sample holder

3.1.5   Determination of mortality

3.1.5.1 Mortality of adults   Fifty gram samples were placed in the box and adult insects were added to the sample. The conveyor was switched on and ensured that it was running at its maximum speed. The power was adjusted to the desired level. The grain, along with the insects, was then kept on the conveyor belt and the sample was subjected to microwave energy. When the box came out of the conveyor, it was gently taken out and the sample was spread on a sheet of paper. The numbers of alive and dead insects were counted. The adult insects were considered dead if they failed to respond to gentle rubbing with a small brush. The sample was allowed to cool and the insects were checked for mortality again after 15 min. When the number of insects recovered was not 100%, the same experiment was repeated until 100% recovery was achieved. A minimum of three replicates were done for all the mortality experiments with infestation levels of five and ten insects per 50 g sample. The control mortality was determined by allowing the grain and the insect to pass on the conveyor with the generator turned off.

3.1.5.2 Mortality of immature life stages   To determine the mortality of the egg stage, the grain along with the eggs were treated with microwave energy and then returned to favorable environment at 35°C and 70% RH, where surviving eggs can develop into larvae. After two weeks, the numbers of larvae that emerged from the eggs were counted. For the larval stage, the experiments were conducted in the same way as for the adult insects. The pupae were subjected to microwave energy and returned to a favorable environment (35°C and 70% RH). After ten days, the total number of adults that emerged from pupae was counted. The mortality of eggs and pupae was corrected

for natural mortality using Abbott's formula when the control mortality exceeds 10% (Abbott 1925):

Mortality percent corrected for control = {(x-y)/x}* 100

where x = percent living in control

y = percent living in treated sample.

The control mortality for eggs and pupae were determined by allowing the grain along with the eggs and pupae to pass on the conveyor with power turned off, returned to favorable environment and checked after two weeks and 10 days, respectively for larval and adult emergence. The control mortality for larvae was determined by allowing the grain and larvae to pass on the conveyor and the mortality of larvae was determined immediately as in adults.

3.1.6 Statistical analysis

The effect of moisture content, power and exposure time on the mortality of insects was analyzed using a factorial design. The significance of the different variables was analyzed using analysis of variance (ANOVA). The analysis of variance was done at 95% confidence interval ($\alpha < 0.05$) and mean comparison was done using Scheffe's test. All the analyses were performed using GLM procedure in SAS (SAS 2002).

3.2 Determination of Germination

Germination of seeds subjected to different levels of microwave power was assessed by plating 25 seeds on Whatman no. 3 filter paper in a 9-cm diameter Petri-dish

saturated with 5.5 mL of distilled water (Wallace and Sinha 1962). The plates were placed in a plastic bag to prevent desiccation of the filter paper and kept at 25°C for 7 days. On the seventh day, the germinated seeds were counted and the germination percentage was calculated. The germination of control samples was also determined at 14, 16, and 18% MC.

3.3   Quality Analysis

3.3.1   Quality characteristics of microwave-treated barley

Various quality parameters were analyzed for grain and malt quality. The analysis includes grain protein and malt analyses include alpha amylase, diastatic power, density, soluble protein and viscosity. The quality tests were done on control samples and the samples treated at 500 W, 28 s and 400 W, 56 s because complete mortality of all life stages was obtained at these power levels and exposure times. Three replications were done for all the samples.

Malt was prepared using a malting system designed to handle 100 samples of 50 g per run. Samples were steeped using the following regime: 10 h wet steep, 17.5 h air rest, 8 h wet steep, and 11.5 h air rest. Samples were germinated for 72 h at 15°C, and 100% RH. Kilning was carried out for 38 h as follows: 3 h at 30°C, 19 h at 40°C, 6 h at 52°C, 6 h at 58°C, and 4 h at 68°C.

Malt extract: Fine grind malt was prepared with a Buhler Laboratory disc mill set to fine grind. Malt extract is a measure of total extractable, mainly carbohydrates, from a heated malt extract. Fine extract is an extract of finely ground malt and is an indication of the extract potential of malt.

Diastatic power indicates the total level of amylases. Alpha amylase indicates the level of alpha-amylase enzymes in malt extract by measuring the production of reducing sugars. When a starch substrate reacts with malt extract, amylases in the extract, breakdown the starch substrate to reducing sugars. The alpha amylase and diastatic power were determined using an auto analyzer (Technicon Autoanalyzer, Technicon Instruments Corporation, Tarrytown, NY; Pulse Instrumentation Ltd, Saskatoon, Canada).

The grain protein was analyzed using a grain protein analyzer (Grainspec, Foss Electric, Wheldrake, England). The density of the malt was measured using a density meter (DMA 58, Anton Paar, Austria, Europe) (Fig. 4). The soluble protein, which is required for adequate foam stability in beer, was determined using a spectrophotometer (Model: 550, Pye Unicam Ltd, Cambridge, England).

Viscosity is a measure of the breakdown of β-glucans and is highly correlated to the combination of glucan and glucanase levels which indicates the cell breakdown of the malt (Noonan 1997). Viscosity of the malt was determined using a Cannon-Fenske capillary U-tube viscometer (Model: 9721-B50, Cannon Instrument Company, State College, PA, USA) (Fig. 5).

Figure 4. Density meter

Figure 5. Cannon-Fenske capillary U-tube viscometer

3.3.2 Quality characteristics of microwave-treated rye

Cereal grains contain 5-15% of cell wall material and this fibrous component influences the processing and the end-use quality (Meuser and Suckow 1986). The principal polysaccharide constituents of the cell wall in rye are arabinoxylan (7-12% of kernel), β-glucan (1-2%) and cellulose (1-2%) (Saastamoinen et al. 1989; Vinkx and Delcour 1996). The cell wall of wheat contains lower concentration of arabinoxylan than rye (Knudsen et al. 1995).

3.3.2.1 Milling   The rye samples were sub-sampled to 20 g and milled in a Udy cyclone sample mill (Model: 3010-080P, UDY Corporation, Fort Collins, Colorado, USA) using a 1.0 mm screen. The milled samples were left to cool overnight.

3.3.2.2 Falling number   A 7 g ground sample of rye was mixed with 25 ml of distilled water in a test tube and shaken thoroughly forming a slurry. A stirrer was placed in the tube and the test tube containing the slurry was placed in the hot water bath (Fig. 6 and Fig. 7). The total time taken by the stirrer to reach the bottom is the falling number which reflects the sprout damage.

Figure 6. Falling number test

Figure 7. Samples for falling number test

3.3.2.3 Protein analyzer   The milled rye sample was used to analyze protein content

using a Leco FP-528 Protein Analyzer (Leco Corporation, St.Joseph, MI) (Fig. 8 and Fig.

9) according to AACC 46-30. To determine the protein content, 0.2 g of sample was

weighed into a tinfoil cup and the foil was carefully twisted and sealed. The sample identification, mass, and protein factor were logged in the data logging system and the samples were then placed into a carousel. The sample was dropped into the sample drop block, which was analyzed and the results were displayed on the screen.

Sample holder

Figure 8. Leco protein analyzer

Figure 9. Samples for Leco protein analyzer

3.3.2.4 SDS Sedimentation Rye flour sub-sample, 2.5 g, was weighed and 25 mL of distilled water was added. The test tube was covered with a cap and shaken well for 6 s in a vortex and the sample was allowed to stand for 15 min. The cap was removed and 25 ml of SDS solution was added to the test tube, the test tube was capped and inverted 10 times. The test tube was then allowed to stand for 20 min and then using a ruler, the sediment height of each tube was measured in mm. By using a SDS sedimentation conversion chart, the sediment height was recorded in ml.

3.3.2.5 Mixograph Mixograph analysis was done using a 10 g mixograph (Agriculture Canada Engineering Division, Ottawa) according to AACC 54-40A, at 53% water absorption for rye flour. The parameters measured were mixing development time (MDT), energy to peak (ETP), peak height, peak bandwidth (PBW) and bandwidth energy.

3.3.2.6 Farinograph Brabender Micro Farinograph (C.W. Brabender Instruments Inc., Hackensack, N.J.) (Fig. 10) of 10 g flour capacity was used. The sample flour mass was based on 14% moisture content sample, hence

Sample mass = w x $(100 - m_1)/(100 - m_2)$

where w= 10 g, m_1 = 14%, m_2 = sample moisture content.

Flour and water were filled in the mixer where the suspension was subjected to mechanical stress by the rotating blades. The resistance of the dough against the blade was measured as torque and plotted on a graph as a function of time.

Figure 10. Farinograph

3.3.2.7 Baking Microwave-treated rye flour was mixed with commercial Robinhood wheat flour in 20:80 proportion (Odean Lukow, Cereal research Centre, Winnipeg, Personal Communication; Beranbaum et al. 2003). In Hungary, the rye flavored bread should contain 15-40% rye while the rye breads should have rye content of more than 40% (Hungarian Food Codex 1997 cited from Füle et al. 2005). Since an increase in rye content deteriorates baking properties, rye content is varied only between 20-30% with wheat flour (Ragaee et al. 2001; Heiniö et al. 2003).

Dough was made from 100 g flour mixed with water, salt, yeast, shortening, potassium bromate, ammonium phosphate, malt syrup, whey and ascorbic acid. Dough was made using a 100 g mixer (National Manufacturing Company, Lincoln, Nebraska) and rested for 15 min at 30°C. The dough was then lightly punched seven times, rested

15 min, sheeted and molded for 30 s. The dough was then placed in baking pans, proofed and baked for 25 min. After 30 min cooling time, loaf volume was measured by a rapeseed displacement method (AACC 10-10B; Preston et al. 1982).

3.3.2.8 Scanning Electron Microscope The scanning electron microscope (SEM) images of whole rye kernels and cross section were obtained to determine whether there was a difference in the structure of control and microwave-heated rye. The samples were first freeze dried to remove all the moisture content from the grain. The freeze dried samples were cut with a surgical steel blade number 11 (Feather Industries Limited, Tokyo, Japan). The cut samples were then mounted on carbon tapes and placed in a Sputter Coater (Model: S150B) and coated with gold and palladium for 20 nm thickness. The coated samples were then viewed in the SEM (Model: Stereoscan 120, SEM Cambride Instruments, England) at an accelerating voltage of 20 keV and images were taken at magnifications of 100, 200, 400 and 1000.

3.3.3 Statistical analysis

The effect of moisture content, power, and exposure time on the quality characteristics of microwave treated barley and rye was analyzed using analysis of variance ($p < 0.05$) with mean separation done by Scheffe's test. The general linear model (GLM) procedure in SAS (version 9.1) (SAS 2002) was used for all the statistical analysis.

3.4 Temperature Distribution Studies

3.4.1 Grain samples

The barley cultivar "Stander", rye cultivar "Musketeer", oats (*Avena sativa* L.) cultivar "AC Marie" and sunflower (*Helianthus annuus* L.) cultivar "Pioneer" were used for the experimental study. The initial moisture content of the sample was determined by drying 10 g of unground grain, in triplicate at 130 ± 2^oC for 20 h for barley, 16 h for rye, 22 h for oats, and 3 h for sunflower seeds (ASABE 2006) in a hot air oven (Thelco Laboratory Oven, Winchester, VA) and was expressed on a wet mass basis. The barley, rye, and oats were then conditioned to 14, 16, and 18% moisture content and sunflower seeds were conditioned to 8, 10, and 12% MC by adding a calculated quantity of distilled water and rotating in a grain mixture for about an hour. The samples were then kept in polythene bags and stored in a refrigerator for 72 h for uniform moisture distribution. Samples were mixed within the bag every 4 h during the day to ensure uniform distribution of moisture. The moisture content was then verified by drying 10 g samples, in triplicate, and the moisturized grain was then kept in air-tight plastic bags in a refrigerator until used for the experiments.

3.4.2 Infrared thermal camera

An uncooled focal planar array type infrared thermal camera with 320 x 240 pixels was used to take thermal images of the microwave-treated grain (Model: Therma-CAM^{TM} SC500 of FLIR systems, Burlington, ON, Canada; Spectral range: 7.5 − 13.0 μm). The thermal sensitivity of the camera was 0.07^oC at 30^oC. While taking thermal images, the emissivity of the grain was set as 0.98 for all the experiments.

3.4.3　Experimental procedure

A polystyrene microwavable rectangular box, of dimensions 30 cm x 3 cm x 1 cm was made to hold a 50 g sample of grain. The experiments were conducted by placing the grain sample in the box. The sample was spread along the sample holder and flattened by hand to avoid unevenness in the sample. The length of the sample was 30 cm and the thickness of the sample layer was around 8-9 mm. The sample holder was then placed on the conveyor and the required power and exposure time was selected on the control panel. The sample was then subjected to microwave heating. As the grain sample came out of the conveyor, a thermal image of the sample was captured using the thermal camera (Model: ThermaCAM ^{TM} SC500 of FLIR systems, Burlington, ON, Canada). The sample was then taken out, allowed to cool to room temperature and the mass of the sample was measured, to determine the moisture loss. The same procedure was repeated for rye, oats, and sunflower seeds at 200, 300, 400, and 500 W and at two exposure times of 28 and 56 s.

From the thermal image obtained for each sample, the maximum, minimum and average temperatures were extracted using ThermaCAM Researcher 2001 software (FLIR systems, Burlington, ON, Canada) and the differences between the maximum and minimum surface temperatures ($\triangle$t) of the grain were obtained.

3.4.4　Statistical analysis

The effect of moisture content, power and exposure time on the average surface temperature and $\triangle$t (difference between the maximum and minimum temperature) was analyzed using a factorial design. The significance of the different type of grain was

analyzed using ANOVA. The analysis of variance was done at 95% confidence interval ($\alpha < 0.05$) and mean comparison was done using Scheffe's test. All the analyses were carried out using GLM procedure in SAS (SAS 2002).

4. RESULTS AND DISCUSSION

4.1   Mortality Results

4.1.1   Mortality of insects in wheat

The mortality of *T. castaneum*, *C. ferrugineus* and *S. granarius* in wheat at 14, and 16% MC were determined as a part of a Master's thesis (Vadivambal et al. 2007b). The mortality of the three insect species at 18% MC was determined as a part of this thesis and the complete results are reported and discussed.

4.1.1.1 Mortality of life stages of *T. castaneum* in wheat   The mortality percentages for the life stages of *T. castaneum* at various power levels, moisture contents and exposure times are shown in Table 8.

The mortality of *T. castaneum* eggs were 64, 81 and 100% at 250, 300, and 400 W, respectively for 14% MC wheat at 28 s exposure time. The complete mortality of eggs was obtained at 400 W at 28 s. There was no significant difference in the mortality of eggs at 14, 16, or 18% MC wheat.

One hundred percent mortality was achieved for the larval stage at 500 W for an exposure time of 28 s and at 400 W for an exposure time of 56 s. Analysis of variance showed that mortality of larvae was not significantly different in wheat at 14 and 16% MC, or at 16 and 18% MC, but the mortality was significantly higher at 18% MC wheat than at 14% MC wheat ($P < 0.05$).

Table 8[#]. Mortality (mean ± SE) of life stages of *T. castaneum* exposed to microwave radiation in wheat at 14, 16, and 18% moisture contents and at different power levels and exposure times.

Insect life stage	Power (W)	Moisture content					
		14 %		16 %		18 %	
		Exposure time					
		28 s	56 s	28 s	56 s	28 s	56 s
Tribolium castaneum eggs	0	20 ± 0	30 ± 10	33 ± 11.5	20 ± 10	20 ± 0	20 ± 10
	250	64 ± 11.7	84 ± 13.9	58 ± 15.5	84 ± 11.6	68 ± 22.1	88 ± 11.2
	300	81±18.9	93 ± 11.1	85 ± 15	100	88 ± 11.2	96 ± 10.2
	400	100	100	100	100	100	100
	500	100	*	100	*	100	*
Tribolium castaneum larvae	0	0	0	0	0	0	0
	250	53 ± 3.6	79 ± 2.2	61 ± 5.1	77 ± 4.2	63 ± 0.57	78 ± 1
	300	72 ± 4.4	93 ± 1.3	74 ± 5.6	95 ± 0.7	78 ± 4.04	96 ± 1.7
	400	91 ± 4.6	100	93 ± 6.3	100	95 ± 3.7	100
	500	100	*	100	*	100	*
Tribolium castaneum pupae	0	7 ± 5.8	3 ± 5.8	10 ± 0	7 ± 5.8	7 ± 5.8	3 ± 5.8
	250	43 ± 1.1	74 ± 3.4	44 ± 1.7	78 ± 5.1	59 ± 4.7	78 ± 4.7
	300	55 ± 9.4	86 ± 2.3	67 ± 1.7	94 ± 2.8	72 ± 2.5	91 ± 0.5
	400	76 ± 3.0	100	78 ± 4.5	100	87 ± 3.6	100
	500	100	*	100	*	100	*
Tribolium castaneum adults	0	0	0	0	0	0	0
	250	45 ± 11.6	77 ± 2.9	56 ± 2.9	81 ± 4.9	55 ± 11.2	73 ± 9.1
	300	58 ± 1.1	90 ± 1.7	68 ± 7.2	95 ± 4.2	66 ± 6.1	93 ± 3.9
	400	85 ± 5.0	100	86 ± 2.5	100	90 ± 2.3	100
	500	100	*	100	*	100	*

*Since 100% mortality was achieved at 400 W, experiments were not performed at 500 W for 56 s

[#] Part of data from Master's work (Vadivambal et al. 1997b)

The mortality percentages for *T. castaneum* pupae at 28 s exposure time were 43, 55, 76, and 100% for 250, 300, 400, and 500 W, respectively. For 56 s exposure time, mortality was 74, 86 and 100% respectively, for 250, 300, and 400 W on 14% MC wheat. Analysis of variance showed that mortality of pupae was significantly higher at 18% MC followed by 16% and lower at 14% MC wheat.

At a power level of 250 W and an exposure time of 28 s, the mortality of *T. castaneum* adults was 45% at 14% MC. At 300, 400, and 500 W, the mortality increased to 58, 85, and 100%, respectively. As exposure time was increased, higher mortality was achieved at lower power levels. For example, at 500 W, 100% mortality was obtained at an exposure time of 28 s. When the exposure time was increased to 56 s, 100% mortality was achieved at a power of 400 W. Results of ANOVA showed that mortality varied significantly with exposure time and power. Based on Scheffe's grouping there was no significant difference in the mortality of *T. castaneum* adults at 14, 16, and 18% MC wheat. The mortality of all the life stages increased as either the power or the exposure time was increased.

