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Development Of A One Pass Microwave Heating Technology For Rice Drying And Decontamination

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Development Of A One Pass Microwave Heating Technology For Rice Drying And Decontamination

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by

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ABSTRACT

An industrial microwave (MW) system operating at 915 MHz frequency was used to dry high moisture content (MC) (23% to 24% wet basis) medium-grain rough rice samples (cv. Jupiter). The rice beds were contained in a modified tray that accommodated up to 9 kg of rice separated by thin fiberglass mesh in 3 kg increments. Each layer of rice was fitted with fiber optic sensors connected to a real time data logger during MW treatments. It was determined that drying rice to a MC of 14% to 16% was feasible with the application of MW specific energy at 600 kJ/kg-grain followed by 4 hours of tempering at 60°C. Resulting head rice yield (HRY) was not significantly different from that of control samples dried gently using natural air. Increasing MW specific energy resulted in an increase in rice surface lipid content (SLC), rice protein content, final and peak viscosities. Total color differences (TCD) decreased with increasing MW specific energies. Increasing MW specific energy resulted in decreases in rice microbial loads. At the highest specific energy of 900 kJ/kg-grain, the reduction of the aerobic bacterial and aflatoxigenic fungal loads was 4.56 and 2.93 log CFU/g-grain, respectively. Varying rice bed thickness had significant effects ($p < 0.05$) on rice final surface temperature, HRY, milled rice yield (MRY) and aerobic bacteria count. Highest MRY and HRY were observed at the top and middle layer with bottom layer having the smallest. Similar trends were observed for the aerobic bacteria response. Optimization analyses suggest that a power of 10.00 kW and a heating duration of 6.00 min are preferred for optimum aerobic bacteria and A. flavus mold count, MRY, HRY and FMC of rice beds of equivalent bed thickness of 15 cm. These factor levels equate to a specific energy of 400.00 kJ/kg-grain. At these parameter settings, a ton of freshly harvested rice the energy required to dry a ton of freshly harvested rough rice was 111.11 kWh. Drying at this MW specific energy for batch processes will cost \$9.88 per ton of rice.

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INTRODUCTION

Rice (*Oryza sativa L.)* is the second highest produced agricultural product worldwide just after maize. Since maize is mostly grown for grain feed and fodder for livestock, purposes other than human consumption, rice is arguably one of the most important grains about human nutrition and caloric intake (Food and Agricultural Organization of the United Nations, 2004). More than 3.5 billion people depend on rice for more than 20% of their daily calories. In 2009, rice provided 19% of global human per capita energy and 13% of per capita protein (Maclean, 2002). By contrast, maize only provides 5% of global human per capita energy and less than 10% of per capita protein.

Of all the rice-producing states in America, Arkansas continues to be the largest regarding acres of rice planted as well as production. In 2003, Arkansas had 1,466,600 acres planted with rice Arkansas is only rivaled by California and Louisiana, which produced only 509,000 and 455,000 acres of rice in the same year, respectively. The annual Arkansas rice crop is extremely integral to the state's economy as it contributes more than $6 billion to the state's economy every year and accounts for over 25,000 jobs (Arkansas Rice, 2011). The five largest rice-producing counties in the state of Arkansas were Poinsett (134,944 harvested acreage), Arkansas (117,675 harvested acreage), Cross (106,254 harvested acreage), Jackson (101,762 harvested acreage), and Lawrence (99,480 harvested acreage) in the year 2003, which represented nearly 36% of the state's total land acreage under rice production (Wilson et al., 2007).

One of the most important economic considerations in rice processing is the preventing of rice kernel fissuring. A Rice kernel loses half of its value after being broken; this is why farmers harvest their rice at high moisture contents (MC) to prevent fissuring of the kernels in the field. The MC of freshly harvest rice is usually between 18% and 24 % wet basis (w.b). Rice at such high MCs is susceptible to contamination by a vast plethora of microorganism including fungi and spoilage bacteria. It is, therefore, necessary for farmers to quickly reduce the rice MC to a level that is safe for long-term storage, which is typically around 12% w.b (Perdon et al. 2000). The drying is necessary to minimize any quality deterioration from spoilage and mold growth during storage (Sadaka and Hardke, 2015). However, inappropriate postharvest management practices, specifically at the drying and milling stages, can lead to quality losses from microbial contamination and broken kernels as a result of the formation of fissures.

Temperature and MC gradients that develop during convective heated- and natural-air drying of rice may also cause differential stresses within the rice leading to kernel fissuring and an overall weakening of the rice mechanical properties. The formation of fissures on a rice kernel makes it more susceptible to breakage during subsequent hulling and milling processes. Breakage as a result of fissure formation negatively impacts the rice milling yield which, to a great part, is quantified by the HRY (HRY) (USDA-GIPSA, 2010 and Kunze, 1979). HRY comprises milled rice kernels that are at least three-fourths of the original kernel length; HRY represents the mass percentage of a rough rice lot that remains as head rice after milling. Preventing HRY reduction during drying is very critical and bears significant economic importance to the rice industry (Cnossen and Siebenmorgen, 2000).

In addition to the economic need for an effective drying method for rough rice, there also exists a humanitarian need. As earth's population is steadily increasing the demand for rice will only grow. It is estimated that approximately 2000 million metric tons of rice are needed to meet the projected demands of a growing population by 2030 (FAO, 2002). Therefore, considerable increases in yield are required over this century to continue feeding the world’s growing population. Meeting this 35% increase in demand will require considerable increases in yield and thusly-significant improvements in the life cycle of rice production. However, at present, there is very limited potential to increase arable land. The challenge, therefore, exists in feeding this growing population using less land and water. The solution to this dilemma will be through ensuring that all the agricultural resources and energy inputs employed are used as efficiently as possible by maximizing agricultural production on existing farmland (Daily, & Ehrlich, 1992). An additional challenge exists as rice consumers represent one of the most demanding cereal markets with regards to product quality (IRRI, 2002; Coats, 2003, Ondier et al. 2010). Therefore any innovation regarding rice drying practices must be able to produce a product that is, if not, at par with current rice quality or better.

As an alternative to conventional rice drying methods, which rely on conduction and convection from hot surfaces to deliver energy into the product leading to MC and temperature gradients, a phenomenon known as volumetric heating as accorded by microwaves will be explored for drying rice.