Comparing the susceptibility of life stages of *T. castaneum*, eggs were the most susceptible followed by larvae. There was no significant difference between the susceptibility of pupae and adults, and they were the least susceptible to microwave energy. This result is comparable to the results of Menon and Subramanyam (2000). They conducted heat disinfestation studies on life stages of *T. castaneum* and concluded that pupae are more heat tolerant followed by late instar larvae, adults, early instar larvae and eggs. Susceptibility of life stages of stored-grain insects are reported by Mahroof et al. (2003a, 2003b), Halverson et al. (2003), Shayesteh and Barthakur (1996), Watters

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(1976), Hamid and Boulanger (1969) and results are inconsistent. Mahroof et al. (2003a) reported that during heat treatment of mills at 50-60° C, old instars and pupae appeared relatively heat tolerant compared with other life stages. Mahroof et al. (2003b) conducted experiments to study time-mortality relationships for life stages of *T. castaneum* at 50-60°C. They concluded that young larvae were the most heat–tolerant stage. Halverson et al. (2003) reported that eggs are the least susceptible and the most vulnerable stage was pupae.

4.1.1.2 Mortality of *C. ferrugineus* and *S. granarius* adults in wheat   The mortality percentages of *C. ferrugineus* and *S. granarius* adults at various moisture contents, power levels and exposure times were given in Table 9.

The control mortalities of *C. ferrugineus* and *S. granarius* adults were zero. For *C. ferrugineus*, the mortality was 23, 43, 69, and 100% at 250, 300, 400, and 500 W, respectively, for an exposure time of 28 s for the 14% MC. wheat. When the exposure time was increased to 56 s, the mortality increased to 61, 75, and 100% for 250, 300, and 400 W, respectively. The effect of power level and exposure time on mortality was the same for *C. ferrugineus* as for *T. castaneum*. Results of ANOVA showed that there was a significant difference in the mortality of *C. ferrugineus* with moisture content, exposure time and power. As the power or the exposure time increased, the mortality increased significantly and vice versa. The mortality was significantly higher at 16% and 18% MC. wheat than in 14% MC wheat ($P< 0.05$).

Table 9[#]. Mortality (mean ± SE) of adult *C. ferrugineus* and *S. granarius* species exposed to microwave radiation in wheat at 14, 16, and 18% moisture contents and at different power levels and exposure times.

Insect species	Power (W)	Moisture content					
		14 %		16 %		18 %	
		Exposure time					
		28 s	56 s	28 s	56 s	28 s	56 s
Cryptolestes	0	0	0	0	0	0	0
ferrugineus adults	250	23 ± 4.0	61 ± 8.3	34 ± 3.3	72 ± 5.0	33 ± 4.0	69 ± 10.0
	300	43 ± 11.3	75 ± 6.5	47 ± 5.0	91 ± 2.8	49 ± 8.9	88 ± 6.9
	400	69 ± 8.7	100	73 ± 2.3	100	76 ± 4.9	100
	500	100	*	100	*	100	*
Sitophilus granarius	0	0	0	0	0	0	0
adults	250	41 ± 12.8	73 ± 4.0	44 ± 12.0	78 ± 7.6	52 ± 6.5	80 ± 7.4
	300	64 ± 5.0	100	70 ± 10.0	100	70 ± 13.2	100
	400	84 ± 7.4	100	87 ± 7.4	100	92 ± 4.0	100
	500	100	*	100	*	100	*

*Since 100% mortality was achieved at 400 W, experiments were not performed at 500 W for 56 s

[#] Part of data from Master's work (Vadivambal et al. 1997b).

The mortality of *S. granarius* at 250, 300, 400, and 500 W was 41, 64, 84, and 100%, respectively, for 28 s exposure time in 14% MC wheat. At an exposure time of 56 s, 100% mortality was obtained at 300 W as compared to 400 W for the other two species of adult insects. This shows that *S. granarius* was more susceptible at the longer exposure time. The mortality of *S. granarius* varied significantly with moisture content, exposure time and power. The mortality was significantly higher at 16% and 18% MC wheat than in 14% MC wheat ($P<0.05$). Mortality of *C. ferrugineus* was significantly lower compared to *T. castaneum* and *S. granarius*.

Mortality was significantly higher at 16% MC wheat for adult *T. castaneum* and *C. ferrugineus,* and significantly higher at 18% MC wheat for *S. granarius,* than at 14% MC. Since the dielectric properties of grain vary with moisture content (Nelson 1982), higher mortality was expected with higher moisture content wheat. With an increase of power or exposure time at any moisture content, the temperature of the sample and the mortality of the insects increased.

4.1.2   Mortality of insects in barley

The results of the mortality of the life stages of *T. castaneum* and the adult stage of *C. ferrugineus* and *S. granarius* in barley are discussed in this section.

4.1.2.1 Mortality of life stages of *T. castaneum* in barley The mortality percentages for *T. castaneum* eggs, larvae, pupae and adults at several power levels, exposure times and moisture contents of barley are listed in Table 10.

Table 10. Mortality (mean* ± SE) of life stages of *Tribolium castaneum* in barley at 14, 16, and 18% moisture contents and at different power levels and exposure times.

Insect life stage	Power (W)	Moisture content					
		14 %		16 %		18 %	
		Exposure time					
		28 s	56 s	28 s	56 s	28 s	56 s
Tribolium	0	18 ± 13.3	23 ± 23.0	18 ± 4.1	18 ± 13.3	22 ±13.3	28 ±13.3
castaneum eggs	200	41 ± 11.8	91 ±10.6	19 ±12.9	88 ± 10.7	43 ±10.9	81 ±11.4
	300	94 ± 10.0	100	82 ± 10.0	100	84 ± 12.8	100
	400	100	100	100	100	100	100
	500	100	#	100	#	100	#
Tribolium	0	2 ± 4.1	0	0	0	0	0
castaneum larvae	200	32 ± 9.8	67 ± 10.3	30 ± 8.9	73 ± 8.2	33 ± 8.2	70 ± 8.9
	300	68 ± 9.8	100	67 ± 8.2	100	47 ± 12.1	100
	400	95 ± 8.4	100	97 ± 5.2	100	95 ± 8.4	100
	500	100	#	100	#	100	#
Tribolium	0	18 ± 9.8	20 ± 10.9	17 ± 10.3	17 ±10.3	15 ±12.2	22 ± 7.5
castaneum pupae	200	19 ± 10.1	63 ± 11.2	30 ± 4.9	60 ± 9.8	45 ± 9.8	74 ± 7.9
	300	41 ± 11.8	94 ± 6.6	68 ± 9.8	90 ± 11.8	78 ±11.6	91 ±10.6
	400	100	100	100	100	100	100
	500	100	#	100	#	100	#
Tribolium	0	0	0	0	0	0	0
castaneum adults	200	12 ± 9.8	67 ± 10.3	20 ± 6.3	45 ± 8.4	12 ± 9.8	63 ± 5.2
	300	52 ± 13.3	90 ± 8.9	50 ± 8.9	83 ± 13.7	38 ± 4.1	85 ± 12.2
	400	87 ± 10.3	100	85 ± 8.4	100	82 ± 4.1	100
	500	100	#	100	#	100	#

* Average of six replicates (three replicates for five insects per 50 g and three replicates for 10 insects per 50 g of sample)
# since 100% mortality was achieved at 400 W, experiments were not performed at 500 W for 56 s.

The mortality percentages for *T. castaneum* eggs at 0, 200, 300, and 400 W, were 18, 41, 94, and 100%, respectively, for 14% MC barley at 28 s exposure time and the corresponding temperatures at 0, 200, 300, and 400 W were 27, 43, 54, and 67°C, respectively. The mortality percentages were 23, 91, and 100%, at 0, 200, and 300 W, respectively at 56 s exposure time and the corresponding temperatures were 27, 57, and 76°C, respectively. One hundred percent mortality was achieved at 400 W for 28 s and at 300 W for 56 s exposure time. Analysis of variance showed that mortality was significant at various moisture contents with higher mortality at 14% MC and lower at 16% MC. The mortality was significantly higher at higher power levels and exposure time.

The mortality of *T. castaneum* larvae at 0, 200, 300, 400, and 500 W for 28 s exposure time was 2, 32, 68, 95, and 100%, respectively for 14% MC barley. The mortality at 0, 200, and 300 W for 56 s exposure time was 0, 67, and 100%, respectively. There was no significant difference in the mortality of larvae at 14, 16, and 18% MC. The mortality was significantly higher at higher power levels and exposure time.

The mortality of *T. castaneum* pupae at 0, 200, 300, and 400 W was 18, 19, 41, and 100%, respectively for 14% MC barley. The mortality was 20, 63, 94, and 100%, at 0, 200, 300, and 400 W, respectively, for an exposure time of 56 s with significantly higher mortality at higher power level and exposure time. There was a significant difference in the mortality at various moisture contents with higher mortality at 18% followed by mortality at 16% and 14% MC.

The mortality of *T. castaneum* adults at 0, 200, 300, 400, and 500 W for 28 s exposure time was 0, 12, 52, 87, and 100%, respectively for 14% MC barley. The mortality at 0, 200, 300, and 400 W for 56 s exposure time was 0, 67, 90, and 100%,

respectively. The mortality increased with increasing power levels and exposure times at all the moisture contents. One hundred percent mortality was achieved at 500 W for 28 s exposure time and at 400 W for 56 s exposure time. The results of ANOVA showed that there was no significant difference in the mortality at various moisture contents. The mortality was significantly higher at higher power levels and exposure times. Similar kind of mortality was observed for the life stages of *T. castaneum* at 16 and 18% MC barley. Among the life stages of *T. castaneum,* egg stage was the most susceptible stage followed by larval, pupal and adult stage.

4.1.2.2 Mortality of *C. ferrugineus* and *S. granarius* adults in barley   The mortality of *C. ferrugineus* and *S. granarius* adults at different power level, exposure time and moisture content are shown in Table 11.

The mortality of *C. ferrugineus* adults at 0, 200, 300, 400, and 500 W at 28 s exposure was 0, 0, 32, 70, and 100%, respectively, and for 56 s exposure was 0, 28, 68, and 100%, for 0, 200, 300, 400, and 500 W, respectively, for 14% MC barley. Similar to *T. castaneum* adult, the ANOVA showed that there was no significant difference in the mortality at various moisture contents but the mortality was significantly higher at higher exposure time and power level.

The mortality of *S. granarius* at 28 s exposure time was 0, 13, 63, 88, and 100% for 0, 200, 300, 400, and 500 W, respectively. At the higher exposure time of 56 s, the mortality increased to 0, 57, 92, and 100% for 0, 200, 300, and 400 W, respectively. One hundred percent mortality was achieved at 500 W for 28 s exposure and at 400 W for 56 s exposure. Comparable with other two adult insects, there was no significant difference

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in the mortality at various moisture contents but the mortality was significantly higher at different higher power levels and exposure times.

Table 11. Mortality (mean[*] ± SE) of adult *Cryptolestes ferrugineus* and *Sitophilus granarius* in barley at 14, 16, and 18% moisture contents and at different power levels and exposure times.

Insect species	Power (W)	Moisture content					
		14 %		16 %		18 %	
		Exposure time					
		28 s	56 s	28 s	56 s	28 s	56 s
Cryptolestes	0	0	0	0	0	0	0
ferrugineus	200	0	28 ± 9.8	3 ± 5.2	30 ± 8.9	0	32 ± 9.8
adults	300	32 ± 7.5	68 ± 13.3	37 ± 5.2	78 ± 9.8	42 ± 9.8	67 ± 10.3
	400	70 ± 8.9	100	70 ± 8.9	100	72 ± 11.7	100
	500	100	#	100	#	100	#
Sitophilus	0	0	0	0	0	0	0
granarius adults	200	13 ±10.3	57 ± 10.3	27 ± 8.6	55 ± 8.4	17 ± 8.2	47 ± 8.2
	300	63 ±10.3	92 ± 7.5	60 ± 6.3	92 ± 9.8	65 ± 8.4	88 ± 9.8
	400	88 ± 9.8	100	97 ± 5.2	100	95 ± 8.4	100
	500	100	#	100	#	100	#

* Average of six replicates (three replicates for five insects per 50 g and three replicates for 10 insects per 50 g of sample)
# since 100% mortality was achieved at 400 W, experiments were not performed at 500 W for 56 s.

The comparison of mortality means by Scheffe's grouping among moisture content and among power level are shown in Tables 12 and 13, respectively.

Table 12. Comparison of mortality means at different moisture content barley for *Tribolium castaneum, Cryptolestes ferrugineus* and *Sitophilus granarius*.

Insect species and life stage	Moisture content		
	14 %	16 %	18 %
Tribolium castaneum eggs	90.8a	86.1b	88.6ab
Tribolium castaneum larvae	82.7a	83.3a	80.6a
Tribolium castaneum pupae	77.1c	81.0b	86.1a
Tribolium castaneum adults	75.8a	72.9a	72.5a
Cryptolestes ferrugineus adults	62.3a	64.8a	64.0a
Sitophilus granarius adults	76.7a	78.7a	76.5a

Means within the same row followed by the same letter are not significantly different (P < 0.05).

Table 13. Comparison of mortality means at different power levels for *Tribolium castaneum, Cryptolestes ferrugineus* and *Sitophilus granarius* in barley.

Insect species and life stage	Power			
	200 W	300 W	400 W	500 W
Tribolium castaneum eggs	60.5c	93.5b	100.0a	100.0a
Tribolium castaneum larvae	50.8c	80.3b	97.8a	100.0a
Tribolium castaneum pupae	48.4c	77.1b	100.0a	100.0a
Tribolium castaneum adults	36.4d	66.4c	92.2b	100a
Cryptolestes ferrugineus adults	15.6d	53.9c	85.3b	100a
Sitophilus granarius adults	35.8c	76.7b	96.7a	100a

Means within the same row followed by the same letter are not significantly different (P < 0.05).

4.1.3 Mortality of insects in rye

The results of the mortality of the life stages of *T. castaneum* and the adult stage of *C. ferrugineus* and *S. granarius* in rye are discussed in this section.

4.1.3.1 Mortality of life stages of *T. castaneum* in rye   The mortality of life stages of *T. castaneum* in rye at various moisture contents, power levels and exposure times along with the control mortalities are shown in Table 14.

The control mortality was zero for adult and larval stages whereas higher control mortality occurred for egg and pupal stages. One hundred percent mortality was obtained for eggs, larvae and pupae at 400 W for 28 s exposure time corresponding to a temperature of 72°C and at 300 W for 56 s exposure time corresponding to a temperature of 85°C. At an exposure time of 28 s, one hundred percent mortality was obtained at 500 W for adults, but there was no significant difference between 400 and 500 W. The mortality was significantly higher as the power level increased from 200 to 400 W or when the exposure time was increased from 28 to 56 s.

The mortality increased with increase in power level or exposure time or both. There was no significant difference in the mortality of life stages at 14, 16, or 18% MC rye. The Scheffe's grouping showed that eggs were the most susceptible to microwave energy followed by larval and pupal stage with no significant difference between the two. The adults were the least susceptible to microwave energy.

Complete mortality of life stages of *T. castaneum* can be achieved at 400 W for exposing to 28 s and at 300 W for exposing to 56 s in rye. Among the various life stages of *T. castaneum*, eggs were the most susceptible and adults were the least susceptible to microwave energy.

Table 14. Mortality (mean* ± SE) of life stages of *Tribolium castaneum* exposed to microwave radiation in rye at 14, 16, and 18% moisture contents and at different power levels and exposure times.

Insect life stage	Power (W)	Moisture content					
		14 %		16 %		18 %	
		Exposure time					
		28 s	56 s	28 s	56 s	28 s	56 s
Tribolium	0	18 ± 16	20 ± 16.7	17 ± 10.3	15 ± 15.2	22 ± 16	18 ± 9.8
castaneum eggs	200	31 ± 16.7	98 ± 4.9	36 ± 9.8	96 ± 6.2	27 ± 13.4	98 ± 4.9
	300	94 ± 10.0	100	94 ± 6.6	100	94 ± 10.9	100
	400	100	100	100	100	100	100
	500	100	#	100	#	100	#
Tribolium	0	0	0	0	0	0	0
castaneum larvae	200	42 ± 9.8	77 ± 10.3	37 ± 10.3	80 ± 6.3	40 ± 11	63 ± 10.3
	300	77 ± 10.3	98 ± 4.1	75 ± 12.2	97 ± 8.2	73 ± 15.1	100
	400	100	100	100	100	100	100
	500	100	#	100	#	100	#
Tribolium	0	8 ± 9.8	13 ± 8.2	10 ± 8.9	13 ± 8.2	13 ± 8.2	13 ± 8.2
castaneum pupae	200	42 ± 9.0	75 ± 11.4	46 ± 11.3	77 ± 7.3	50 ± 9.4	70 ± 9.3
	300	82 ± 11.4	100	74 ± 11.4	100	83 ± 9.7	100
	400	100	100	100	100	100	100
	500	100	#	100	#	100	#
Tribolium	0	0	0	0	0	0	0
castaneum adults	200	35 ± 8.4	75 ± 8.4	32 ± 9.8	67 ± 12.1	32 ± 9.8	68 ± 9.8
	300	63 ± 10.3	100	62 ± 9.8	100	63 ± 10.3	100
	400	98 ± 4.1	100	97 ± 8.2	100	93 ± 8.2	100
	500	100	#	100	#	100	#

\# since 100% mortality was achieved at 400 W, experiments were not performed at 500 W for 56 s.

* Average of six replicates (three replicates for five insects per 50 g and three replicates for 10 insects per 50 g of sample).

4.1.3.2 Mortality of *C. ferrugineus* and *S. granarius* adults in rye   The mortality of adult *C. ferrugineus* and *S. granarius* adults in rye are shown in Table 15. The mortality of *C. ferrugineus* adults at 0, 200, 300, 400, and 500 W at 28 s exposure time was 0, 8, 48, 85, and 100%, respectively and for an exposure time of 56 s the mortality was 0, 42, 92, and 100%, for 0, 200, 300, and 400 W, respectively for 14% MC rye. The temperature of 14% moisture content rye corresponding to 0, 200, 300, 400, and 500 W was 28, 49, 59, 72, and 83°C, respectively, at 28 s exposure time. The temperature of 14% moisture content rye corresponding to 0, 200, 300, and 400 W was 27, 65, 85, and 101°C, respectively, at 56 s exposure time. The mortality was not significant at various moisture contents but the mortality was significantly higher at higher power levels and exposure time.

The mortality of *S. granarius* adults was 0, 38, 67, and 100% for 0, 200, 300, and 400 W, respectively at an exposure time of 28 s for 14% MC rye. One hundred percent mortality of adult *S. granarius* was obtained at 400 W for 28 s and 300 W for 56 s at all the moisture contents. When the mortality of all the three adult insects in rye was compared, there was no significant difference in the mortality of *T. castaneum* and *S. granarius* whereas the mortality of *C. ferrugineus* was significantly lower. One hundred percent mortality at 28 s exposure time was obtained at 400 W for *T. castaneum* and *S. granarius* and at 500 W for *C. ferrugineus*. There was no significant difference in the mortality of the adult insects at various moisture contents, similar to barley.