LITERATURE REVIEW

Rice drying at the industrial level in the state of Arkansas is done in either one of two main ways, convective heated air or natural air in-bin drying, both of which are accomplished by blowing large volumes of dry air through the grain. The fundamental difference between natural air in-bin drying and convectively heated air drying is the temperature at which drying is done and consequently the drying duration. Convective heated air drying employs high temperatures for quick drying and allows for suitable drying air conditions to be set. Mechanisms inside the dryer allow for grain re-circulation giving rise to uniformly dried grains, and the ability to control the air conditions (temperature, volumetric flow rate, and relative humidity) allows the user to maximize the drying rate at the same time reducing overheating or over-drying. The drying process is complete in a matter of days to weeks depending on the amount of grain to be dried. However, this process creates temperature gradients thus reducing the milling quality. Additionally, increases in drying air temperature enhance the water desorption rate from the kernel surface, however, this results in a greater MC gradient inside the kernel which then leads to the formation of fissures.

Natural air in-bin drying methods, as the name implies, involve the use of either unheated natural air or air slightly heated at low temperatures usually less than 10°F to dry grain in bins. The principle of this drying method is by controlling the relative humidity (RH) rather than the temperature of the drying air so that all grain layers in the deep bed reach equilibrium moisture content. Natural air, in-bin drying employs a slow and gentle drying process that maintains the grain quality with low energy requirements. The drawback of using this method is that it can take anywhere from weeks to months depending on the amount of grain to be dried and can lead to bottlenecks at the most crucial stages of postharvest processing. In other words, natural air in-bin methods provide superior milling quality but the drying period takes longer.

The issue with these two drying methods is that they require multiple passes to circumvent seemingly unavoidable temperature and MC gradients that eventually lead to an overall weakening of the rice kernel's mechanical properties. Solutions were found in drying rice in multiple stages or passes to maintain milling quality. These solutions, however, are often very energy-intensive and time-consuming. Low drying rates can negatively affect the rice milling industry by creating bottlenecks as a result of the limited drying capacity, especially at peak harvest times (Berruto et al. 2011).

Rice millers, employ efforts to avoid fissure formation as a result of MC and temperature gradients by incorporating a tempering step**.** The process of tempering allows for the slowing down of evaporation from the surface of the kernel and the continuation of diffusion of moisture from the center outwards. As a result, any MC or temperature gradients in the grain eventually subside establishing an equilibration of moisture from the center to the surface of the grain thus reducing fissure formation.

There are two types of fissures observed in rice kernels; desorption and adsorption fissures. Rice kernels are hygroscopic and hence adsorb or desorb moisture depending on the environment. MC gradients that develop within rice grains due to the moisture adsorption/desorption phenomenon may lead to the development of internal stresses. These internal stresses along with the external stresses from the milling process cause rice kernels to fissure.

Adsorption fissures occur when the low-moisture grain reabsorbs moisture from any source to which it is exposed. Moisture adsorption can happen in the field, in the holding bin of a combine, ahead of the drying front in a deep bed dryer, or wherever low moisture grains are exposed to a humid environment (Kunze and Prasad, 1978). Moisture adsorbed through the grain surface causes the starch cells to expand and produce compressive stresses. Since the grain is a "free body", compressive stresses are countered by equal but opposite tensile stresses at the grain center. When the compressive stresses at the surface exceed the tensile strength of the grain at its center, a fissure develops.

By contrast, desorption forces occur when the grain surface receives moisture from the interior and expands while the grain interior loses moisture and contracts. As this combination of stresses (compressive at the surface and tensile at the center) develop with time, the grain fails in tension by pulling itself apart at its center (Kunze, 2008).

Fissures (whether formed by adsorption or desorption) affect the milling quality of the rice by reducing the rice kernel's ability to withstand the processes of hulling and bran removal without breaking apart. Fissured kernels negatively affect rice millers because they are more susceptible to HRY reductions and decreased rates of seed germination as well as insect and microbial attacks; microorganisms may pose the threat of mycotoxin contamination.

The head rice yield (HRY) is often the most important quality parameter to rice millers since the HRY is linked to payment received for rice delivered at milling facilities. Under ideal conditions, a perfect HRY recovery would be about 70% of the total rough rice produced after the rice hulls and bran are removed. However, with current conventional rice drying methods, HRY recovery averages only about 58%, and can be even lower depending on other pre-harvest and post-harvest factors (USDA, 2014; Atungulu et al., 2015).

Mycotoxins are toxic secondary metabolites produced by species of filamentous fungi often found growing on high MC grains before harvest or in storage (Hammond et al. 2004). Mycotoxins are well known for their deleterious effects to human and animal health (Probst, Njapau, & Cotty, 2007; Reddy & Raghavender, 2007). Mycotoxins have the potential for both acute and chronic health effects in animals and humans via ingestion, skin contact, and inhalation (Boonen, J. et al. 2012). These toxins can enter the blood stream and lymphatic system; they inhibit protein synthesis, damage macrophage systems, inhibit particle clearance of the lung, and increase sensitivity to bacterial endotoxin (Godish, 2001).

Harvested grains harbor various species of fungi including *Aspergillus flavus* (CDC, 2012); however, conventional drying methods are not metered to inactivate the heat-tolerant, aflatoxin-producing fungal spores. Such spores typically survive conventional heat treatments. As a result, here prevalence on grain resulting in the formation of toxins such as aflatoxins remains a large threat to rice consumers.

As the demand for rice continues to increase to meet earths growing population, there is a critical need to improve current drying processes to minimize revenue losses related to fissuring and aflatoxin contamination (FAOSTAT, 2007; Ricestat, 2007). This thesis research aims to address these concerns by developing a one-pass drying technology using a 915 MHZ industrial microwave to achieve rapid one-pass drying of rough rice with significantly better HRY and improved rice safety than air-drying.

Microwaves are electromagnetic radiations with wavelengths ranging from 1 mm to 1000 mm in free space with a frequency between 300 GHz to 300 MHz, respectively. In microwave drying, heat is generated by directly transforming electromagnetic energy into molecular kinetic energy causing heat to be generated from within the material to be dried. The relatively high-energy flux and volumetric heating phenomenon resulting from microwave heating hold the potential to dry rough rice with reduced inter-kernel rice temperature and MC gradients thereby minimizing rice fissuring and maintaining milled rice quality and improved HRY. Also, the high and rapid heat flux accorded by microwave heating holds the potential to inactivate harmful microorganisms especially aflatoxigenic mold spores such as *A. flavus* thus reducing incidences of aflatoxin contamination and spoilage of rice.

Microwave heating is fundamentally different from conventional heating. During microwave heating, heat is evenly distributed throughout the entire volume of a flowing liquid, suspension or semi-solid. This process is known as microwave volumetric heating. This is in contrast to traditional thermal processing, which relies on conduction and convection from hot surfaces to deliver energy into the product. The heating is very rapid as the material is heated by energy conversion rather than by energy transfer as with conventional techniques. Microwave heating is a function of the material being processed, and there is almost 100% conversion of electromagnetic energy into heat, largely within the sample itself, unlike with conventional heating where there are significant thermal energy losses.