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Table 15. Mortality (mean[*] ± SE) of adult *Cryptolestes ferrugineus* and *Sitophilus granarius* species in rye at various moisture contents, power levels and exposure times.

Adult insect species	Power (W)	Moisture content					
		14 %		16 %		18 %	
		Exposure time					
		28 s	56 s	28 s	56 s	28 s	56 s
Cryptolestes ferrugineus adults	0	0	0	0	0	0	0
	200	8 ± 7.5	42 ± 13.3	5 ± 8.4	47 ± 8.2	5 ± 8.4	52 ± 9.8
	300	48 ± 9.8	92 ± 7.5	45 ± 8.4	87 ± 8.2	55 ± 8.4	92 ± 9.8
	400	85 ± 8.4	100	75 ± 8.4	100	82 ±13.3	100
	500	100	#	100	#	100	#
Sitophilus granarius adults	0	0	0	0	0	0	0
	200	38 ± 9.8	65 ± 8.4	42 ± 4.1	68 ± 9.8	45 ± 8.4	62 ± 9.8
	300	67 ± 8.2	100	75 ±10.5	100	72 ± 9.8	100
	400	100	100	100	100	100	100
	500	100	#	100	#	100	#

* Average of six replicates (three replicates for five insects per 50 g and three replicates for 10 insects per 50 g of sample)
# since 100% mortality was achieved at 400 W, experiments were not performed at 500 W for 56 s.

The comparison of mortality means by Scheffe's grouping among moisture contents and power levels are shown in Table 16 and Table 17, respectively. There was no significant difference in the mortality of life stages of *T. castaneum* or the adult *C. ferrugineus* or *S. granarius* between 14, 16, and 18% MC rye (Table 16, 17).

Table 16. Comparison of mortality means at different moisture content for *Tribolium castaneum*, *Cryptolestes ferrugineus* and *Sitophilus granarius* in rye.

Insect species and life stage	Moisture content		
	14 %	16 %	18 %
Tribolium castaneum eggs	90.4a	90.8a	89.6a
Tribolium castaneum larvae	86.7a	86.0a	84.6a
Tribolium castaneum pupae	87.4a	87.2a	87.8a
Tribolium castaneum adults	84.4a	82.1a	82.3a
Cryptolestes ferrugineus adults	71.9a	69.8a	73.3a
Sitophilus granarius adults	83.8a	85.6a	84.8a

Means within the same row followed by the same letter are not significantly different (P < 0.05).

Table 17. Comparison of mortality means at different power levels for *Tribolium castaneum*, *Cryptolestes ferrugineus* and *Sitophilus granarius* in rye.

Insect species and life stage	Power			
	200 W	300 W	400 W	500 W
Tribolium castaneum eggs	64.4b	96.9a	100.0a	100.0a
Tribolium castaneum larvae	56.4c	86.7b	100.0a	100.0a
Tribolium castaneum pupae	60.1c	89.8b	100.0a	100.0a
Tribolium castaneum adults	51.4c	81.9b	98.3a	100a
Cryptolestes ferrugineus adults	26.7d	69.7c	90.3b	100a
Sitophilus granarius adults	53.3c	85.6b	100a	100a

Means within the same row followed by the same letter are not significantly different (P < 0.05).

4.1.4 Mortality of *S. granarius* egg and larval stages

Sitophilus granarius adults drill a hole in the kernel, deposits egg and seal the hole with a gelatinous secretion. The larva completes its growth, pupates and develops into an adult weevil within a kernel (Agriculture Canada 1981c). Since it was difficult to collect large number of kernels with *S. granarius* eggs, mortality was determined only on 14% MC wheat, barley and rye. The results of mortality of egg and larval stages of *S. granarius* are given in Table 18.

One hundred percent mortalities of *S. granarius* eggs and larvae were achieved at 400 W for 28 s and at 300 W for 56 s in all the three grains: wheat, barley and rye. There was no significant difference between the egg and larval mortality in *S. granarius*. Comparing *S. granarius* egg, larval and adult stages, eggs and larvae were the most susceptible and adults were the least susceptible.

Comparing *S. granarius* and *T. castaneum* life stages, *T. castaneum* eggs were the most susceptible followed by larvae. The pupae and adults were the least susceptible to microwave energy. Whereas *S. granarius* eggs and larvae were the most susceptible and adults were the least susceptible to microwave energy.

Table 18. Mortality (mean[*] ± SE) of life stages of *Sitophilus granarius* in wheat, barley and rye at 14% moisture content, and at different power levels and exposure times.

Insect life stage	Power (W)	Grain					
		Wheat		Barley		Rye	
		Exposure time					
		28 s	56 s	28 s	56 s	28 s	56 s
Sitophilus granarius eggs	0	43 ± 5.8	40 ± 10	27 ± 23.1	27 ± 23.1	27 ± 11.5	33 ± 30.6
	200	41 ± 9.8	89 ± 9.8	36 ± 15.6	91 ± 15.6	45 ± 0	90 ± 17.3
	300	82 ± 17.5	100	82 ± 15.6	100	91 ± 15.6	100
	400	100	100	100	100	100	100
	500	100	#	100	#	100	#
Sitophilus granarius larvae	0	47 ± 5.8	50 ± 10	47 ± 30.6	40 ± 20	27 ± 23.1	33 ± 11.5
	200	37 ± 10.4	87 ± 23.1	50 ± 21.4	89 ± 19.1	45 ± 27.5	90 ± 17.3
	300	75 ± 21.9	100	87 ± 21.9	100	82 ± 31.8	100
	400	100	100	100	100	100	100
	500	100	#	100	#	100	#

* Average of six replicates (three replicates for five insects per 50 g and three replicates for 10 insects per 50 g of sample)
# since 100% mortality was achieved at 400 W, experiments were not performed at 500 W for 56 s.

Nelson and Kantack (1966) studied the mortality of adult granary weevils in wheat and corn of the same moisture content and showed that insects suffered lower mortalities in wheat than in corn at comparable grain temperatures. Hence the electric field intensity to which insects are subjected to depends on the dielectric properties of the insects and their host medium.

Hamid and Boulanger (1969) studied the mortality of larvae and adults of *T. confusum* and stated that the mortality of larvae was the same as the adults at different temperatures. Watters (1976) determined that eggs are the most susceptible to microwave energy followed by pupae, adults and larvae. Tilton and Brower (1983) stated that the embryonic stage of an insect is a time of extreme radio sensitivity and adult insects are more radio resistant than the other stages (Hasan and Khan 1998).

Johnson et al. (1994) studied the thermal death kinetics of life stages of *T. castaneum* using a heating block system. Their study showed that eggs and younger larvae are the most susceptible life stages, followed by pupae and adults. The older larvae were found to be the most heat tolerant life stage of *T. castaneum*. Shayesteh and Barthakur (1996) determined the mortality of *T. confusum* and showed that eggs are the most susceptible to microwave energy followed by pupae, adults and larvae and the temperature of the medium was above 80°C when 100% mortality was obtained. Hasan and Khan (1998) reviewed the effect of irradiation on major stored-product insects. Their review revealed that larvae are more resistant to radiation than eggs, and adult insects are more resistant than the other developmental stages of the insects.

Halverson et al. (2003) reported that eggs and young larvae are less susceptible and the most vulnerable stage was pupae. Mahroof et al. (2003a) reported that during

heat treatment of mills at 50-60°C using gas heaters, old instars and pupae appeared relatively heat tolerant compared to other life stages. Mahroof et al. (2003b) conducted experiments to study time-mortality relationships for life stages of *T. castaneum* exposed to elevated temperature of 50-60°C. They concluded that young larvae were the most heat–tolerant stage. Menon and Subramanyam (2000) studied the effect of high temperatures on life stages of *T. castaneum* during steam heat treatment. Their study reported that degree of heat tolerance was the highest in pupae, followed by late instar larvae, adults, early instar larvae, and eggs. Differences in larval and adult susceptibility seem to vary among species (Nelson 1996). Lethal temperatures for mortality of insects vary not only with the species but also with the developmental stage of insects (Fields 1992).

Arthur (2006) studied the initial and delayed mortality of late instar larvae, pupae and adults of *T. castaneum* and *T. confusum*. They stated that there is a possible shift in susceptibility of life stages at different temperatures. At 46°C pupae were the most heat tolerant life stage but at temperatures of 50°C or higher early instars were the most heat tolerant life stage showing that there is an interaction between temperature and life stage of the species.

Rami Reddy et al. (2006) studied the effect of soft electron treatment on bean weevil (*Callosobruchus chinensis*). Soft electrons are a safer form of ionizing radiation for food irradiation than gamma rays, X-rays or high energy electron-beam radiation. Their results showed that eggs are the most susceptible to soft electron treatment and adults are the most tolerant to radiation. Imamura et al. (2004) studied the effect of soft-electron treatment on the life stages of *T. castaneum*, *Plodia interpunctella* (Hubner), *C.*

chinensis. Their results indicated that soft electrons at 170 kV effectively killed the eggs, larvae and pupae of *T. castaneum* and *P. interpunctella* but the adults survived after long periods of exposure (5-10 min) but were killed by the treatment for 10 and 15 min, respectively. These studies indicate that adult stage is the most tolerant to radiation treatment compared with the early life stages. Our study also confirms that eggs of *T. castaneum* are the most susceptible and the adults are the least susceptible to microwave energy. The effect of radiation on insects is related to their constituent cells. Cell division and tissue differentiation occur during embryonic development in eggs. The dividing cells are very sensitive to radiation and hence eggs are highly susceptible to radiation whereas the adult stage is more resistant (Ahmed 2001).

When the mortality of all the three adult insects was analyzed, the mortality was the highest for *S. granarius* and lowest for *C. ferrugineus,* irrespective of wheat, barley or rye. Variation in the mortality of various stored-product insects can be attributed to the differences in the size and geometry of the insects. When treated with radio frequency (39 MHz), the mortality was higher for *S. oryzae* and *S. granarius* compared to *T. confusum* and *T. castaneum* (Nelson and Kantack 1966). Tilton and Brower (1987) have stated that radio-sensitivity differences among species are substantial and the most resistant beetles are six to seven times more resistant than the most sensitive species; the bruchids (bean weevils) and curculionids (grain weevils) are the most sensitive, the cucujids (grain beetles) and tenebrionids (flour beetles) are intermediate in sensitivity, and the anobiids, dermestids and ptinids (spider beetles) are most resistant. The sensitivity of the species is affected by many factors such as age, sex, strain, food, temperature, type of radiation and the dose rate.

Tateya and Takano (1977) have also determined that higher susceptibility was observed in *S. oryzae* than *T. confusum* at 2.45 GHz frequency. Shayesteh and Barthakur (1996) studied the mortality of *T. confusum* and *P. interpunctella* using microwave treatment and observed higher mortality in the larger sized *P. interpunctella* than *T. confusum*. The larger size of *P. interpunctella* may favor a high probability of direct microwave absorption and heat transfer from the medium than the smaller *T. confusum* at each power input. The length of adult *S. granarius* is 5 mm (Agriculture Canada 1981c), adult *T. castaneum* is 4 mm (Agriculture Canada 1981a) and adult *C. ferrugineus* is 2 mm (Agriculture Canada 1981b). The wet masses of adults are 2.4, 2.0 and 0.2 mg, respectively for *S. granarius*, *T. castaneum* and *C. ferrugineus* (White and Sinha 1987). The mortality of the larger sized *S. granarius* was the highest followed by the medium sized *T. castaneum* followed by the smaller sized *C. ferrugineus*. Also, *C. ferrugineus* may be more heat resistant compared to the other insects.

Tateya and Takano (1977) observed no significant differences in insect mortality when adult *S. oryzae* was treated in 12.3 to 16% MC wheat. No significant difference in the mortality of adult rice weevil treated at 39 MHz in 11.4% and 12.8% MC wheat was reported by Whitney et al. (1961 cited from Nelson 1973b). Shayesteh and Barthakur (1996) observed that mortality was significantly reduced at 12% MC compared with 6 and 9% MC at each input power level. We also observed that there was no significant difference in the mortality of all the three adult insects in 14, 16, and 18% MC barley and rye.

To summarize, *C. ferrugineus* was the least susceptible and the *S. granarius* was the most susceptible in wheat, barley, and rye. Among the life stages of *T. castaneum* in

barley and rye, eggs were the most susceptible, and adults the least susceptible with larvae and pupae lying between the two with no significant difference between the two. In wheat, eggs were the most susceptible followed by larvae, and the least susceptible were pupae and adults with no significant difference between the two.

Comparing the mortality at different moisture contents, there was no significant difference in the mortality of the three adult species in barley and rye and the life stages of *T. castaneum* in rye. The mortality of *T. castaneum* egg in barley was significantly higher at 14% and lower at 16 and 18% MC. The mortality of *T. castaneum* pupae, in barley was significantly higher at 18% and lower at 14% MC. In wheat, there was no significant difference between the mortality of *T. castaneum* eggs and adults at 14, 16, or 18% MC whereas, the mortality was significantly higher at 18 and 16% and lower at 14% MC for larvae and pupae of *T. castaneum*, and adults of *C. ferrugineus* and *S. granarius*.

4.2   Germination Results

The results of the germination tests for wheat, barley, and rye at three moisture content, four power level and two exposure times are discussed in this section.
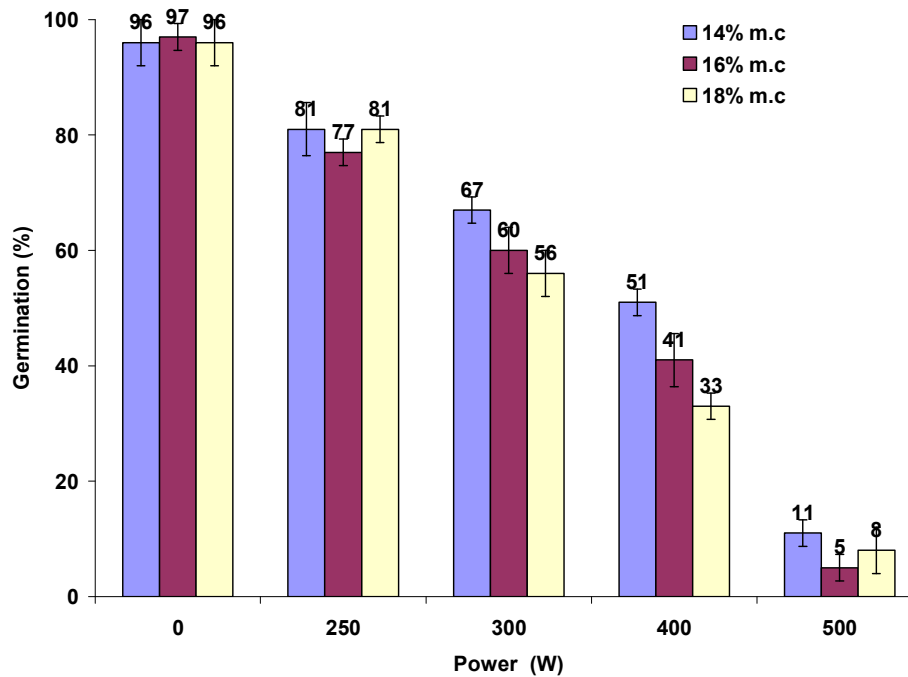
4.2.1   Germination of wheat

Figure 11. Germination percentages of 14, 16, and 18% MC wheat exposed to 28 s at different power levels of microwaves (Vadivambal et al. 2007b)
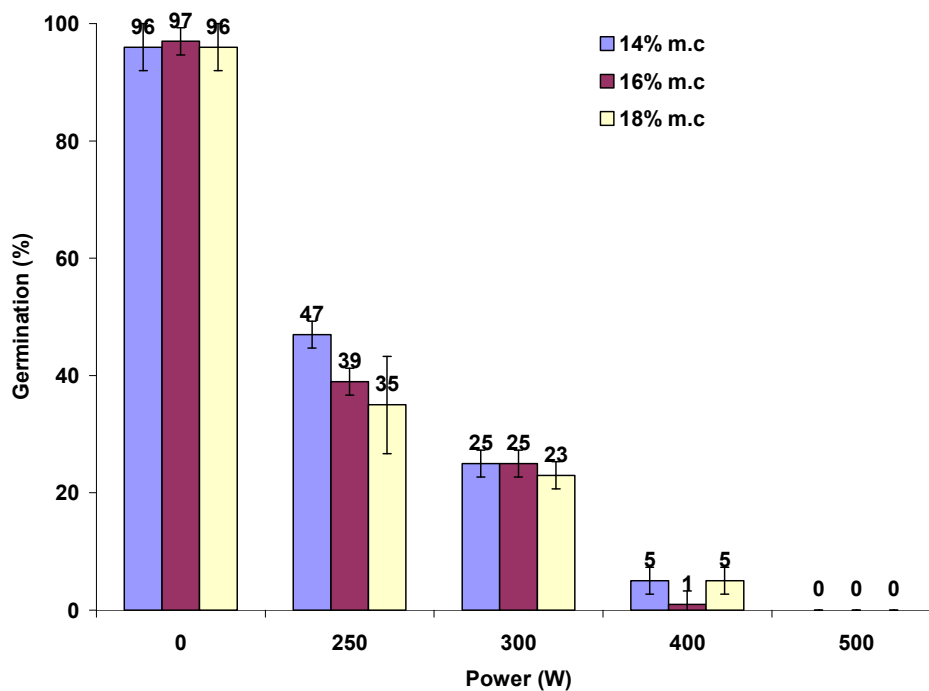

Figure 12. Germination percentages of 14, 16, and 18% MC wheat exposed to 56 s at different power levels of microwaves (Vadivambal et al. 2007b)

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The results of the germination test conducted for 14, 16, and 18% moisture content wheat at various power levels and at exposure times of 28 and 56 s are shown in Figs. 11 and 12, respectively. At 250 W, germination percentage was 81 and 47% for 28 and 56 s, respectively. At 500 W, the germination was 11 and 0% for exposure times of 28 and 56 s, respectively. The germination of the control sample was around 96-97%. As the power and exposure time were increased, the germination was lowered significantly. Hence, with an increasing power or exposure time, the germination of the seed was lowered significantly. The decrease in germination at higher power or exposure time was due to the increase in temperature of the sample. Higher temperature affects the germination capacity of the seed. Results of ANOVA showed that germination differed significantly with moisture content, exposure time and power level. The LSD tests showed that germination was significantly higher at 14% MC wheat than at 16 and 18% MC. Similar result was obtained by Manickavasagan et al. (2007) when they studied the germination of 12, 15, 18, and 21% MC wheat subjected to microwave heating. Their result suggested that germination of wheat decreased with increasing initial moisture content.