Microwave processing has found various applications for home cooking and are widely used in many industrial applications including meat tempering, potato chips processing and bacon cooking (Gamble & Rice, 1987) blanching of fruits and vegetables (Boyes et al. 1997), drying of fruits, vegetables and dairy products (Funebo and Ohlsson 1998; Mullin 1995), stabilization of rice bran (Tao et al. 1993), enzyme inactivation in cereal grains (Yadav et al. 2010), control of enzymatic browning in frozen chapattis (Yadav et al. 2008) and pre-treatment of oilseeds for efficient oil extraction (Irfan and Pawelzik 1999). The use of microwaves in the grain processing industry has also found a potential for killing insects (Wang et al. 2003, Antic and Hill 2003).

At present, there is no commercial use of microwave technology for rice drying. Most of the reports found in literature agree to the fact that microwave treatment accords high thermal efficiency and shorter drying durations compared to conventional hot air drying (Prabhanjan et al., 1995; Maskan, 2001; Kaasová et al., 2002; Vadivambal and Jayas, 2007). Some lab based reports indicated that compared to hot air drying, microwave heating in the range of 90 W to 500 W with drying durations in the range of 6 to 56 minutes resulted in no changes in physical and chemical characteristics of the rice (Kaasová et al., 2002). Although microwave heating is expected to be volumetric, introducing a tempering stage to rice dried at elevated temperatures may aid with the stepwise cooling and moisture redistribution within kernels, which will ultimately improve the milling quality of dried rice.

Microwaves have also been documented to be beneficial for the bacterial decontamination of food (Latimer & Matsen, 1977; Herzallah et al. 2008). Lab scale tests conducted using microwave radiation as a method for bacterial decontamination has concluded that microwave radiation proved successful in the elimination of clinical isolates of *E. coli, P. mirabilis, P. vulgaris, P. aeruginosa, S. marcescens, S. aureus, S. epidermidis* and *enterococcus* after a 5 min exposure. Additionally, regrowth of these bacteria was stunted 24 hours after treatment. Samples that were not treated with microwave heating showed regrowth after 24 h (Latimer & Matsen, 1977). Based on the literature as mentioned earlier it is anticipated that the high-energy fluxes afforded by microwaves have the potential to decontaminate freshly harvested rough rice from similar heat-tolerant bacteria and mycotoxin producing mold. At present, the energy fluxes associated with convectively heated air has proven to not be sufficient in doing so (Wilson, 2016).

HYPOTHESIS

Based on the literature review, the central hypotheses for this study are that;

1) The volumetric heating associated with microwave technology will help reduce MC and temperature gradients within individual rice kernels resulting in better HRYs compared to those achieved with conventional air drying methods;

2) The high heat fluxes associated with the MW heating will lead to one-pass drying of rough rice, from harvest MCs to safe storage MCs (12.5%);

3) The attainment of the targeted MC reduction will have negligible effects on rice physicochemical properties; and

4) There is a simultaneous decontamination of rough rice kernels from harmful mold and spoilage bacteria during the MW drying as a result of the associated high heat fluxes.

OBJECTIVES

At present, there is no commercial use of microwave technology for rice drying. Therefore the overall purpose of this study was to develop a microwave heating technology that can sufficiently dry rough rice kernels in one pass using a 915-MHz industrial microwave system. To successfully implement microwave technology for rice drying, there is need to optimize the process such that rice milling yield is improved and the rice nutritional and functional quality indices are maintained. As a result, the objectives of this study were three-fold:

1. Determine the effectiveness of a one-pass microwave heating treatment to dry rough rice to achieve safe storage MC without negatively impacting the milled rice quality, especially the HRY.

At the industrial level, the demand for high drying throughputs necessitates the need to investigate the implications of microwave power and heating duration on the quality of rice at various rice bed thicknesses. To optimize the throughput during rice drying with microwave in an industrial scenario, producers need to maximize the thickness of the rice bed. Therefore, alongside objective 1, the following specific objectives were also considered:

2. Determine the maximum rice bed thickness that could be used at different power levels and heating duration combinations to achieve:
    a. Uniform MC removal throughout the rice bed thickness
    b. Optimum rice milling yield concerning HRY.
    c. Microbial load reduction, especially the aflatoxin producing *A. flavus* mold.
3. Determine the implications of microwave drying of rice on the physiochemical characteristics of milled rice in terms of surface lipid content, protein content, color parameters and pasting properties.

The rice samples procured for this thesis research were freshly harvested medium grain rice of cultivars: Jupiter from Newport, Ark. and CL271 from Cash, Arkansas; and the rice were grown in commercial fields in the 2014 and 2016 rice harvesting seasons, respectively. The samples were at initial MC of 23% to 24% (w.b) at harvest.

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Assessment of The Feasibility Of One-Pass Drying of Rough Rice With An Industrial Microwave System on Milling Quality

ABSTRACT

The volumetric heating phenomenon of microwaves has the potential to dry rough rice rapidly with reduced inter-kernel rice temperature and moisture content (MC) gradients, thereby minimizing rice fissuring and maintaining milled rice quality. The objective of this study was to determine the feasibility of using an industrial-type microwave heating system to achieve one-pass rice drying with minimum implications on rice milling quality, especially the head rice yield. Freshly-harvested, medium-grain rice samples (cv. Jupiter) at initial moisture content (IMC) of 23% to 24% (wet basis) were heated using an industrial microwave system with a frequency of 915 MHz. The equipment was set to transmit energy to rice at power levels of 2, 5, 10 and 15 kW for durations of 1, 2, 3 and 4 minutes. The effects of natural air and forced air cooling and tempering of the rice after microwave treatments on moisture removal and head rice yield reduction were determined. The goodness of fit of linear, quadratic and cubic models to describe the kinetics of the head rice yield reduction due to the treatments was determined. Results showed that microwave treatments at power levels of 5 kW and 15 kW for 4 and 1 minutes, respectively, bore much promise in decreasing the rice MC to 13.0% (wet basis) for a rice bed thickness at 0.015 m. Supplying microwave energy of up to 600 kJ/kg-grain followed by 4 h of tempering at 60°C dried the rice to final MCs of 14% to 16%, depending on rate of energy supply, with head rice yield not significantly ($p > 0.001$) different from that of rice dried with natural air (25°C and relative humidity of 65%). Without a tempering step, microwave heating with energy input exceeding 300 kJ/kg of the rice resulted in head rice yield lower than that of *the control samples. The cubic model best fitted the correlation of specific energy input and the head rice yield with Root Mean Square Errors (RMSE) of 1.19%, 4.70% and 5.56% and coefficient of determination (R^2) of 0.597, 0.911, and 0.889 for treatment with microwave heating followed by tempering and natural air cooling, microwave heating followed by forced air cooling, and microwave heating followed by natural air cooling, respectively. Optimizing the microwave drying technology to achieve commercially viable throughput for rapid drying of high MC rice would benefit the rice industry in minimizing head rice yield reduction.*

Keywords: Rice Drying, Milling yield, Head rice yield, Microwave heating, Tempering

INTRODUCTION

Temperature and moisture content (MC) gradients, which develop during convective heated- and natural-air drying of rice, may cause differential stresses within the rice leading to kernel fissuring and an overall weakening of mechanical properties, which negatively impact the rice milling yield. The rice milling yield, to a significant part, is quantified by the head rice yield (HRY) (USDA-GIPSA 2010). Head rice yield comprises milled rice kernels that are at least three-fourths of the original core length; HRY represents the mass percentage of a rough rice lot that remains as head rice after milling. Preventing HRY reduction during drying is very critical and bears significant economic importance to the rice industry (Cnossen and Siebenmorgen, 2000). This study hypothesized that the volumetric heating phenomenon that is accorded by microwave heating might reduce tensile stresses caused by temperature and MC gradients within the rice kernel and potentially improve the rice milling yield. Also, the high and rapid heat flux accorded by microwave heating may achieve one-pass drying of high-MC rice to storage MC with minimized quality reduction.

Microwave heating is fundamentally different from conventional heating. Microwaves are electromagnetic radiations with wavelengths ranging from 1 mm to 1000 mm in free space with a frequency between 300 GHz to 300 MHz, respectively. Today, microwave at the 2.45 GHz frequency are used almost universally for industrial and scientific applications. In the microwave process, the heat is generated internally within the material instead of originating from external sources, and hence there is an inverse heating profile. The heating is very rapid as the material is heated by energy conversion rather than by heat transfer, which occurs in conventional techniques. Microwave heating is a function of the material being processed, and there is almost 100% conversion of electromagnetic energy into heat, largely within the sample itself, unlike with conventional heating where there are significant thermal energy losses.

Microwave heating has many advantages over conventional heating methods (Roy and Yang, 1985; Komameni and Roy, 1986; Snyder et al., 1990; Beatty et al., 1992; Clark et al., 1993). Some of these advantages include time and energy savings, very rapid heating rates (>400°C/min), considerably reduced processing times, fine microstructures and hence improved mechanical properties, and environmentally friendly processing (Mullin, 1995; Thuery, 1992).

Microwave processing has found various applications for home cooking and is widely used in many industrial applications including meat tempering, potato chips processing and bacon cooking (Gamble & Rice, 1987). At present, there is no commercial use of microwave technology for rice drying. Most of the reports found in literature agree to the fact that microwave treatment accords high thermal efficiency and shorter drying durations compared to conventional hot air drying (Cho et al. 1990; Prabhanjan et al., 1995; Maskan, 2001; Kaasová et al., 2002; Vadivambal and Jayas, 2007). Some lab-based reports indicated that compared to hot air drying, microwave heating in the range of 90 W to 500 W with drying durations in the range of 6 to 56 minutes resulted in no changes in physical and chemical characteristics of the rice (Kaasová et al., 2002). At the industrial level, the demand for high drying throughputs necessitates the use of elevated levels of microwave power; Hence there is need to investigate the implications of microwave heating on the quality of rice dried at high levels of microwave power.

Although microwave heating is expected to be volumetric, introducing tempering of rice at slightly elevated temperatures may aid stepwise cooling and moisture redistribution within kernels, which ultimately improve the quality of dried rice. During the tempering stage, the microwave energy is not transferred to the grain, but the grain is held at a certain temperature to rest. The tempering stage allows time for equilibration of moisture from the center to the surface of the grain, if any, and is especially important before another heating cycle as may be the case of multi-pass drying (Li et al., 1999; Nishiyama et al., 2006). Tempering eliminates the moisture gradient inside the grain imposed during the previous drying stage. Adding a tempering step to the drying process leads to a reduction of energy consumption by reducing the duration required for drying. Continuous drying alone would increase the rice temperature while removing less moisture compared to sequential drying and tempering process (Thakur and Guta, 2006). Also, it is possible to use the sensible heat from the rice to remove more moisture in a natural cooling process after tempering.

OBJECTIVES

To successfully implement microwave technology for rice drying, there is need to optimize the process such that rice milling yield is improved and the rice nutritional and functional quality indices are maintained. The objective of this research was to determine the feasibility of using an industrial-type microwave heating system to achieve one-pass rice drying with minimum implications on the rice quality. The specific objectives of this study were the following:

1) Investigate the effects of microwave heating power and treatment time on rice moisture removal.
2) Study the effectiveness of microwave heating of rice to achieve one-pass drying without adversely affecting the rice milling yield.
3) Study the implications of introducing tempering steps after microwave heating on rice milling yield.
4) Investigate the effect of natural and forced air cooling of the rice after microwave treatment on the rice milling yield.

MATERIALS AND METHODS

Rice samples

Freshly harvested, medium-grain rice samples (cv. Jupiter) at an initial MC of 23% to 24% (wet basis) were used in this study. The samples were cleaned using a dockage equipment (MCi Kicker Dockage Tester, Mid-Continent Industries Inc., Newton, KS). The equipment used a series of small sized sieves to provide a fast, accurate and consistent way of separating shrunken, broken, scalped material, broken kernels, splits and dust from rice. The cleaned rice was stored in a laboratory cold room set at 4°C. At the beginning of the experiments, the samples were retrieved from the cold room and allowed to equilibrate with room conditions (25^{o} C) before conducting any experiments. The MCs of the samples reported in this study were determined using an AM 5200 Grain Moisture Tester (PERTEN Instruments, Hägersten, Sweden), which was calibrated using the American Society of Biological Engineers (ASABE) standard (Jindal and Siebenmorgen, 1987). The MC of each sample was measured by placing 15 g duplicate samples into a conduction oven (Shellblue, Sheldon Mfg., Inc., Cornelius, OR) which was set at 130°C for 24 h, followed by cooling in a desiccator for at least half an hour (Jindal and Siebenmorgen, 1987). All reported MCs are on wet basis.

Microwave equipment and treatments

An industrial microwave system (AMTek, Applied Microwaves Technology Inc., Cedar Rapids, IW) was used in this study. The system (Fig. 2.1) consists of a transmitter, a wave guide, and the microwave heating zone (oven) and operates at a frequency of 915 MHz. The transmitter is a high-powered vacuum tube that works as a self-excited microwave oscillator. It is used to convert high-voltage electric energy to microwave radiation. The waveguide consists of a rectangular pipe through which the electromagnetic field propagates lengthwise. It is used to couple microwave power from the magnetron into the lab oven. The lab oven is the internal cavity of the microwave that provides uniform temperatures throughout while in use.