4.2.2 Germination of barley

The results of the germination tests for barley at 28 s and 56 s exposure time are shown in Figs. 13 and 14, respectively. The germination of the control sample for 14, 16, and 18% MC are 92, 88, and 88%, respectively. The germination percentage for 14% MC barley at 28 s exposure time was 92, 39, 24, and 4% at 200, 300, 400, and 500 W, respectively and at 56s exposure time was 33, 7, and 0% for 200, 300, and 400 W,

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respectively. The germination at 200 W and 28 s exposure time was the same as the germination of the control sample but the germination was significantly reduced at higher power levels and exposure times. At 500 W and 28 s exposure time, the germination was between 4-7% and at 400 W and 56 s exposure times, the germination was zero for all the three moisture content barley. The ANOVA showed that there was no significant difference in the germination percentage at 14, 16, and 18% MC but the germination was significantly lowered at higher exposure time and power levels.
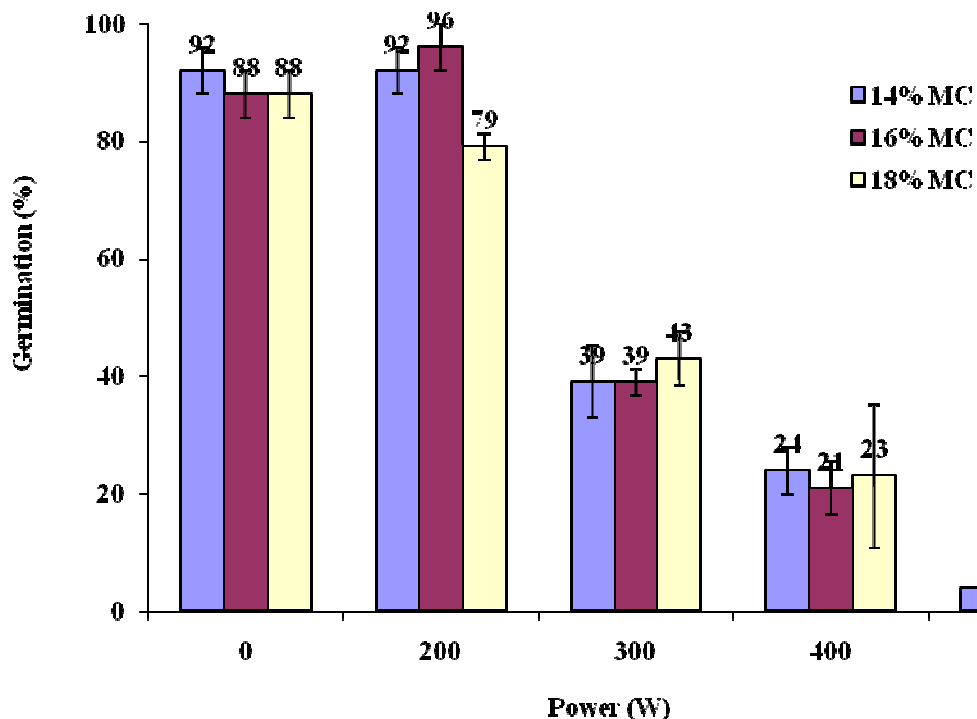

Figure 13. Germination percentages of 14, 16, and 18% MC barley exposed to 28 s at different power levels of microwaves

Figure 14. Germination percentages of 14, 16, and 18% MC barley exposed to 56 s at different power levels of microwaves

4.2.3 Germination of rye

The germination percentages of rye at 14, 16, and 18% MC exposed to 28 and 56 s at different power levels are shown in Figures 15 and 16, respectively.

Figure 15. Germination percentages of 14, 16, and 18% MC rye exposed to 28 s at different power levels of microwaves
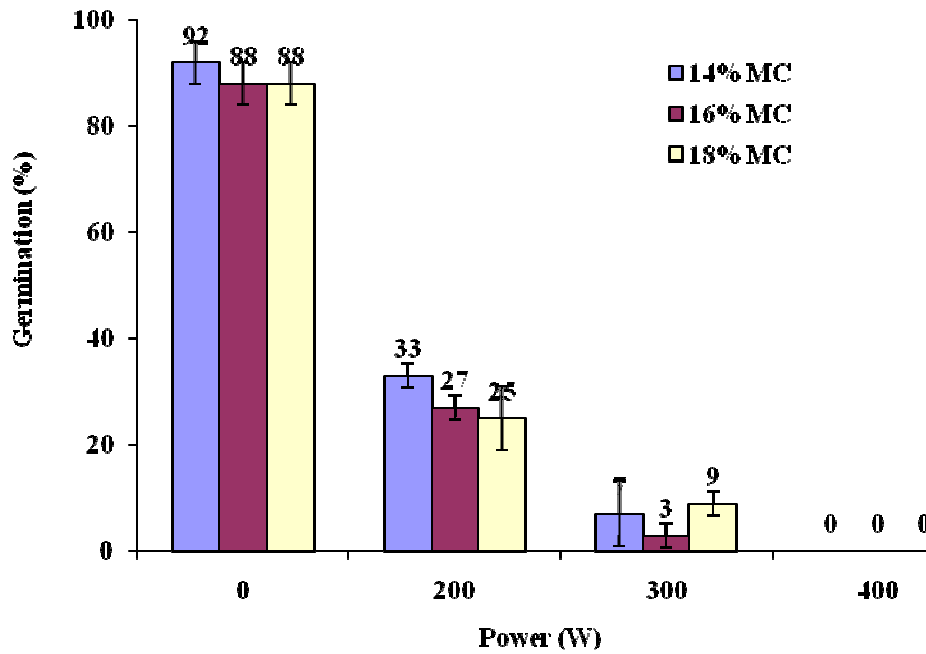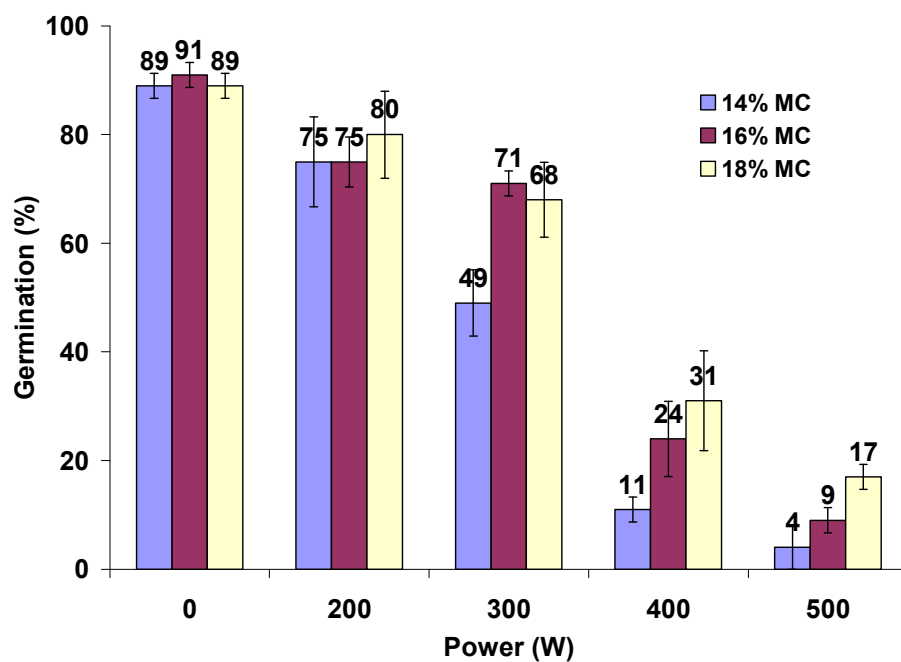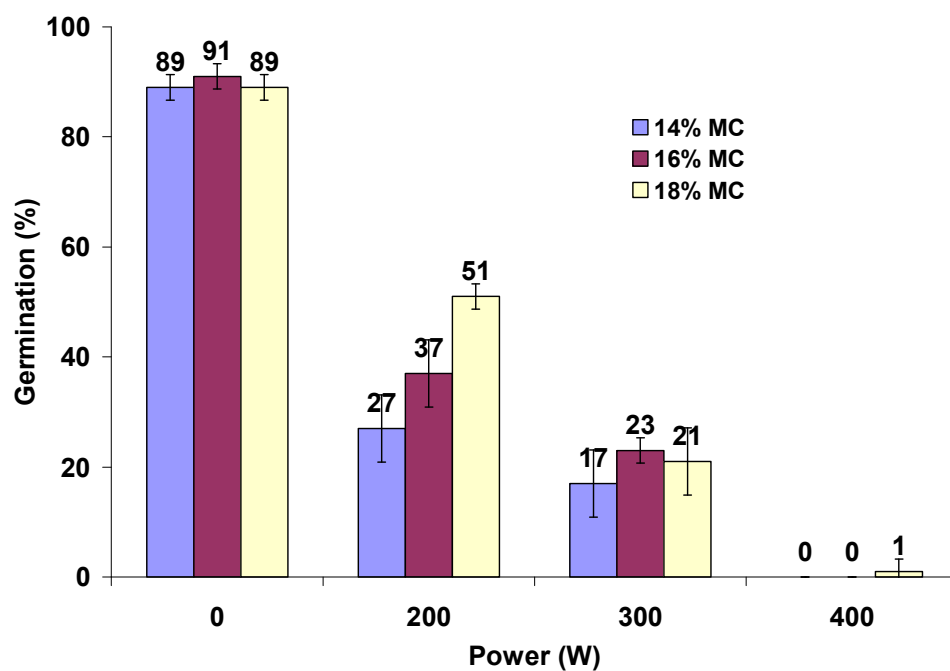

Figure 16. Germination percentage of 14, 16, and 18% MC rye exposed to 56 s at different power levels of microwaves

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The germination of control samples 14, 16, and 18% MC rye was 89, 91, and 89%, respectively. The germination of 14% MC rye at 200, 300, 400, and 500 W was 75, 49, 11, and 4%, respectively for 28 s exposure time. As the exposure time was increased to 56 s, the germination percentage decreased to 27, 17, and 0% for 200, 300 and 400 W, respectively. The germination decreased with increase in power or exposure time or both. Analysis of variance showed that moisture content, power, and exposure time had a significant effect on the germination of rye. The germination was significantly higher at 18%, followed by germination at 16% and the lowest at 14% MC. This germination trend can be related to the temperature effect. The temperature was the lowest at 18% MC and hence the germination was the highest.

Kirkpatrick and Roberts (1970) studied the effects of microwaves (2450 MHz) on the germination of soft red winter wheat exposed to 2000 W. Their results showed that a 10 s exposure reduced the germination by 8% or less.

Wesley et al. (1974) studied the effect of microwave drying on cottonseed. The control germination at 10, 16, and 22% moisture content was 72.0, 53.8, and 54.3%, respectively. After heating the seeds at 200 W for 2 min, the germination of the 10, 16, and 22% MC seeds increased to 76.7, 63.3, and 61.0%, respectively. They suggested that the influence of microwave energy on seed germination may be due to the thermal stresses produced in the seed due to treatment. The seed germination decreased at higher power levels.

Blanco et al. (1977) studied the effects of low level microwave radiation on germination and growth rate in corn seeds. In their study, the growth of corn seedlings was completely inhibited at low power level of 10 mW/cm^2. The reason for complete

inhibition was stated to be due to a loss of turgor resulting from water loss, since full turgor pressure is necessary for the growth of plant cells.

Tran (1979) studied the effect of microwave energy on *Acacia* seeds and determined that germination of *Acacia longifolia* Paxton and *Acacia sophorae* (Labill.) R.Br was enhanced by microwave energy at 2450 MHz. Thuery (1992) has stated that exposure of seeds to 650 W microwave power (2450 MHz) for about 30 s is sufficient to ensure a high rate of germination. The effect of the radiation varies according to the species: clover, peas, beans, and spinach respond favorably whereas wheat, corn, and cotton are less sensitive.

Ghaly and Taylor (1982) studied the temperature effect on the germination of wheat using a fluidized bed dryer. They stated that an inlet air temperature of $60^{o}C$ did not affect germination or vigor and a temperature of 100 and $120^{o}C$, severely damaged the seeds. At $80^{o}C$, significant damage occurred to the vigor of the seeds when exposed to about 15 min and hence could not be considered as a safe temperature.

Conkerton et al. (1991) evaluated the use of microwave heating (700 W, 2450 MHz) to prevent deterioration of cottonseed during storage and determined the germination of cottonseed subjected to microwave heating. They concluded that microwave heat treatment for 1 min caused a significant reduction in the germination capacity of cottonseed while longer heat treatment completely inhibited the germination capacity of the seeds.

Shivhare et al. (1991) studied the effects of different factors on microwave treatment of corn, the drying characteristics and the quality of corn seed. They suggested that high seed germination could be maintained by using microwave power levels of 0.25

W/g of wet seeds. Though some of the studies have shown that exposure to microwave enhances germination, Campana et al. (1993) studied the physical, chemical and baking properties of wheat dried with microwave energy and concluded that germination capacity was decreased by exposure to microwave energy. The decrease in germination capacity was related to the final temperature and the initial moisture content of the grains.

Vendin and Gorin (1995) studied the effect of temperature on the germination capacity of oat, barley and wheat treated with UHF electromagnetic field and stated that when the seed of high moisture content (20%) has to be treated, the rate of heating and the end temperature should be kept within the limits of $0.4\text{-}0.5^{o}C/s$ and $50^{o}C$, respectively. While treating low moisture content seeds, these limits could be extended.

Bhaskara et al. (1998) studied the effect of microwave treatment on quality of wheat seeds infected with *Fusarium graminearum* (Schwabe). Their results showed that eradication of the pathogen increased with the total microwave energy, but the seed viability and seedling vigor decreased accordingly.

More et al. (1992) studied the effect of microwave heating on the germination, FFA value, and fungal contamination of sorghum (*Sorghum bicolor* (L.) Moench) grain at 12, 14, and 16% MC and the microwave oven had nine power levels with output power of 650 W at 2450 MHz. One hundred gram samples were treated at three power levels PL3, PL6 and PL9 for 30 or 60 s. The treated samples were then tested for germination, FFA and fungal contamination. The results of the experiment showed that at 14 and 16% MC for PL3 and PL6, the germination was higher than the control and for 12% MC, the germination was same as the control. Whereas there was a significant

reduction in the germination of sorghum treated for 60 s at PL6 and PL9. The mean FFA value for control grain was 13 while that exposed to microwave treatments varied between 10 to 16 with no significant difference between the treated and control. Microwave treatment at 60 s effectively eliminated almost all fungi from seeds at every moisture content and power level. Their result showed that moisture content was not a significant factor during microwave treatment in many grain quality characteristics.

Stephenson et al. (1996) studied the effect of microwave treatment (2.45 GHz, 750 W) on the barley seed germination and vigor. The effect of combination of various factors such as absorbed microwave power (AMP, 0.2 to 0.6 W/g of seed), treatment duration (30 to 90 min), pulsing (PUL, time in seconds, the microwave is on/off, 20/40 to 60/0) and initial seed moisture content (SMC, 15 to 27%) was studied. The seed viability was assessed by standard germination test in sand (Agriculture Canada 1979) and seedling vigor was measured as the mean plumule length (MPL). The germination percentage for control sample was 92.5% and control MPL was 77 mm while the minimum acceptable germination of barley seed certification is 85% (Agriculture Canada 1967). The germination of microwave treated seed varied between 79.5% to 97.5% with an overall mean of 91.1%, with a very few combinations resulting in germination less than 85% germination. The MPL for microwave treated seeds varied between 48.7 to 95.9 mm. Their study revealed that a reduced germination percentage of less than 90% was observed at combinations of high AMP and high PUL when SMC and duration were fixed at 21% and 75 min, respectively.

Aladjadjiyan (2002) studied the influence of microwave radiation on germination of ornamental perennial crops. The effect of microwave radiation on the germination of

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seeds and germination energy of *Gleditschia triacanthos* L., *Caragana arborescens* Lam., *Laburnum anagiroides* Med., *Robinia pseudoacacia* L. has been studied. Their results showed that there was a gradual increase of germination and germination energy at an initial power of 425 W, but at 850 W the seed germination was lowered. The accelerated germination and improved germination energy could be due to the disturbance of the seed coat under the influence of microwave treatment, which facilitated water penetration into the seeds and the start of initial development stages. Aladjadjian and Svetleva (1997) studied the influence of magnetron irradiation on common bean seed and reported that root and shoot length increased as a result of irradiation for 30 s at 120 W power and 2450 MHz frequency.

Velázquez-Marti et al. (2006) has stated that although temperature increase using microwave radiation within certain limits may increase germination, beyond a threshold the germination of seeds are inhibited when exposed to microwave radiation (Davis et al. 1971; Menges and Wayland 1974).

Seeds of many legumes pose a germination problem due to hard seeds. Although the hard seeds are viable, an impermeable seed coat prevents moisture entry, necessary to initiate germination. As a result, the germination of seeds is delayed and they may not have sufficient time to mature before harvest. These hard seeds, when heated to an appropriate temperature, results in an improved germination (Venkatesh and Raghavan 2004).

The exposure of seeds to microwave radiation has resulted in both increase and decrease in the germination of seeds based on the power level, exposure time and the type of seed. Our experimental results have shown a decrease in the germination

percentage of wheat, barley and rye as the power level or exposure time or both increased.

4.3 Quality Analysis Results

4.3.1 Wheat

The various quality characteristics tested for microwave-treated wheat are grain protein, flour protein, flour yield, flour ash, farinograph and loaf volume of the bread. The results of the quality characteristics are shown in Table 19.

Table 19[#]. Quality characteristics (mean of 3 replicates ± SE) of microwave-treated wheat.

Power W	Exposure time (s)	MC (%)	Grain protein (%)	Flour protein (%)	Flour yield (%)	Flour ash (%)	Stability (min)	Loaf volume (cc)
Control	0	14	13.9±0.11	12.9±0.10	77.2±0.21	0.51±0.02	18.2±0.23	1018±37.8
500	28	14	13.8±0.05	12.7±0.11	76.9±0.35	0.50±0.03	18.0±0.25	1022±65.1
500	28	16	14.1±0.11	13.1±0.35	77.3±0.23	0.47±0.03	16.4±0.92	1050±13.2
400	56	14	13.8±0.11	12.8±0.23	76.5±1.06	0.51±0.03	18.0±0.26	992±40.4
400	56	16	14.1±0	12.9±0.11	77.4±0.40	0.47±0.02	16.6±0.83	992±45.1

[#] Data from Master's work (Vadivambal et al. 2007b).