Figure 2.1: Industrial type microwave used in the showing the transmitter (1), wave guide (2), heating zone (3), the conveyor belt (4), and control panel (5).

The implication of three different microwave treatment methods was studied; the treatment methods included 1) microwave heating followed by natural cooling, 2) microwave heating followed by tempering and natural cooling, and 3) microwave heating followed by forced-air cooling. For all the treatments a sample of 2000 g rice was massed out and placed into microwave safe trays for the treatment. The outsides of the trays were made of polypropylene with a Teflon coated fiberglass mesh at the bottom to hold the samples. The trays with rice sample were set in the oven on the belt and treated at various power levels and durations (Table 2.1). The temperature of rice after microwave heating was measured using an infrared thermometer (Fluke Corporation, Everett, WA).

In the case of microwave heating followed by natural cooling, the samples were transferred immediately after heating to an Equilibrium Moisture Content (EMC) chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 25°C and relative humidity of 65% and allowed to cool naturally to room temperature conditions.

After cooling, the weight of the samples was determined, and the percentage point of moisture removed was calculated. In the case of microwave heating followed by tempering and natural cooling treatments, the samples were transferred immediately after heating to glass jars and sealed air tight. A HOBO sensor (Onset Computer Corporation, Bourne, MA) was placed in the jars to determine the changes in temperature and relative humidity inside the jars. The jars were placed in an environmental chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 60°C and relative humidity of 65%. The rice was tempered for 4 h. After the tempering, the samples were spread uniformly on a tray, transferred to an EMC chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 25°C and relative humidity of 65%. The samples were allowed to cool naturally to 25°C. After cooling, the weight of the samples was determined, and the percentage point of moisture removed was calculated. In the case of microwave heating followed by tempering, the samples were transferred immediately after heating to glass jars and sealed air tight. In the case of microwave heating followed by forced air cooling and natural cooling, the samples were not tempered. After treatment, the samples were spread uniformly on a tray, transferred to an environmental chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 25°C and relative humidity of 65%. At the bottom of the perforated tray, a fan was installed to force air through the rice during cooling. The apparatus to allow the forced air cooling consisted of a fan (DAYTON blower, Dayton Electric Mfg., Niles, IL) with air flow rate of 37.82 cfm through the rice and cool the rice to 25°C. After cooling, the weight of the samples was determined and the percentage point of moisture removed was calculated.

After the MC of the rough rice had been determined, the treated samples were left in the environmental chamber to dry to an MC of 12.5%, which is typically used to perform milling quality tests. Control samples constituted samples that were not treated with microwave but dried to an MC of 12.5% in an EMC chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 25°C and relative humidity of 65%.

Table 2.1: Drying methods, microwave power levels and heating durations used in the rice drying experiments ǂ.

	Cooling Method	**Power (kW)**	**Duration (min)**	**Specific Energy (kJ/kg-grain)**
Microwave Heating followed by:	Natural Air Cooling/ Tempering/ Forced Air Cooling	2	1	40
		2	2	80
		2	3	120
		2	4	160
		5	1	100
		5	2	200
		5	3	300
		5	4	400
		10	1	200
		10	2	400
		10	3	600
		10	4	800
		15	1	300
		15	2	600
		15	3	900
		15	4	1200

ǂA full factorial design was not feasible because under some power levels and heating durations the rice would pop. Treatments highlighted in gray resulted in insignificant moisture content reductions or rice burning and were omitted.

Rice Milling

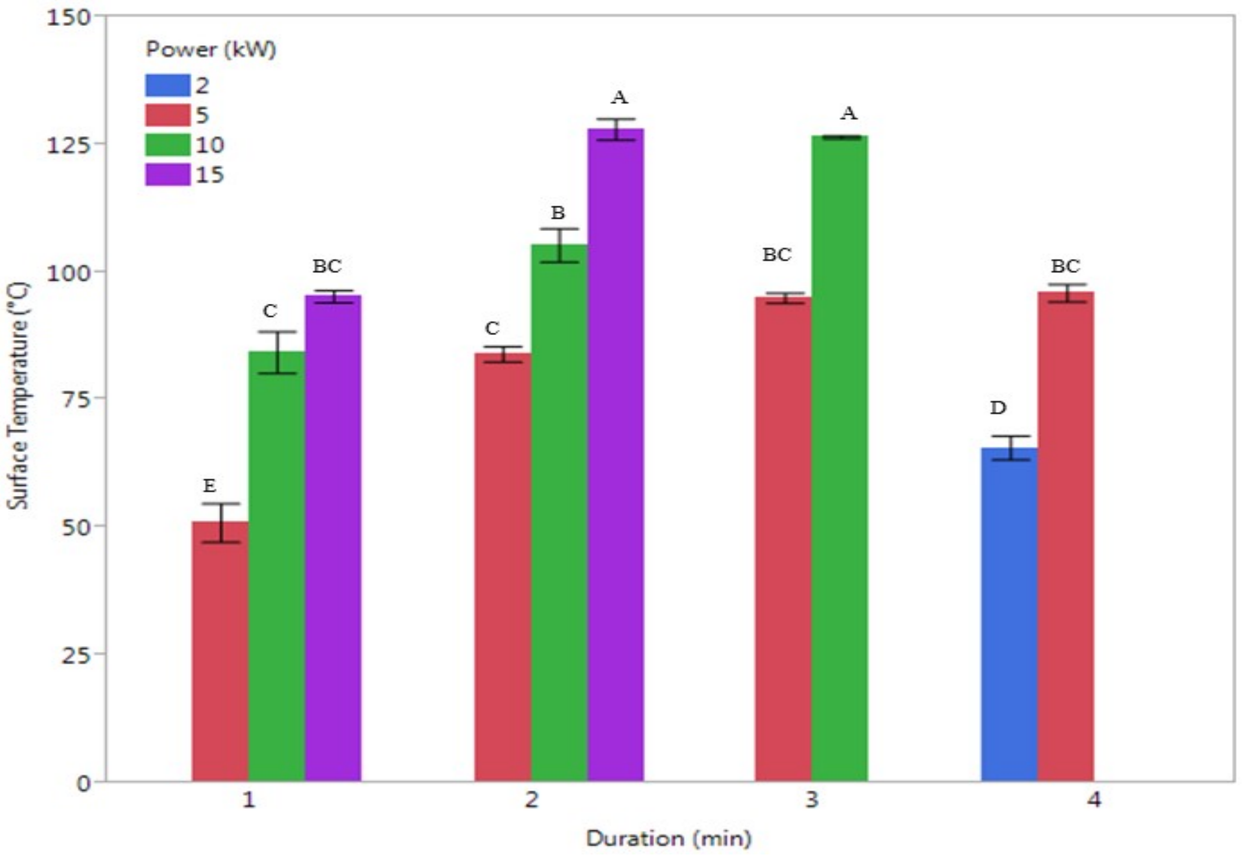
Triplicate, 150 g sub samples of rough rice, obtained from each sample dried to 12.5% MC, were dehulled using a laboratory huller (Satake Rice Machine, Satake Engineering Co., Ltd., Tokyo, Japan), milled for 30 s using a laboratory mill (McGill #2 Rice Mill, RAPSCO, Brookshire, TX) and aspirated for 30 s using a seed blower (South Dakota Seed Blower, Seedboro, Chicago, IL). Milled rice yield was calculated as the mass proportion of rough rice that remains including head rice and broken, after milling. Head rice was then separated from broken kernels using a double tray sizing machine (Grainman Machinery Manufacturing Corp., Miami, FL). Head rice yield was calculated as the mass proportion of rough rice that remains as head rice after complete milling.