The flour protein for the control sample varied between 12.8-13%. The flour protein for the sample exposed to 500 W and 28 s varied between 12.6-13.5% and for the sample exposed to 400 W for 56 s varied between 12.5-13%. Flour yield for the control sample varied between 77-77.4%. Flour yield for the sample exposed to 500 W for 28 s was between 76.6-77.4% and for the sample exposed to 400 W for 56 s was between 75.3-77.8%. Flour ash content for the control sample was between 0.48-0.52%. For the sample exposed to 500 W for 28 s flour ash varied between 0.45-0.53% and for the

sample exposed to 400 W for 56 s varied between 0.46-0.54%. The loaf volume of the control sample varied between 975-1045 cc. The loaf volume of the sample treated at 500 W and 28 s varied between 955-1085 cc and the loaf volume of the sample treated at 400 W and 56 s varied between 945-1035 cc.

A t-test and analysis of variance between the means of the control sample and microwave treated sample was performed for flour protein, flour yield, flour ash, stability, and loaf volume. The results showed that the microwave-treated samples are significantly the same as the control sample.

Boulanger et al. (1969) determined the effects of high frequency and microwave radiation on the quality of wheat, for a maximum grain heating temperature of 45°C. The results indicated that there were no damaging effects on the milling properties, bread-making quality, and the protein content of the grain, but the loaf volume was reduced slightly for the bread made from microwave treated wheat. Hamid and Boulanger (1970) determined the effects of microwave radiation on the milling and baking qualities of wheat heated to 55, 65, and 80°C and compared it with the control sample. The results indicated that there was no significant difference on the milling and protein content of microwave treated and control sample; however, the bread-making quality was affected as the treatment temperature increased.

Macarthur and d'Appolonia (1979) studied the effects of microwave radiation and storage on hard red spring wheat flour. They examined the physical dough properties and baking characteristics immediately and at definite time intervals after radiation treatment. Analysis of the flour and bread indicated that, exposing the flour to high levels of microwave radiation produced an abnormal faringraph curve exhibiting two peaks,

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whereas low levels produced bread with loaf volumes and overall bread characteristics equal to or better than those of the control flour.

Goebel et al. (1984) studied the effect of microwave heating and convection heating on wheat starch granule transformations. Wheat starch and water at different ratios were heated to 75°C by microwave energy (650 W, 2450 MHz) and by convection heating. At each starch: water ratio, the range of stages of swelling and matrix development was smaller in convection heated samples than in microwave heated samples, but the convection heated samples were at more advanced stages of gelatinization than the microwave heated samples.

Campana et al. (1993) studied the physical, chemical and baking properties of wheat dried with microwave energy. They stated that the protein content was not affected but the functionality of gluten was altered gradually with increasing exposure time.

Yousif and Khalil (2000) studied the effect of microwave heating on the rheological and baking properties of two wheat flours; the first sample with 10.3% MC and 12.82% protein and the second sample of 10.1% MC and 11.35% protein content. The control and microwave treated (1200 W for 60, 120, and 180 s) wheat flour was analyzed with farinograph, amylograph, extensograph, and baking tests including sensory evaluation. Farinograph dough stability and mixing tolerance index of microwave treated flour improved, compared to the control sample. The microwave heating of wheat flour for 120 s improved the elasticity or stretching values of dough. The bread volume of wheat flour sample one was reduced to 91 and 93%, respectively for 120 and 180 s treatments. Whereas the bread volume of flour sample two increased

when subjected to 120 and 180 s. It was observed that microwave treated samples up to 180 s, did not vary significantly in all of the sensory characteristics evaluated.

Yadav et al. (2008) studied the effect of microwave heating of wheat on the activity of polyphenol oxidase (PPO) and subsequent color changes during storage of wheat dough. Wheat samples with moisture content of 12, 15, 18, and 21% were heated in microwave oven (900 W, 2450 MHz) for 40-100 s. Polyphenol oxidase activity was measured by a spectrophotometric method. Microwave heating of wheat resulted in reduction of PPO activity by 72.32 to 95.89% in milled flour with moisture content having a significant effect on the reduction of PPO activity. The maximum losses of PPO activity were 75.18, 82.5, 93.39, and 95.89% for 18% MC wheat after heating for 40, 60, 80, and 100 s, respectively. Their results showed that the microwave heating effectively controlled the enzymatic browning in dough and improved the customer acceptability of chappatis (a flat unleavened hot plate baked product).

Based on our experimental results, there was no significant difference in the quality of grain protein, flour protein, flour yield, flour ash, and loaf volume of the wheat subjected to microwave energy.

4.3.2   Barley

The quality characteristics of control and microwave treated barley are shown in Table 20.

There was no significant difference in the grain protein of the control and treated samples at both power levels. The analysis of variance for alpha amylase, diastatic power, density, soluble protein and viscosity showed that, there was no significant

difference in the control sample and the sample treated at 500 W for 28 s. But the barley samples exposed to microwave energy at 400 W for 56 s, has a significant decrease in the quality of the samples compared to the control samples.

North American two-row barley typically has 10-12% protein while six-row barley has 11-13% protein content (Noonan 1997). The control and treated barley has protein content between 12.5-12.8%. Edney et al. (2006) studied the barley (AC Metcalfe) characteristics of grain harvested in 2003, which were graded as three major CGC malting grades (Special Select, Select, and Standard Select). The protein content of Special Select, Select and Standard Select was 12.0, 12.2, and 12.2%, respectively.

Table 20. Quality characteristics (mean of three replicates ± SE) of microwave-treated barley.

Treatment	Moisture content (%)	Grain protein (%)	Alpha amylase, DU	Diastatic power	Density (g/cm^3)	Soluble protein (%)	Viscosity (cP)
Control	14	12.6 ± 0.23	7.9 ± 0.47	155 ± 4.2	65.2 ± 0.7	4.2 ± 0	1.70 ± 0.60
500 W, 28 s	14	12.6 ± 0.15	8.3 ± 0.45	170 ± 10.2	64.8 ± 0.4	4.2 ± 0.10	1.65 ± 0.03
400 W, 56 s	14	12.5 ± 0.15	6.8 ± 1.02	154 ± 15.4	63.8 ± 1.3	4.1 ± 0.06	1.79 ± 0.06
Control	16	12.6 ± 0.17	6.9 ± 0.35	160 ± 16.8	64.2 ± 0.8	3.9 ± 0.12	1.85 ± 0.23
500 W, 28 s	16	12.6 ± 0.06	7.0 ± 0.21	151 ± 5.3	63.7 ± 0.4	3.9 ± 0.12	1.88 ± 0.15
400 W, 56 s	16	12.5 ± 0.06	5.8 ± 0.98	134 ± 19.7	62.3 ± 1.5	3.8 ± 0.21	1.95 ± 0.04
Control	18	12.8 ± 0.06	7.7 ± 0.36	170 ± 8.7	63.9 ± 0.2	3.9 ± 0.15	1.83 ± 0.24
500 W, 28 s	18	12.6 ± 0	6.2 ± 0.47	146 ± 7.8	62.1 ± 0.6	4.0 ± 0.06	2.07 ± 0.17
400 W, 56 s	18	12.6 ± 0.15	5.2 ± 0.80	123 ± 16.4	60.2 ± 1.6	3.6 ± 0.15	2.42 ± 0.39

Diastatic power (DP) (measured in ^{o}Lintner) expresses the strength of starch-reducing enzymes in the malt and indicates, how well malt will respond to mashing. The DP may be as low as 35-40 for a well-converted low protein British ale malt, around 100 for European malt, 125 or higher for high protein two-row American malt and six-row malts have DP's as high as 160 (Noonan 1997). In our study, DP for the control sample ranged from 155-170, DP for samples treated at 500 W for 28 s was in the range of 146-170 and the samples treated at 400 W for 56 s ranged from 123-154.

Alpha-amylase is expressed in Dextrinizing units (DU) which is defined as the quantity of enzyme required to dextrinize soluble starch at the rate of 1 g/h at 30°C (Tricarico et al. 2007). Diastatic power gives a ratio for all amylase present in the malt while DU breaks out alpha amylase. A range of 35-50 DU is acceptable depending on the malt type while DU for Munich malt may be below 10 (Noonan 1997). The alpha-amylase for our control sample was in the range of 6.5-8.3 DU. The microwave treated sample at 500 W, was in the range of 5.7-8.8 DU and for those treated at 400 W, was in the range of 4.4-8.0 DU.

Viscosity is a measure of the breakdown of beta-glucans during malting, expressed in centipoises units (cP). Malt that has high viscosity over 1.75 cP, will not run well during sparging (Noonan 1997). The viscosity of control sample was in the range of 1.56-2.0 whereas the viscosity of microwave treated sample was in the range of 1.62-2.22 and 1.74-2.78 for 500 and 400 W treated samples, respectively.

The soluble protein of control sample was in the range of 3.8-4.2%, whereas, of the microwave treated samples at 500 and 400 W, were in the range of 3.8-4.3 and 3.5-4.1%, respectively. Soluble protein is required for foam stability in beer, while excess

soluble protein may result in beer hazes and darker colored beers. The soluble protein of Special Select, Select and Standard Select was 4.56, 4.74, and 4.95%, respectively (Edney et al. 2006).

Eduardo (1986) evaluated the seed vigor and malting quality of microwave-treated barley seed. The seeds were exposed to 200 W (2450 MHz), until grain temperatures reached 49, 60, 71, and 82°C. The results showed that exposure of seeds to higher doses of radiation decreased viability and at 115°C, zero germination was observed. Their results suggested that microwave treatment temperature had significant effect on malt recovery, extract yield, soluble protein, diastatic power and alpha-amylase. Soluble protein decreased significantly at 82°C and deactivation of beta amylase was observed as temperature increased. It was reported that alpha-amylase activity was less affected by microwave treatment than beta-amylase.

Sadeghi and Shawrang (2008) studied the effect of microwave radiation (800 W, for 3, 5, and 7 min) on ruminal dry matter, protein and starch degradation characteristics of barley. Microwave exposure for 3 min had no effect, but for 5 and 7 min decreased the dry matter degradability. The crude protein degradability of barley treated for 3, 5, and 7 min decreased by 6, 10, and 13%, respectively. There was no effect on starch degradability when treated for 5 min, but when exposed for 3 and 7 min increased and decreased the starch degradation, respectively.

The statistical analysis of quality characteristics explains that the quality of barley and barley malt was not affected when treated at a power of 500 W exposed for 28 s; however the quality was affected when treated at a power of 400 W and exposed for 56 s.

4.3.3 Rye

The average of three replications of flour protein, falling number, flour yield, SDS sedimentation, mixograph dough development time, farinograph dough development time, farinograph water absorption and loaf volume of bread of microwave-heated and control samples of rye are given in Table 21.

The average flour protein of the control sample was in the range of 9.1-10.3% and the microwave-treated rye was in the range of 9.3-10.1%. There was no significant difference in the protein content of control and microwave-treated rye. The protein content of rye varies between 8-13% and rye is characterized by lower protein content in comparison to wheat (Bushuk 2001). The protein content of annual rye varieties (Kisvárdai-1 and Kisvárdai legelő) is around 12.1% (Füle et al. 2005). Microwave heating of grain did not affect the protein content of rye. Grain protein content is one of the main quality factors and a valuable predictor of overall bread-making quality of wheat (Ohm and Chung 1999; Souza et al. 2004). The protein content of the grain gives strength to the dough allowing it to trap carbon dioxide gas produced during fermentation (Gooding et al. 1999). As the rye proteins contain a higher amount of albumin but lower gliadin and glutenin fractions than wheat, rye does not normally form gluten like wheat. Hence proteins are not important carriers of the baking properties of rye and do not contribute much to the elastic properties of the fermenting dough and are of minor importance for baking performance (Seibel and Weipert 2001). Protein is not evenly distributed in the grains of rye, but is concentrated mainly in the bran portion (Nilsson et al. 1996).

Table 21. Quality characteristics (mean ± SE) of microwave-treated rye.

MC (%)	Treatment, (W, s)	Flour protein (%)	FN (s)	FLY (%)	SDSS (ml)	MDDT (min)	PKH (%)	FDDT (min)	FAB (%)	LV (cc)
14	0, 0	9.8 ± 0.1	124 ± 33	51.6 ± 1.1	13.3±1.2	0.5 ± 0.1	28.9 ± 9.1	3.5 ± 1.1	60.8 ± 0.4	890 ± 30
14	500, 28	10.1 ± 0.3	93±27	50.8 ± 0.7	13 ± 1	0.4 ± 0.1	24.7 ± 2.0	3.5 ± 0.8	60.2 ± 0.2	870 ± 74
14	400, 56	9.4 ± 0.4	107 ± 12	51.4 ± 0.6	12.3 ±0.6	0.5 ± 0.1	31.8 ± 3.3	4.3 ± 0.3	59.4 ± 0.1	855 ± 48
16	0, 0	9.1 ± 0.2	115 ± 8	50.2 ± 0.5	15.3 ± 0.6	0.5 ± 0.1	39.3 ± 1.2	4.6 ± 0.4	59.4 ± 0.1	915 ± 65
16	500, 28	9.3 ± 0.1	120 ± 6	48.4 ± 1.5	15 ± 0	0.5 ± 0.1	39.3 ± 2.2	4.7 ± 0.7	59.3 ± 0.1	882 ± 38
16	400, 56	9.4 ± 0.1	110 ± 10	50.4 ± 0.6	14.7 ± 0.6	0.6 ± 0.2	44.8 ± 5.6	4.7 ± 0.1	59.4 ± 0	912 ± 40
18	0, 0	10.3 ± 0.2	123 ± 13	55.8 ± 0.2	13 ± 1	0.6 ± 0.1	35.5 ± 1.6	4.9 ± 0.1	59.1 ± 0.6	962 ± 32
18	500, 28	9.9 ± 0.2	111 ± 11	45.8 ± 1.7	13.7 ± 1.5	0.4 ± 0.1	35.8 ± 1.8	4.9 ± 0.5	59.5 ± 0.5	948 ± 45
18	400, 56	9.7 ± 0.1	130 ± 10	46.7 ± 0.7	14 ± 1	0.6 ± 0.2	38.0 ± 3.6	4.1 ± 0.5	60.4 ± 0.1	1003 ± 40

FN   - Falling number
FLY   - Flour yield
SDSS   - Sodium Dodecyl Sulfate Sedimentation
MDDT - Mixograph Dough Development Time
PKH   - Peak to Height
FDDT - Farinograph Dough Development Time
FAB   - Farinograph Absorption
LV   - Loaf Volume

The average falling number for control sample was in the range of 115-124 s and the falling numbers for microwave-treated rye was in the range of 93-130 s. The statistical analysis using Scheffe's grouping has grouped the control and microwave-treated rye in a single grouping, showing that there was no significant difference in the falling number of microwave treated rye and the control sample. The minimum falling number requirement for rye flour in the European Union is 100 s and rye that is sound and not sprout damaged normally has a falling number of 150 s (Hansen et al. 2004). Weipert (1997) has stated that minimum falling number requirement for rye is 90 s. The falling numbers of microwave-treated rye was higher than the minimum requirement. The falling numbers of four Austrian rye varieties (Waldstaudenroggen, Cho, Schlagler, Esprit) are in the range of 85-154 s (Nowotna et al. 2006).

The SDS sedimentation test is an indicator of gluten strength and gives a measure of high molecular weight proteins mainly glutenins present in flour (Gooding et al. 1999). Sedimentation volume ranges from 15 ml in wheat with weak glutens to 55 to 60 ml for CWRS wheat. The SDS sedimentation test was performed to predict the gluten strength and baking quality. The SDS sedimentation volumes were in the range of 12-15 ml for microwave treated samples, significantly similar to the control rye.

The flour yield of control rye ranged between 49.7-55.8% whereas the flour yield of microwave treated rye was in the range of 44.0-52.1%. There was a significant difference in the flour yield percentage of microwave treated and control rye. Blaszczak et al. (2002) studied the effect of γ-radiation and microwave heating on endosperm microstructure and stated that microwave radiation affects both technological properties as well as grain microstructure depending on the exposure time and the resulting grain

temperature. Protein denaturation starts occurring at 64°C, and at 79 and 98°C, protein filaments start changing into tiny fibrils in the first stage and later to a dense protein film covering starch granules. The starch granule gelatinization may be the possible reason for decreased flour yield. Starch gelatinization and protein denaturation during microwave heating of wheat was also observed by Dolinska et al. (2004). Weipert (1997) studied the processing performance of rye compared to wheat and stated that during milling, rye behaves like soft wheat and produces a lower flour yield. Lewandowicz et al. (2000) studied the effect of microwave radiation on the physico-chemical properties and structure of cereal starches (wheat and corn). They observed an alteration of the structure of starch granules. Microwave treatment reduced the crystallinity, solubility, and swelling characteristics of wheat and corn starches and increased the gelatinization temperature of the starches.

The important parameters predicted using the mixograph are mixing development time (MDT) and peak to height (PKH). Mixograph dough development time is the mixing time required to reach maximum consistency. The MDDT for the control samples was between 0.4-0.7 min and the microwave-treated samples was between 0.4-0.8 min with no significant difference between the control and the treated samples.

Farinograph dough development time (FDDT) is the mixing time required to reach that point in the maximum consistency range immediately before the first indication of weakening (AACC 1995; Walker and Hazelton 1996 cited from Veraverbeke et al. 1997). The FDDT for control samples varied between 2.4-5.0 min while for microwave-treated samples, varied between 2.5-5.5 min. Water absorption by rye flour is measured by the farinograph method and it determines the amount of water

that could be added to the flour which thereby determines the economically important dough and bread yield achieved from a given amount of flour (Siebel and Weipert 2001). Water absorption by control rye flour varied between 59.2-61.2% and microwave-treated rye flour was between 59.2-60.5% without significant difference between both the samples. Microwave treatment does not affect the water absorption qualities of rye flour. The water absorption capacity measured by the farinograph method for annual rye varieties (Kisvárdai-1 and Kisvárdai legelő) was 59.5% (Füle et al. 2005).

The lack of gluten formation in rye dough makes the role of the swelling substance, arabinoxylan, highly important for the dough structure (Seibel and Weipert 2001). The water absorption of rye flour is dependent on the content and properties of arabinoxylan especially the water extractable arabinoxylan (WEAX) (Biliaderis et al. 1994; Weipert 1997; Füle et al. 2005).

The most important parameter tested during the baking test is the loaf volume of the bread, which is an important factor that determines the economic aspect of bread making. Loaf volume of control bread was in the range of 850-985 cc which was similar to the loaf volume of bread made from microwave-treated rye (800-1050 cc). For different rye cultivars, characteristic differences in dough yield and bread volume have been reported (Weipert 1997). The loaf volume of annual rye varieties for pure rye bread and rye bread with wheat flour mixture (50: 50) are 493 and 647 cc, respectively (Füle et al. 2005). Higher loaf volume of our tests compared to Füle et al. (2005) may be due to the higher wheat content (80:20, wheat: rye) used in our experiments.

4.3.3.1 Scanning Electron Microscope

Among the various quality characteristics tested, the flour yield of rye was significantly lower than the control sample. Therefore, SEM images of the kernels of microwave- treated and control rye was analyzed to determine whether any changes in the structure of the grain occurred during microwave heating which would affect the flour yield. The results of the SEM micrographs were discussed with Leonard G. Dushnicky (2008. Microscopy Technologist, Grain Research Laboratory, Canadian Grain Commission). The cross-sectional images of rye for control and microwave-heated samples at 100, 200 and 400 x magnifications were shown in Figures 17-22. The protein matrix is tight in the control sample whereas it is loosening up in the microwave-heated rye. In rye treated at 400 W for 56 s the SEM images show a very loose protein matrix, with starch granules between the protein matrices. The microwave heating loosened up the protein matrix whereas in the control, the starch and protein is much tighter.

Kubiczek et al. (1989) studied the concentration and distribution of protein in the endosperm of rye varieties using scanning electron microscopic images. Their study revealed that low protein rye varieties contain less protein matrix which is tightly packed with different sized starch granules. High protein rye varieties had more protein matrix in the inner layers of endosperm with the protein more evenly distributed than the low protein varieties.

Palav and Seetharaman (2006) studied the impact of microwave heating on the physico-chemical properties of starch-water model system. They prepared dispersions of wheat starch in distilled water at 33, 40, and 50% solid concentrations and heated them in microwave oven (2450 MHz) for 10, 20, and 30 s, and for conduction heating, the sample

was heated until a final temperature of 95°C was reached. Their study suggested that microwave heating results in starch with different properties compared to that heated by conduction heating. In slower heating rates, as in conduction heating, the temperature increase is gradual and the starch granules undergo all the steps involved in gelatinization such as granule swelling, loss of birefringence, amylase leaching and granule folding. Whereas due to rapid heating rates in microwave heating, the granules are subjected to a rapid increase in temperature, resulting in restriction of granule swelling and the rupture of granules.

The SEM images of microwave treated and control rye shows a difference in the starch and protein matrix which might be the reason for the reduction in the flour yield.
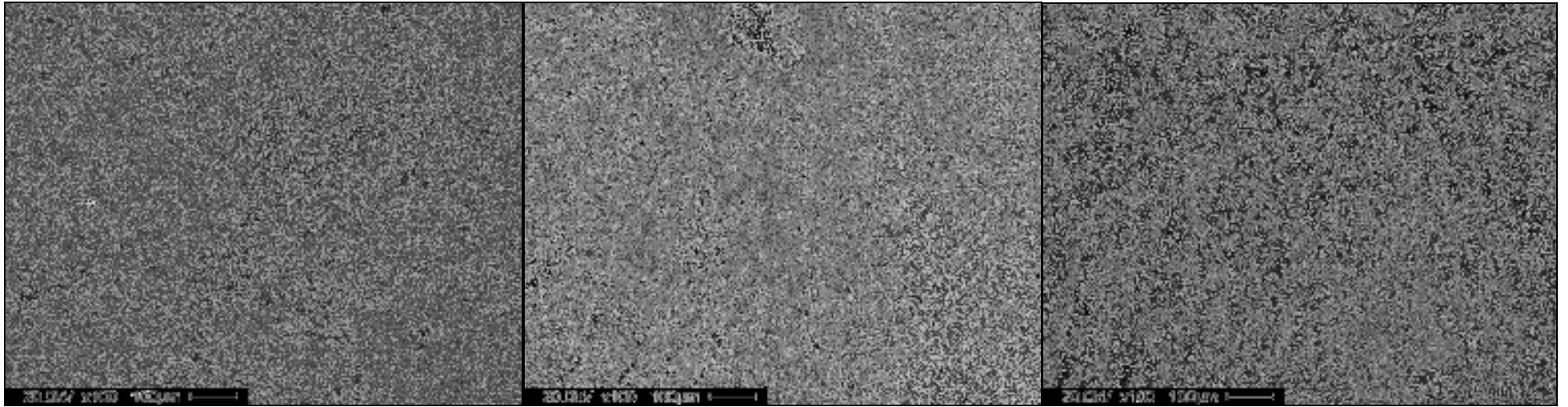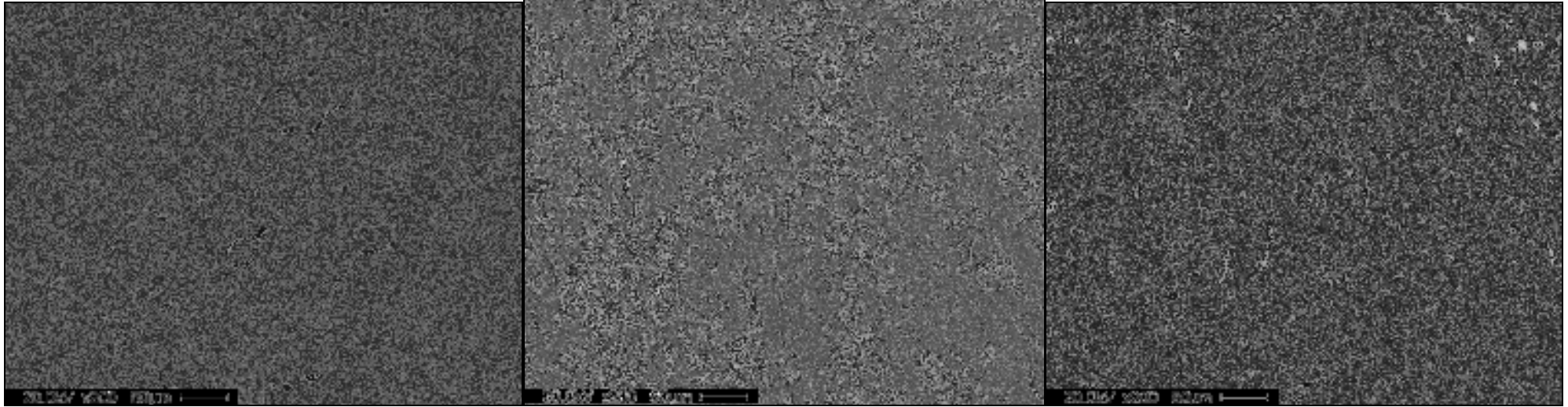
a. Control   b. 500 W, 28 s   c. 400 W, 56 s

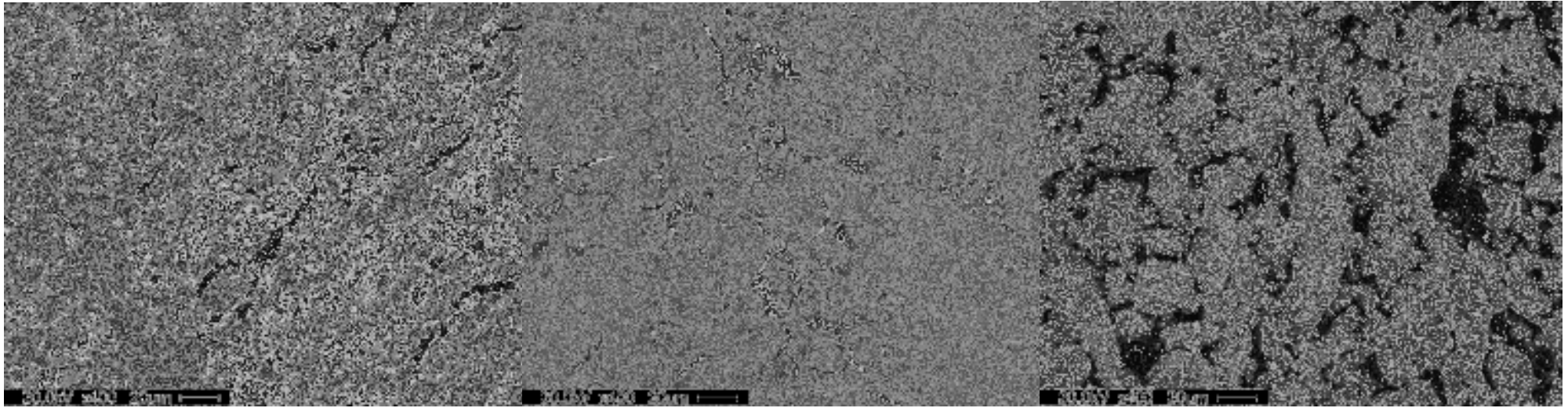**Figure 17. SEM images of rye, 100 x magnification, replication 1**

a. Control   b. 500 W, 28 s   c. 400 W, 56 s

Figure 18. SEM images of rye, 200 x magnification, replication 1

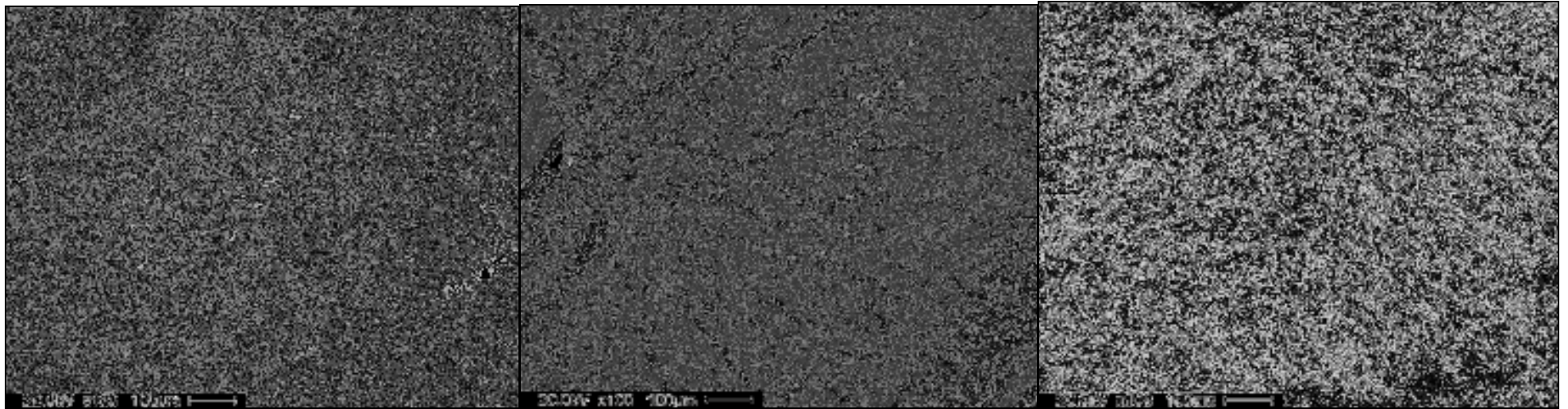a.   Control   b. 500 W, 28 s   c. 400 W, 56 s

Figure 19. SEM images of rye, 400 x magnification, replication 1
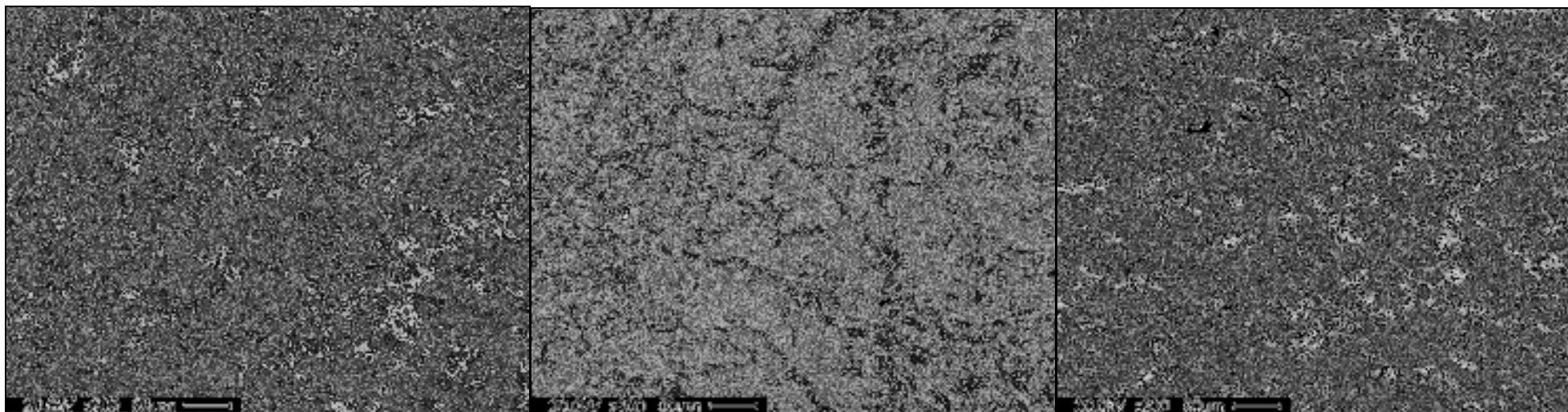
a. Control   b. 500 W, 28 s   c. 400 W, 56 s

Figure 20. SEM images of rye, 100 x magnification, replication 2

a. Control   b. 500 W, 28 s   c. 400 W, 56 s
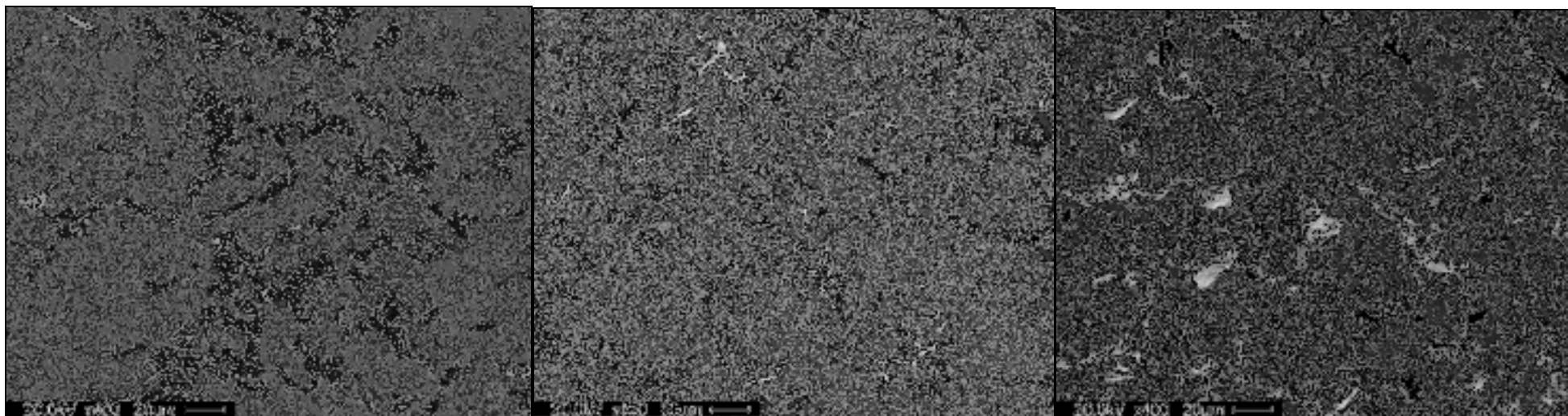
Figure 21. SEM images of rye, 200 x magnification, replication 2

a. Control   b. 500 W, 28 s   c. 400 W, 56 s

Figure 22. SEM images of rye, 400 x magnification, replication 2

4.4 Results of Temperature Distribution Studies

4.4.1 Effect of power and moisture content on average temperature

The average temperature of one replication is the average of all the pixels in the sample. The average temperature of three replications of each of barley, rye, oats, and sunflower seeds are given in Table 22.

The average temperature of 14% MC barley exposed to 0, 200, 300, 400, and 500 W for 28 s were 27.0, 42.6, 53.7, 66.9, and 73.0^{o}C, respectively. The average temperature of 14% MC rye at 0, 200, 300, 400, and 500 W for 28 s were 27.6, 49.2, 59.0, 72.1, and 82.5^{o}C, respectively, and the average temperature of oats were 27.2, 33.1, 35.5, 46.6, and 51.4^{o}C, respectively. The average temperature of sunflower seeds at 8, 10, and 12% MC at 0, 200, 300, 400, and 500 W for 28 s were 23.3, 30.6, 35.1, 39.2, and 43.6^{o}C, respectively. The average temperature was significantly higher at higher power levels and exposure times for barley, rye, oats, and sunflower seeds. The average temperature of barley was significantly higher at 14% MC followed by 16 and 18% MC. The average temperature of rye was significantly higher at 14 and 16% MC than at 18% MC. The average temperature of oats was significantly higher at 18 and 16% MC than at 14% MC. The average temperature of sunflower seeds was significantly higher at 12% followed by 10 and 8% MC.

Comparing barley, rye, oats, and sunflower seeds, the average temperature of rye was significantly higher followed by barley, oats and sunflower seeds at all the power levels and exposure times. Different materials behave differently during microwave heating. The ability of material to store and dissipate electrical energy is based on the dielectric properties of the specified food material. Hence, knowledge of dielectric

properties of food material is essential for proper understanding of the heating pattern during microwave heating (Mudgett 1982). Dielectric properties of a material (dielectric constant and dielectric loss factor) determine the behavior of interaction of the material during the microwave heating process (Nelson 1992). Dielectric constant (ability of material to store charge when used as a capacitor dielectric) for rye, oats, and sunflower seeds is 6.0, 4.9, and 2.0, respectively (dielectric constant of water is 80.3). The higher dielectric constant for rye shows that rye heats faster than oats and sunflower seeds (Khrone 2007). The dielectric constant for wheat is 4.0 and barley is 3.0-4.0. Manickavasagan et al. (2006) studied the temperature distribution on the surface of grain after microwave heating in an industrial microwave dryer. The average surface temperatures obtained at 12, 15, 18, and 21% MC wheat at 500 W and 56 s were 108.8, 103.1, 96.9, and 88.5°C, respectively, and the average surface temperatures of barley at the same conditions were 117.5, 106.6, 104.2, and 90.4°C, respectively. There was not a significant difference in the average temperatures of wheat and barley in most of the treatments. For canola, the average surface temperatures were 97.5, 94.7, 94.1, and 86.7°C, respectively. The average temperature of canola was significantly lower than the wheat and barley because the dielectric constant for canola is 2.3 (Trabelsi and Nelson 2005).