RESULTS AND DISCUSSION

Rice surface temperature

The rice surface temperature for treatments at a power level of 15 kW and 10 kW for heating durations exceeding 2 and 3 minutes, respectively, resulted in rice popping. Figure 2.2 shows the effect of increasing the microwave power and duration of heating on the rice surface temperature. The initial surface temperature of the rice was 17.5°C. The surface temperature of rice increased when the microwave power level and treatment duration increased. For example, the surface temperature of rice increased from 17.5°C to 50°C, 80°C, 95°C, and 95°C when the rice was heated with the microwave at the power level of 5 kW for 1, 2, 3 and 4 minutes, respectively. The treatments at power levels of 15 kW for 2 minutes and 10 kW for 3 minutes resulted in the highest and statistically the same surface temperature of rice (130°C) and also caused the rice to pop. A one-way fixed effect ANOVA was conducted to determine if there was any difference in the rice surface temperature based on treatment power level and heating duration. There was a statistically significant interaction between the treatment power level and heating duration ($p < .0001$). Tukey's HSD post hoc analysis was then conducted to determine where the differences occurred and the results are presented in figure 2.2.

Figure 2.2: Effect of microwave power level and heating duration on the surface temperature of rice initially at 17.5°C. Each error bar is constructed using 1 standard error from the mean. Means with the same type of letters are not significantly different at $\alpha = 0.05$.



Analyses were performed to investigate the correlation of the supplied microwave specific energy with the rice bed surface temperature. The specific energy (E_s) was determined based on the microwave power, the treatment duration, and mass of the treated sample. The higher the specific energy supplied to the rice the higher was the surface temperature (q_s) of the rice with reference to the initial temperature of 17.5°C. Three models of cubic, quadratic and linear degrees were fitted to the data of rice surface temperature versus the specific energy. Table 2.2 contains the model equations; root mean square errors (RMSE) and the R^2 values. Based on the results, the cubic model best fitted (R^2= 0.974, RMSE =5.32 % w.b) the relationship between the specific energy input and the surface temperature rise for rice at IMC of 23.5%, initial surface temperature of 17.5°C, and microwave heating with specific energy input in the range between 0 to 900 kJ/ kg-gain. The R^2 associated with the quadratic and linear models were 0.951 and 0.880, respectively; the RMSE values were 7.16% and 11.05% w.b., respectively. Therefore, the linear and quadratic models gave poorer predictions compared to the cubic model. Figure 3 shows the trend of data fitted to the cubic model in Table 2.2. The solid line of fit is bounded by the confidence of fit and confidence of prediction in figure 2.3.

Table 2.2: Relationship between rice surface temperature (θ_s, °C) and microwave specific energy input (E_s, kJ /kg of rice) †.

Mode Type	Equation	Root Mean Square Error (% moisture content, w.b.)	R^2
Cubic	$\theta_s = 15.2 + 0.3324E_s - 0.00047E_s^2 + 2.656 \times 10^{-7}E_s^3$	5.32	0.974
Quadratic	$\theta_s = 22.63 + 0.0.2075E_s - 0.000105E_s^2$	7.16	0.951
Linear	$\theta_s = 39.29 + 0.1056E_s$	11.05	0.880

† The rice initial moisture content and surface temperature of rice was 23.5±0.5% (w.b.) and 17.5±0.5°C, respectively.

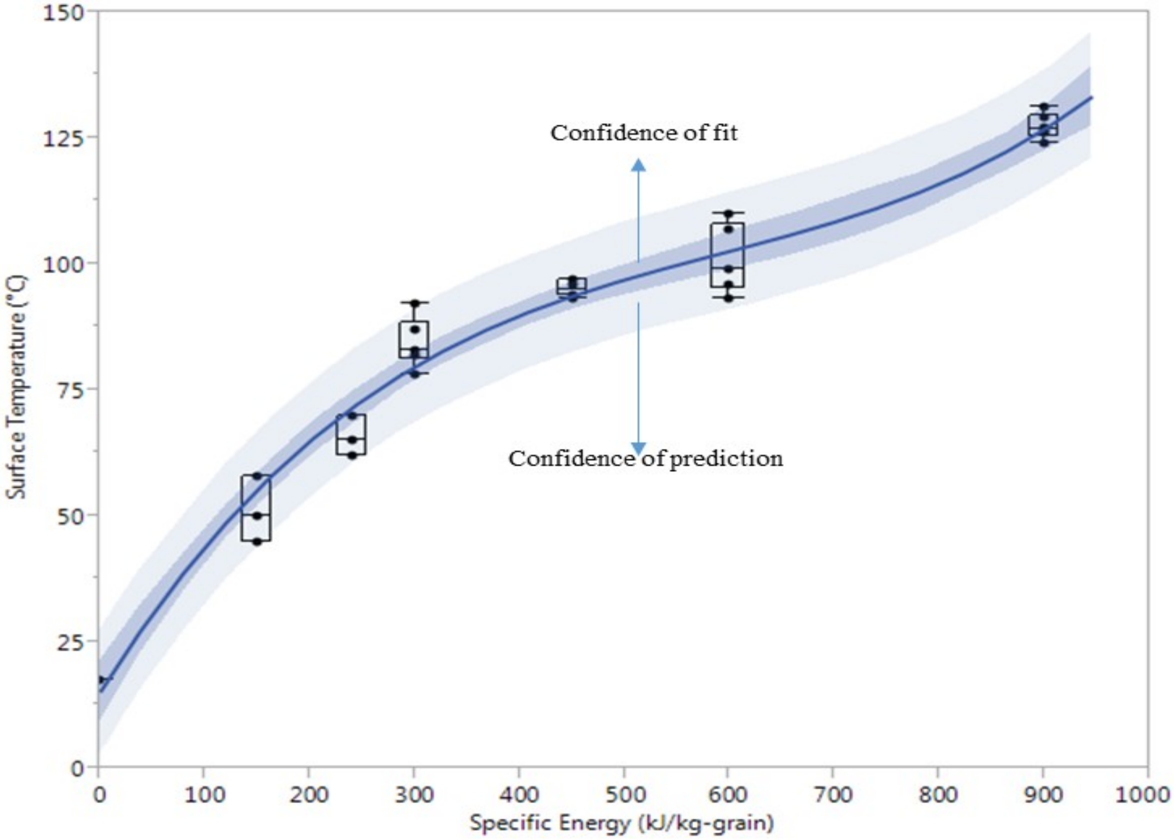


Figure 2.3: Relationship between rice surface temperature and specific energy input during microwave heating fitted to a cubic model