Table 22. Average temperature[#]± SE (^{o}C), measured using a thermal camera, of different moisture content barley, rye, oats, and sunflower seeds exposed to microwave energy.

| Grain	Moisture content (%)	0 W		200 W		300 W		400 W		500 W
		Exposure time (s)								
		28 s	56 s	28 s	56 s	28 s	56 s	28 s	56 s	28 s
Barley	14	27.0 ± 0.2	27.1 ± 0.2	42.6 ± 3.9	57.3 ± 6.5	53.7 ± 6.9	75.5 ± 11.9	66.9 ± 10.5	91.2 ± 15.0	73.0 ±11.1
	16	26.3 ± 0.3	26.3 ± 0.2	44.3 ± 4.1	55.2 ± 6.2	53.8 ± 7.1	71.6 ± 10.2	63.5 ± 8.7	91.1 ± 13.2	70.2± 10.4
	18	25.7 ± 0.3	25.7 ± 0.2	40.0 ± 3.7	52.4 ± 5.5	52.4 ± 5.9	69.2 ± 8.0	61.2 ± 7.6	85.5 ± 11.3	70.4 ± 8.2
Rye	14	27.6 ± 0.1	27.4 ± 0.2	49.2 ± 4.9	65.1 ± 7.9	59.0 ± 7.9	85.4 ± 10.3	72.1 ± 10.4	101.2 ± 9.5	82.5 ± 9.6
	16	26.9 ± 0.2	27.2 ± 0.2	49.2 ± 5.6	66.0 ± 8.3	61.0 ± 7.9	83.7 ± 10.0	72.9 ± 8.2	102.3 ± 9.8	83.9 ± 9.9
	18	28.3 ± 0.2	27.8 ± 0.3	47.2 ± 5.0	62.3 ± 6.7	60.3 ± 7.6	80.1 ± 8.8	70.1 ± 7.9	94.4 ± 9.9	79.8 ± 9.8
Oats	14	27.2 ± 0.3	27.1 ± 0.2	33.1 ± 1.7	43.0 ± 2.9	35.5 ± 3.5	55.5 ± 4.2	46.6 ± 3.3	57.3 ± 4.6	51.4 ± 3.8
	16	27.2 ± 0.3	27.3 ± 0.3	37.7 ± 1.8	43.2 ± 2.7	42.6 ± 2.6	53.3 ± 3.6	49.2 ± 3.0	58.4 ± 4.0	53.1 ± 3.4
	18	27.0 ± 0.4	27.1 ± 0.2	37.2 ± 1.5	42.5 ± 2.4	42.9 ± 2.8	52.4 ± 3.8	49.1 ± 3.0	60.9 ± 3.3	54.6 ± 3.2
Sunflower	8	23.3 ± 0.3	23.3 ± 0.3	30.6 ± 1.8	35.1 ± 3.0	35.1 ± 3.0	41.1 ± 4.4	39.2 ± 4.1	49.6 ± 6.0	43.6 ± 4.7
	10	22.8 ± 0.3	22.8 ± 0.3	30.5 ± 2.1	35.2 ± 2.7	35.7 ± 3.0	44.2 ± 4.2	40.9 ± 3.5	49.9 ± 5.4	45.2 ± 4.3
	12	19.2 ± 0.7	22.5 ± 0.3	30.7 ± 1.8	36.4 ± 3.2	37.4 ± 3.3	44.6 ± 4.8	43.0 ± 4.2	53.8 ± 6.5	47.3 ± 5.3

[#]Average of three replications (for every replication average temperature is the mean temperature of all the pixels).

The thermal images of barley and rye at different power levels and exposure times are shown in Fig. 23 and Fig. 24, respectively, with a temperature scale. The images show that there are hot and cool spots in the grain samples heated by microwave energy.

Since non-uniform temperature distribution is widely seen in all the materials heated with microwave energy, sufficient care has to be taken to ensure whether minimum temperature was reached or maximum safe temperature is not exceeded based on the type of application. For example, while heating meat and related foods, care must be taken to ensure that a minimum temperature is attained that is required to kill pathogens. The safe recommended temperature during heating of any food material is a minimum of 70°C (Ryynanen et al. 2001; Goksoy et al. 1999). While heating grains using microwaves, care has to be taken so that maximum temperature attained at any point is not above the safe temperature (about 60°C) so that the seed is not killed and the end use quality of grain is not affected.
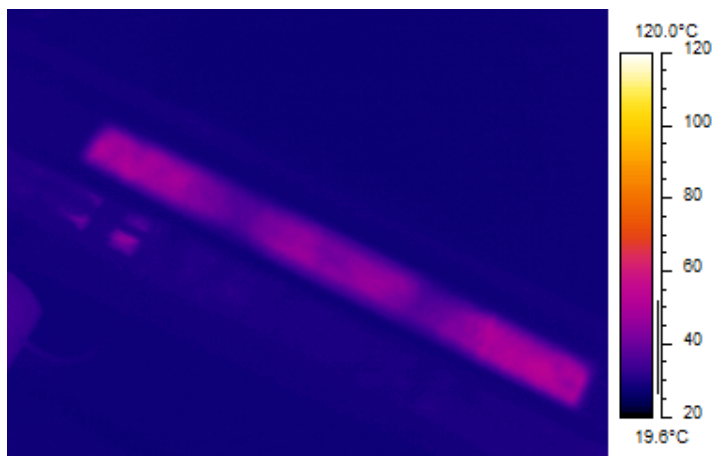
a. 200 W, 28 s
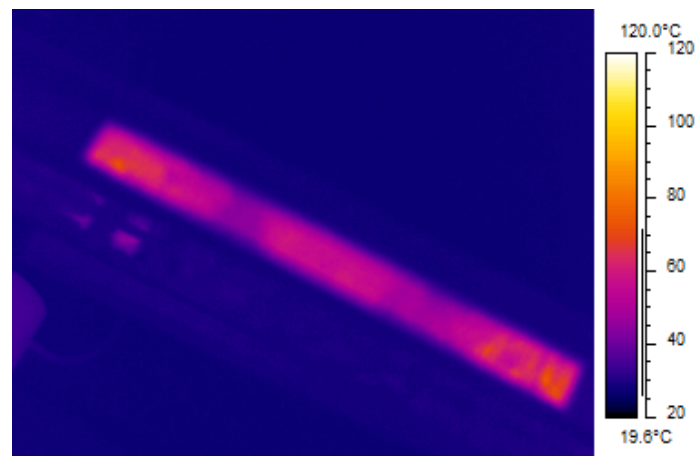
b. 300 W, 28 s
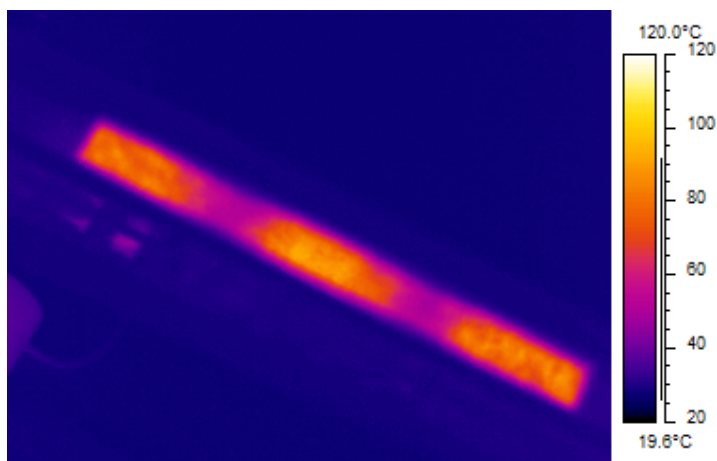
c. 400 W, 28 s

d. 500 W, 28 s

e. 200 W, 56 s

f. 300 W, 56 s

g. 400 W, 56 s

Figure 23. Thermal images of barley at different combinations of microwave powers and exposure times
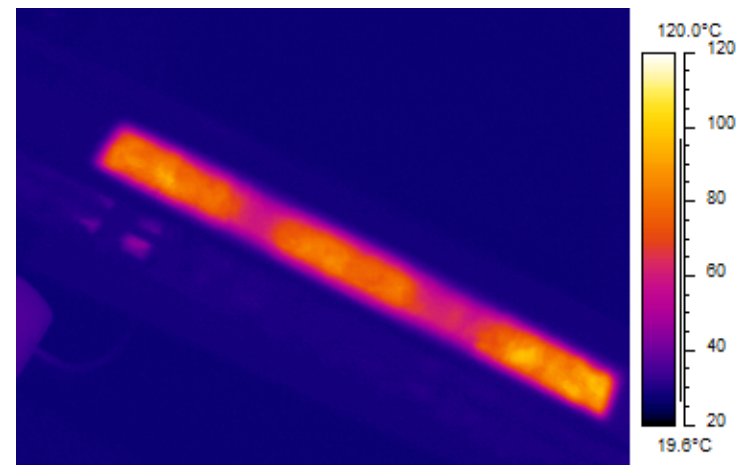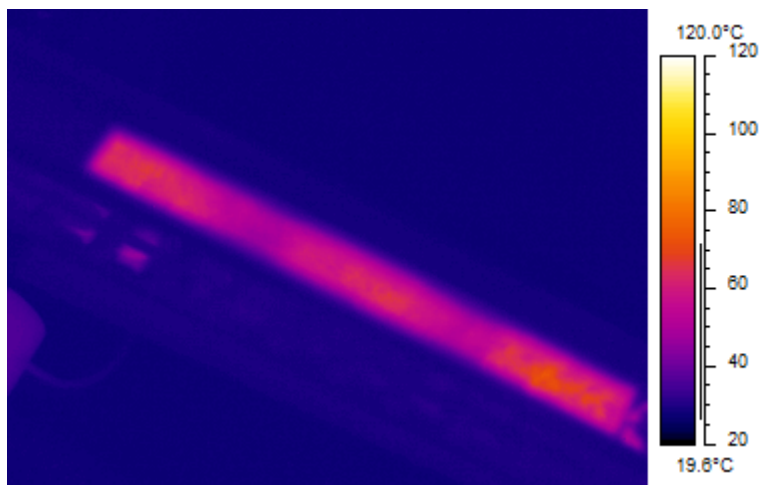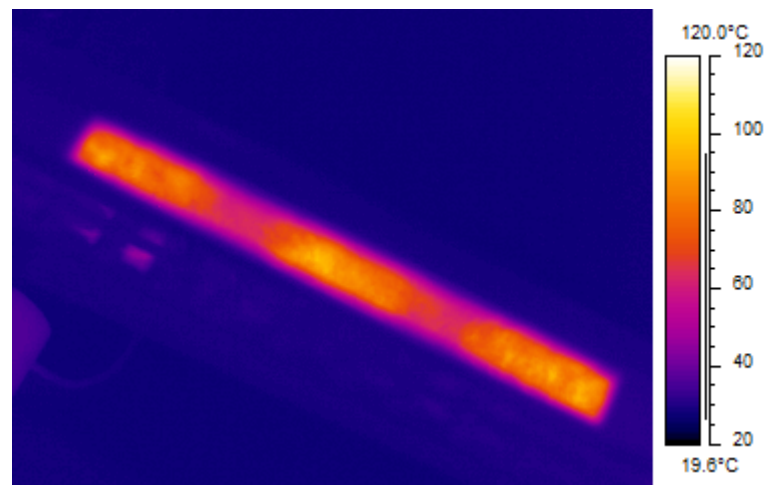
a.   200 W, 28 s

b. 300 W, 28 s

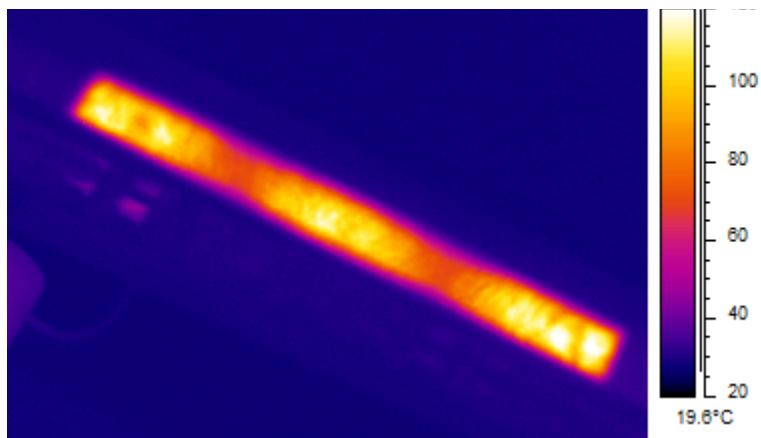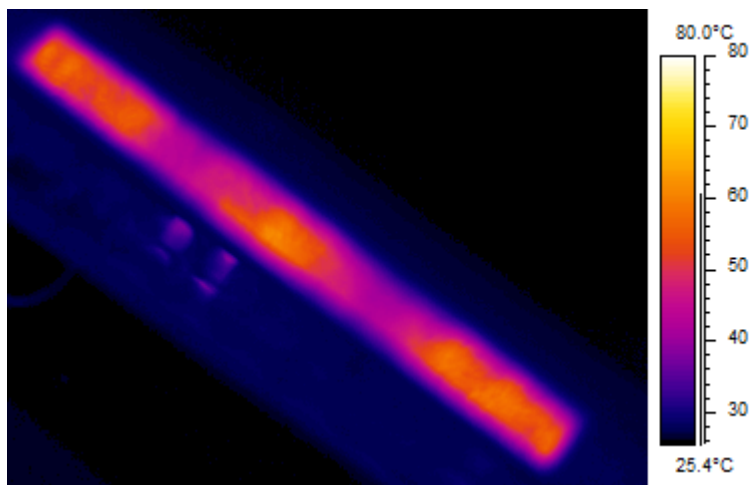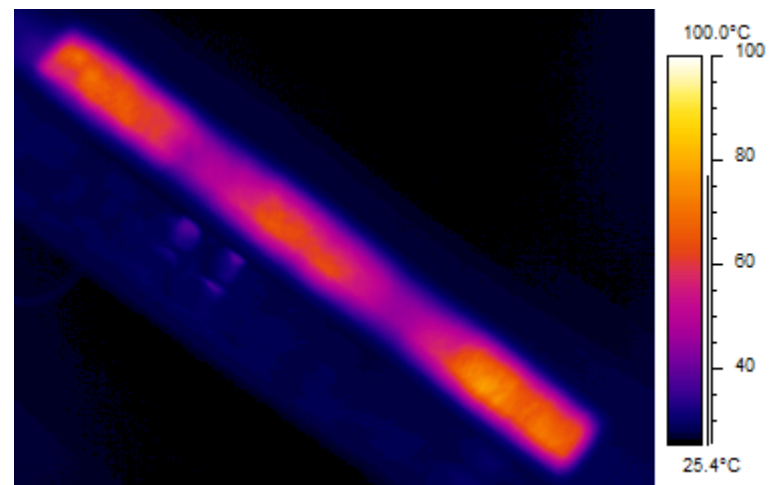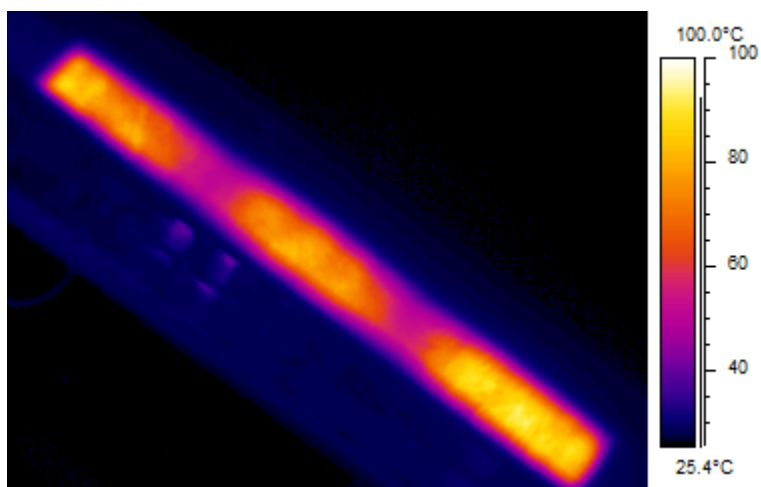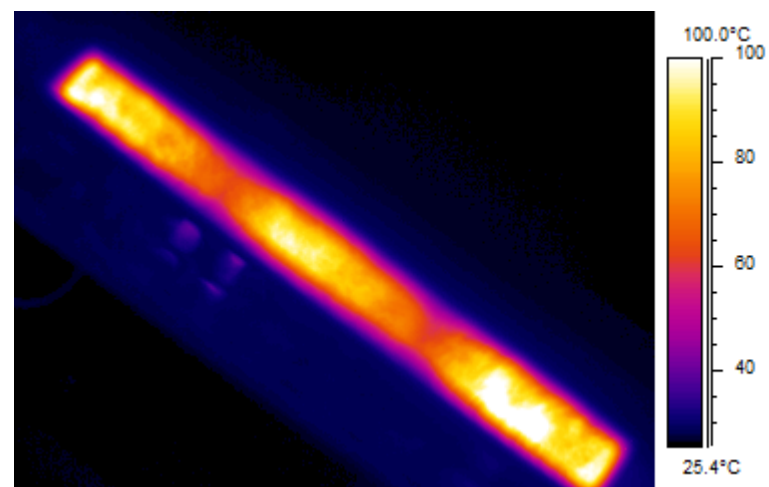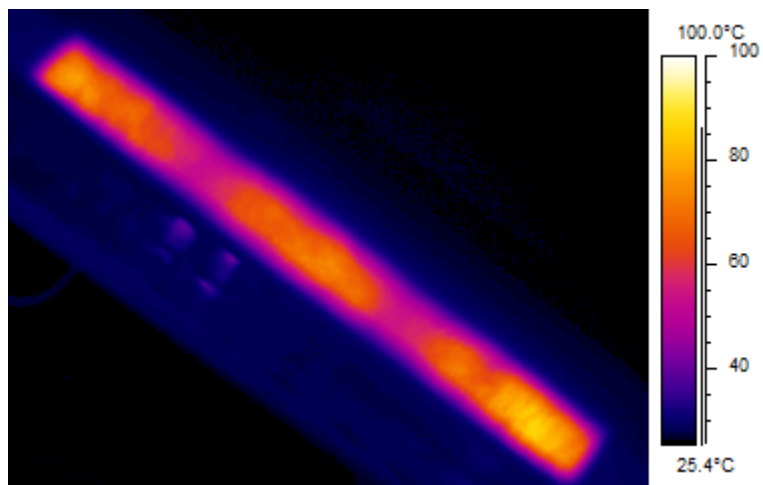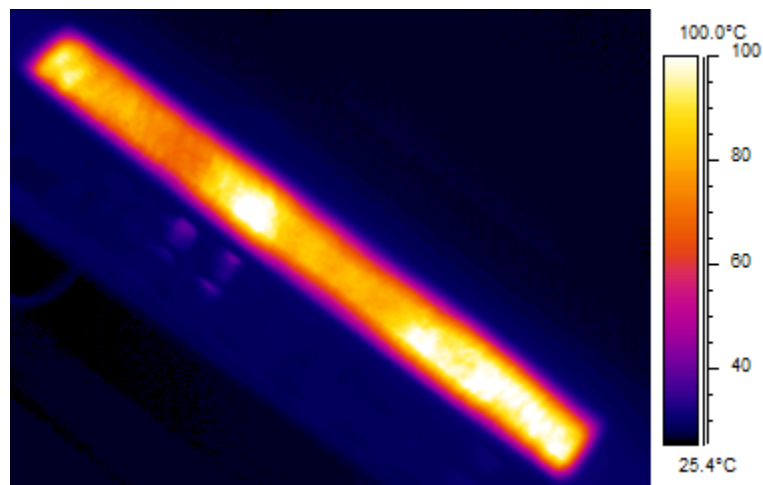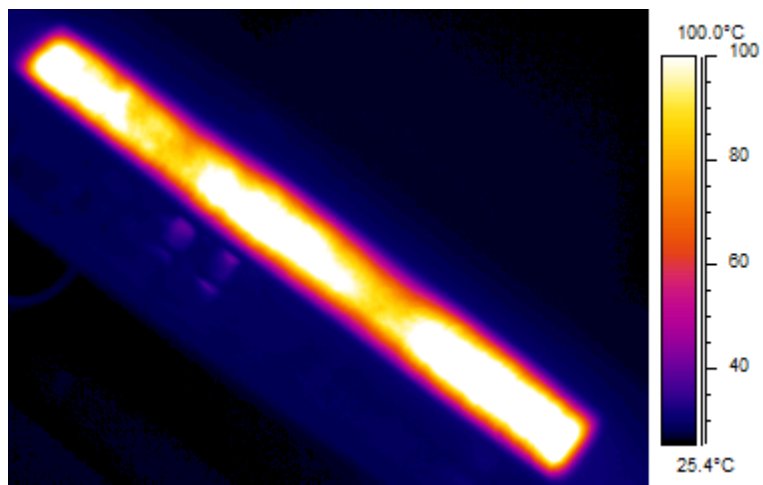b.   400 W, 28 s

d. 500 W, 28 s

e. 200 W, 56 s

f. 300 W, 56 s

g. 400 W, 56 s

Figure 24. Thermal images of rye at different combinations of microwave powers and exposure times