Commercial dryers that use convectively heated air operate at temperatures of around 60°C and use multiple passes through the dryer (Wadsworth, 1994). In this study, it could be observed that supplying microwave energy greater than 250 kJ/kg-grain caused the rice surface temperature to exceed 60°C. The microwave heating process is volumetric and leads to high-energy water molecules rapidly drifting through the rice kernel to the surface where they desorb. The volumetric heating at high energy fluxes of microwaves may allow the use of higher drying temperatures in short durations, compared to convective hot air heating. In conventional hot air heating, the increase in drying air temperature enhances water desorption rate from rice kernel surface, which results in moisture gradient inside the kernel resulting in cracked or broken kernels during milling; therefore, there is a practical upper limit of the drying temperature with convective heating to limit development of large MC and temperature gradients within the rice kernel.

Moisture Removal

The effect of microwave heating duration and power level on rice MC for different drying strategies is shown in figure 2.4. The horizontal x-axis contains two parameters, namely the heating duration which ranged from 1 to 4 minutes and treatment power level 2, 5, 10 and 15 kW. The MCs are shown on the vertical y-axis for the three employed drying strategies. For example, the first column of bar graphs represents the MC readings for control treatment with 0 kW for 1 minute, and the last column of the bar graphs represents results for microwave treatment with 15 kW for 1 minute. The mean IMC for each treatment and the mean MC after microwave heating are also marked on each bar graph. For commercial purposes, the targeted safe storage MC of rough rice should be 13%. Based on the results of this study, multiple passes of microwave treatment would be necessary to dry the rice to safe storage MC when low power levels are used for short heating durations. For instance, using the industrial microwave with setting at 5 kW and heating the rice for 1 minute removed only 1 percentage point of moisture from rice for the studied drying strategies; 5 kW treatment for 2 minutes removed 4 to 5 percentage points, while extending the heating duration to 4 minutes removed some 9 percentage points of moisture from rice. A combination of a high power level and a short treatment duration, or a low power level and a long treatment duration might be employed to achieve a one-pass microwave drying of rice with the studied strategies. The 5 kW heating for 3 and 4 minutes, and the 15 kW heating for 1 minute dried the rice to near safe storage MCs. From a practical standpoint, it might be possible to use a hybrid approach that employs microwave heating to remove some amount of moisture from rice without impacting the rice quality and complete the drying of rice to safe storage MC with hot air or other drying means. Such a hybrid approach may significantly reduce the rice drying duration compared to using the conventional hot air drying alone. Based on the study, one-pass microwave heating at power levels of 15 kW for 1 minute followed by natural air cooling and 5 kW for 4 minutes followed by natural air cooling resulted in rice final MCs of 16.1% and 14.2%, respectively; one-pass microwave heating at power levels of 15 kW for 1 minute followed by forced air cooling and 5 kW for 4 minutes followed by forced air cooling resulted in rice final MCs of 16.1% and 14.5%, respectively; and one-pass microwave heating at power levels of 15 kW for 1 minute and 5 kW for 4 minutes followed by tempering and natural air cooling resulted in rice final MCs of 15.6% and 14.5%, respectively. Practically, it might be feasible to finish driving out the remaining 1 to 3 percentage points of moisture in the preceding microwave treated rice with hot air, or other drying means to achieve the safe storage MC of 13%.