4.4.2 Effect of power and moisture content on $\triangle t$

The $\triangle t$ is the difference between the hottest and the coolest spot in a sample. The $\triangle t$ at 14% MC for 200 W and 28 s exposure time for barley, rye, and oats were in the range of 17.8-21.3, 23.4-26.2, and 7.7-10.3°C, respectively. The $\triangle t$ at 500 W and 28 s exposure time for barley, rye and oats were in the range of 56.8-59.2, 42.5-57.7, and 16.2-20.2°C, respectively. The $\triangle t$ for sunflower seeds at 8% MC for 200 W and 28 s exposure time was in the range of 7.3-8.7° C and for 500 W and 28 s exposure time was in the range of 18.9-21.1°C.

The $\triangle t$ increased as power level or exposure time increased for barley, rye, oats, and sunflower seeds, showing that temperature difference between hot and cold spots increased, as power and exposure time increased for both the cereals and oilseed. Similar results were obtained by Manickavasagan et al. (2006a) when wheat, barley, and canola were treated with microwave energy. They reported that $\triangle t$ was in the range of 55.5 to 67.8C, 57.7 to 69.4°C, and 25.9 to 40.1°C for wheat, barley, and canola, respectively, at a power of 500 W and an exposure time of 28 s.

There was no significant difference in the $\triangle t$ for the 14, 16, and 18% MC rye sample showing that moisture had no significant contribution in the non-uniform temperature distribution in rye. Whereas in oats, the $\triangle t$ was higher at 18 and 16% MC compared to 14% MC and in barley the $\triangle t$ was higher at 14 and 16% MC compared to 18% MC. In sunflower seeds the $\triangle t$ was significantly higher at 12% MC than at 8 and 10% MC.

Comparing barley, rye, oats and sunflower, the $\triangle t$ was higher for barley followed by rye, sunflower and oats. This implies that the non-uniform heating or the

difference between the maximum and minimum temperature was higher in barley and oats has a more uniform temperature distribution compared to others. Oliveira and Franca (2002) in their study on modeling of microwave heating stated that temperature distribution in a microwave-heated sample is dependent on the sample size and shape. Manickavasagan et al. (2006) stated that $\triangle t$ was lower for canola compared to wheat and barley due to the relatively small and spherical shape of the canola seed. The temperature uniformity in food materials was also dependent on product composition (Fakhouri and Ramaswamy 1993); higher fat content improved the temperature uniformity and the product heating rate, whereas, higher protein content resulted in non-uniform temperature distribution. In general, $\triangle t$ was higher at higher power levels and higher exposure times at all moisture contents for all the grains studied.

4.5   Moisture Loss

The moisture loss during microwave heating is an important factor while designing microwave processes for grain or other foods. Uneven heating, such as edge overheating, increases the moisture loss (Ni et al. 1999). The moisture loss of barley, rye, oats and sunflower seeds due to microwave heating for 28 s and 56 s exposure times are shown in Table 23.

The moisture loss for 14% MC barley at 200, 300, 400, and 500 W at 28 s exposure time were 0.6, 0.9, 1.2, and 1.5 percentage points, respectively. The moisture loss at 200, 300, 400, and 500 W for 28 s exposure times were 0.8, 1.2, 1.7, and 2.2 percentage points, respectively for 14% MC rye. As the exposure time was increased to 56 s, the moisture loss of rye increased to 1.4, 2.5, and 3.9 percentage points for 200,

300, and 400 W, respectively. The moisture loss for 14% MC oats at 200, 300, 400, and 500 W were 1.1, 1.6, 2.3, and 3.5 percentage points, respectively. The moisture loss of oats increased to 1.9, 3.2, and 4.5 percentage points as the exposure time was increased. As the power and exposure time were increased, the moisture loss increased in both cereals and oilseed. Analysis of variance shows that moisture content, power, and exposure time had significant effects on the moisture loss. The moisture loss was highest at 18% MC followed by 16% MC and lowest at 14% MC for barley, rye and oats. The moisture loss for sunflower seeds were significantly highest at 12% MC followed by 10% and lowest at 8% MC. These results indicate that, higher the initial moisture content, higher the moisture loss in both cereals and oilseed.

Comparing the moisture loss in barley, rye, oats, and sunflower seeds, the moisture loss was highest in oats followed by sunflower seeds, rye and lowest in barley. The relation between $\triangle t$ and moisture loss was inverse. Barley had the highest $\triangle t$ and lowest moisture loss whereas oats had the lowest $\triangle t$ and highest moisture loss among the crops studied. This shows that when $\triangle t$ was higher, non-uniform heating was prominent resulting in hot and cool spots and hence lower moisture loss. Whereas, when the $\triangle t$ was lower, more uniform heating has occurred as a result the moisture loss was higher.

Table 23. Average moisture loss (in percentage points) ± SE of barley, rye, oats, and sunflower seeds heated with microwave energy at different moisture contents, power levels, and exposure times.

Grain	Moisture content (%)	Exposure time						
		28 s				56 s		
					Power			
		200 W	300 W	400 W	500 W	200 W	300 W	400 W
Barley	14	0.6 ± 0.1	0.9 ± 0.1	1.2 ± 0.1	1.5±0.1	1.0 ± 0	1.6 ± 0.1	2.3 ± 0.1
	16	0.7 ± 0.1	0.9 ± 0	1.3 ± 0.1	1.7±0.2	1.2 ± 0.1	1.8 ± 0.1	2.6 ± 0.1
	18	0.7 ± 0	1.0 ± 0.1	1.3 ± 0.1	2.0±0	1.1 ± 0.1	1.9 ± 0.1	3.0 ± 0.1
Rye	14	0.8 ± 0.2	1.2 ± 0.1	1.7 ± 0.1	2. 2± 0.1	1.4 ± 0.1	2.5 ± 0.1	3.9 ± 0.1
	16	0.9 ± 0	1.3 ± 0	1.9 ± 0	2.5 ± 0.1	1.8 ± 0	2.7 ± 0.1	4.3 ± 0.2
	18	1.0 ± 0	1.6 ± 0.1	2.1 ± 0.1	2.8 ± 0.1	2.0 ± 0	3.1 ± 0	4.6 ± 0.1
Oats	14	1.1 ± 0.1	1.6 ± 0.1	2.3 ± 0.1	3.5 ± 0.1	1.9 ± 0.1	3.2 ± 0.3	4.5 ± 0.3
	16	1.6 ± 0.1	2.4 ± 0	3.1 ± 0.2	3.9 ± 0.1	2.7 ± 0.1	4.2 ± 0.1	6.0 ± 0.1
	18	1.8 ± 0.2	2.6 ± 0.1	3.8 ± 0.1	4.3 ± 0.1	3.7 ± 0.3	5.4 ± 0	7.4 ± 0.3
Sunflower	8	1.2 ± 0.2	1.5 ± 0.0	1.9 ± 0.1	2.3 ± 0.1	1.4 ± 0.1	2.7 ± 0.1	3.6 ± 0.0
	10	1.4 ± 0.1	1.9 ± 0.0	2.5 ± 0.1	2.9 ± 0.1	1.7 ± 0.0	3.0 ± 0.1	3.4 ± 0.1
	12	2.0 ± 0.0	3.0 ± 0.0	3.5 ± 0.0	4.1 ± 0.0	3.0 ± 0.1	4.2 ± 0.1	5.5 ± 0.1

Higher moisture loss in oats at all the power levels and exposure times may be because more water may be held in the husk of oats, which is lost faster during heating. Possibly because of the higher moisture loss, the temperature of the oats is lower than the rye.

When the moisture loss of grain corresponding to complete kill of insects were analyzed, moisture loss in barley was around 1.5-3.0 percentage points. In rye, the moisture loss corresponding to one hundred percent mortality of insects was between 2.2-4.6 percentage points. Hamid et al. (1968) conducted experiments to control insects using microwave energy and their study showed that the moisture content in wheat drops by less than one percentage points for exposure times greater than that corresponding to total mortality of the three wheat insects. Boulanger et al. (1969) achieved a moisture reduction around 1-3 percentage points in their experiments. Vadivambal et al. (2007b) had shown that the moisture content of wheat was reduced by two percentage points, while one hundred percent mortality of stored-grain insects was achieved using microwave energy.

4.6   Cost Economics for Microwave Disinfestation

When any new technology or process is introduced, the major concern is the cost effectiveness compared to the existing methods. The cost of microwave treatment was one of the major drawbacks that microwave processing has not yet made a major breakthrough (Mullin 1995). The cost of microwave treatment of grain is too high to justify dielectric heating (Nelson 1996).

Although, microwave processing was seen as a method which involves higher cost, major improvements are being made in the microwave equipment and processing

conditions. Also, microwave processing has energy savings and space saving benefits because energy is not expended in heating the walls of the apparatus or the environment. The increase in processing rate, makes it feasible to design more compact equipment and hence, the plant capacity could be increased several fold without additional building space. Improvements in microwave generator efficiency have resulted in decrease in capital costs (Mullin 1995). Wang and Tang (2001) and Wang et al. (2007) analyzed the cost of RF and microwave treatment with chemical fumigation treatment and concluded that electrical cost of RF treatment was comparable to that of fumigation for commercial in-shell walnuts.

4.6.1 Cost calculation for disinfestations using pilot-scale microwave dryer

To disinfest 1 t of wheat (1000 kg)

At 3 m/min, average flow rate = 40 kg/h

To disinfest 1 t, at 40 kg/h = 1000/40 = 25 h

Complete kill of all insect species achieved at 500 W (speed = 3m/min)

Total power required to treat 1 t of wheat= 500 W x 25 h = 12,500 W h = 12.5 kWh

Cost of electricity: 6 cents/kWh (Manitoba Hydro 2008)

Total cost of electricity to disinfest 1 t of wheat = 12.5 x 0.06 = $ 0.75 / t

Hence, excluding initial investment, the operational cost to disinfest 1 t of wheat using a pilot-scale microwave dryer is $ 0.75 / t

Rate of malathion required/1000 kg of wheat = 415 g / 1000 kg

Cost of Malathion to kill insects in wheat = $ 1.19/1000 kg   (Saskatchewan Ministry of Agriculture 2008).

Hence energy (operational) cost of microwave disinfestation is only 63 % of chemical costs.

Langlinais (1989) studied the economics of controlling weevils in rice using microwave energy and compared it to the cost of fumigation. The study revealed that fumigation cost for rice milling and packaging to be around $ 0.1128/CWT (one hundred pounds). Disinfestation studies were conducted on rice weevils with a portable microwave unit and concluded that microwave treatment dosage levels above 0.0036 kWh/kg (0.009 kWh/lb) and grain temperatures above 34.6^{o}C resulted in complete destruction of live insects and eggs. The microwave energy costs were calculated to be approximately 6.3 cents/CWT as compared to 11 cents/CWT for fumigation costs.

Halverson et al. (1999) calculated the total cost of electrical energy as $ 0.67/ t for the control of stored-product insects using extremely high frequency. They estimated that the capital, fixed, and operating cost may increase the total cost to be around $ 0.97/ t. The estimated cost of installation of RF device is $ 40,000 and the treatment cost for 1 t of grain is about $ 2 (Zajtzev 2001).

The energy cost for disinfestation using fluidized bed is $ 1.43/t, spouted bed is 1.30/t and pneumatic conveyor is 1.50/t (Qaisrani and Banks 2000). Although the initial investment in microwave disinfestation is higher, microwave disinfestation is economic in terms of energy cost. Teitel et al. (2000) developed a method of microwave heating for greenhouses. The results of their study showed that only 55% of energy was required for microwave heating of greenhouses as compared with hot-air heating systems (Qaisrani and Banks 2000).

The cost factors change with time and hence looking into the future, microwave disinfestation seems to have a high potential to be used in stored-grain.

4.6.2 Microwave disinfestation: Would it be a reality

The disinfestations study conducted on three different grains infested with major stored-grain insects has shown that, one hundred percent mortality could be achieved using microwave energy. Since the germination of the microwave treated seeds were significantly lowered, the microwave-treated grain could not be used for seed purposes. The analysis of quality characteristics of the grain has shown that the end use quality of grain was not affected. Another concern for microwave disinfestations is that post-treatment sanitation practices should have to be followed to prevent re-infestation because when treated with electromagnetic radiation, there is no residual protection to the stored-grain (Nelson 1972).

The most important key element in the development of an acceptable alternative insect control method using microwave energy is to identify a balance between minimized thermal impact on the product quality and complete killing of the insect population. To achieve a balance between complete eradication of the insects and to maintain the product quality, thorough knowledge of the dielectric properties and tolerance of the material being treated and thermal resistance of the insect species should be known. It is also important to transfer the technology from small scale laboratory models to actual large scale commercial implementation. Based on the results of the disinfestation study conducted, it seems that microwave disinfestation could have a great potential to be an alternative for chemical disinfestation methods.

5. CONCLUSIONS

1. One hundred percent mortality of the adults of three species of insects in barley and wheat and *T. castaneum* and *C. ferrugineus* in rye was achieved at 500 W for 28 s exposure time and at 400 W for 56 s exposure time whereas complete mortality of *S. granarius* in rye was achieved at the combination of 400 W, 28 s or at 300 W, 56 s.

2. Among the mortality of life stages in barley and rye, the *T. castaneum* eggs were the most susceptible to microwave energy and adults were the least susceptible to microwave energy with no significant difference between larvae and pupae.

3. Among the mortality of life stages of *T. castaneum* in wheat, the eggs were the most susceptible to microwave energy followed by larvae; adults and pupae were the least susceptible with no significant difference between the two.

4. The average temperatures of wheat, barley, and rye at 500 W and 28 s were around 80, 71 and 82°C, respectively. The average temperatures of wheat, barley, and rye at 400 W and 56 s were around 93, 89, and 99°C, respectively.

5. Mortality was significantly higher at higher exposure time and power levels.

6. There was no significant difference in the mortality of the adult insects of three species and larval stages of *T. castaneum* in 14, 16, and 18% MC barley but there was a significant difference in the mortality of eggs and pupae.

7. There was no significant difference in the mortality of the adult insects of three species and life stages of *T. castaneum* and *S. granarius* in rye at 14, 16, and 18% MC.

8. There was no significant difference in the mortality of *T. castaneum* eggs and adults at 14, 16, or 18% MC wheat whereas the mortality of *T. castaneum* larvae, pupae, *C. ferrugineus* and *S. granarius* adults were significantly higher at 18 and 16% MC compared to 14% MC wheat.

9. Germination of wheat, barley and rye decreased significantly with increase in power level or exposure time or both.

10. There was no significant difference in the grain protein of the control and microwave treated barley samples at both combinations of microwave power and exposure time. But for alpha amylase, diastatic power, soluble protein, density, and viscosity there was no significant difference in the control sample and the sample treated at 500 W, 28 s whereas there was a significant decrease in the quality of samples treated at 400 W, 56 s.

11. There was no significant difference in the flour protein, falling number, SDS sedimentation, dough mixing properties, and loaf volume of bread of microwave-heated and control samples of rye but the flour yield of microwave treated rye was significantly reduced.

12. There was no significant difference in the grain protein, flour protein, flour yield, flour ash, farinograph parameters and loaf volume of microwave treated and control wheat.

13. Non-uniform temperature distribution was observed during microwave heating of barley, rye, oats and sunflower seeds with most non-uniform heating observed in rye.

14. When complete mortality of stored-grain insects was achieved at 500 W and 28 s, the moisture loss was around 1.9, 2.5 and 2.0 percentage points for barley, rye, and wheat, respectively.

15. When complete mortality of stored-grain insects was achieved at 400 W and 56 s, the moisture loss was around 2.6, 4.2 and 3.0 percentage points for barley, rye, and wheat, respectively.

6. RECOMMENDATIONS FOR FUTURE RESEARCH

1. Determine the mortality of the three insect species at a higher speed by increasing the speed of the conveyor to asses if lower exposure times could improve the germination of the seeds.

2. Since only major stored-grain insect pests have been studied, other stored-grain insect mortalities could be studied.

3. Determine the mortality of storage pests in oilseeds and pulses using microwave energy and analyze their quality characteristics.

4. Determine the mortality of the stored-grain insects using radio-frequency heating and compare the results from microwave and radio-frequency heating.

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