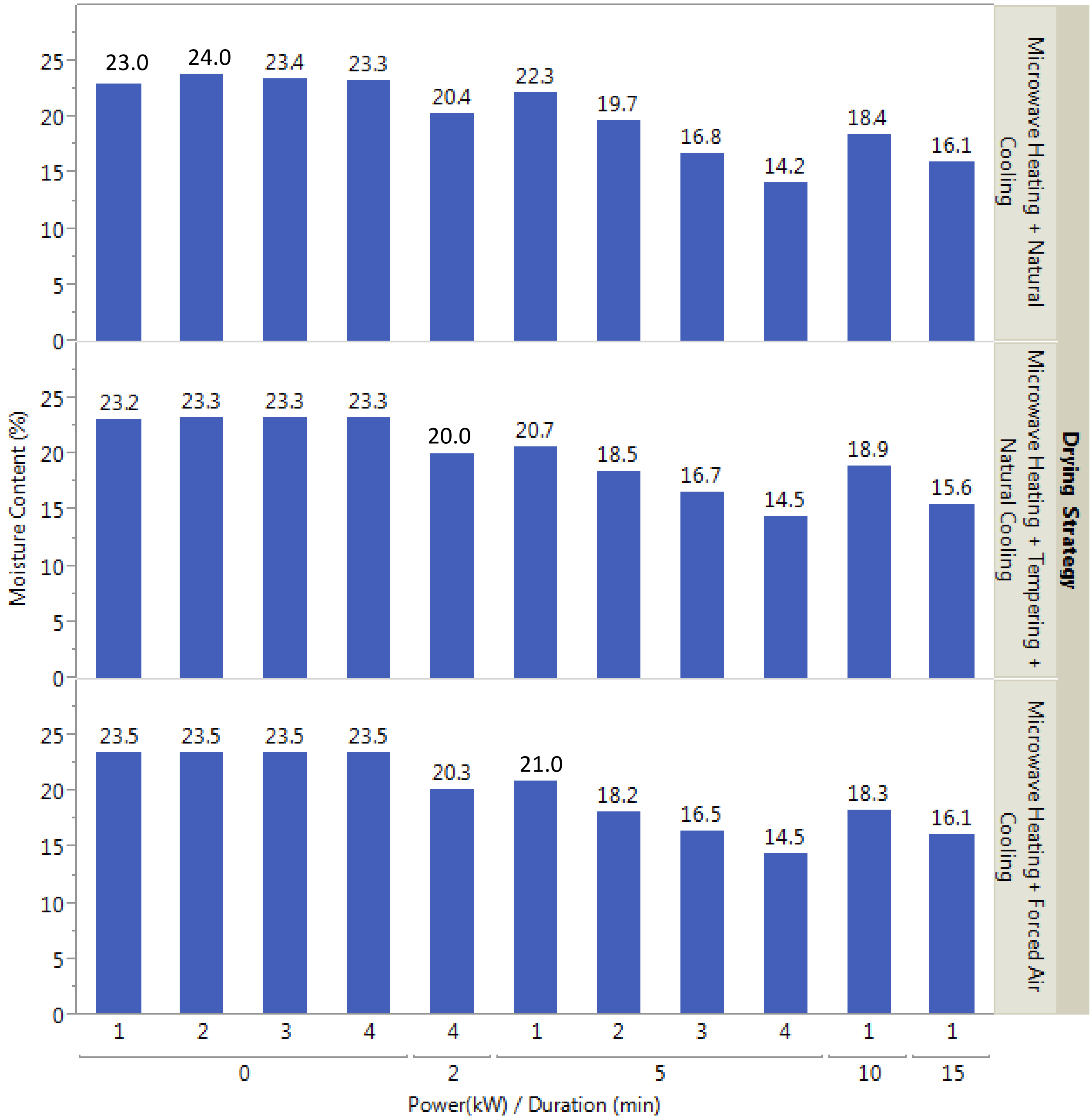


Figure 2.4: Effect of microwave heating duration and power level on moisture removal for different rice drying strategies

Statistical analyses were performed to determine if there were significant differences among the final MCs of the rice and the treatment specific energy (Table 2.3). There was a statistically significant interaction ($p < .0001$) between drying strategy and specific energy. Also, there was a statistically significant difference in MC of rice based on the type of strategy employed to dry the rice (*p* < .0421). Tukey's post hoc test was done to explain the differences in more details (Fig. 2.5).

Table 2.3: Statistical analyses indicating the interaction of the drying strategy and specific energy during microwave heating of rice on the rice final moisture content

Source	**Number of parameters (Nparm)**	**Degrees of freedom**	**Sum of Squares**	**F Ratio**	**Prob > F**
Drying Strategy	2	2	1.9148	3.2626	0.0421*
Specific Energy (kJ/kg-grain)	5	5	1230.8988	838.9315	<.0001*
Drying Strategy*Specific Energy (kJ/kg-grain)	10	10	6.2467	2.1287	0.0280*

*Statistically significant (p<0.05)

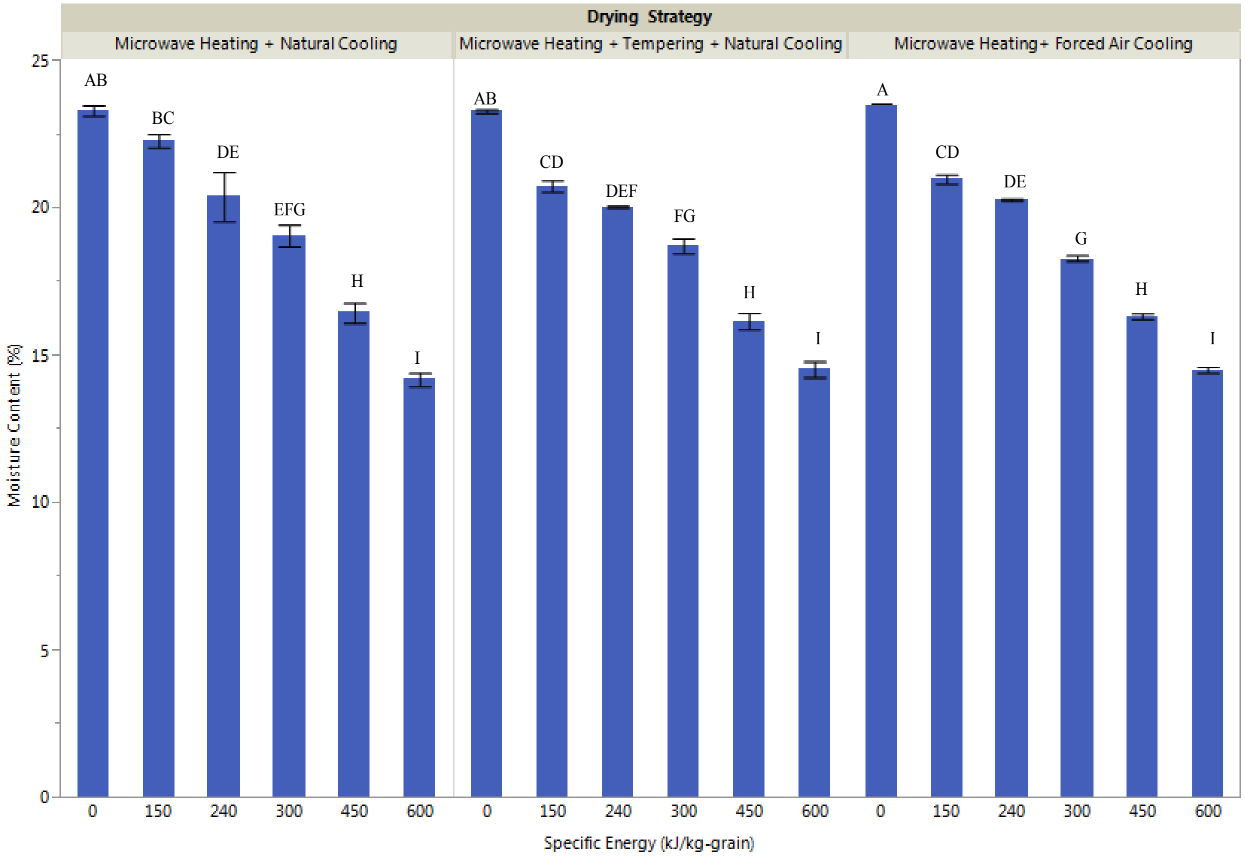


Figure 2.5: Effect of specific energy supplied by microwave heating on the moisture content of the dried rice for different drying methods. Each error bar is constructed using 1 standard error from the mean. Means with the same type of letters are not significantly different at $\alpha = 0.05$.

The specific energy (to remove 1 kg of water) during the studied drying processes was calculated. Statistical analyses were performed to determine if there were significant differences in the energy required to remove 1 kg of moisture for the drying strategies and the supplied specific energy (Table 2.4). Tukey's HSD post hoc analysis was then conducted to determine where the difference occurred (Fig. 2.6). There was a statistically significant difference ($p < .0001$) in the energy required to remove 1 kg of water for the studied drying strategies and the supplied specific energy for the microwave heating.

Table 2.4: Statistical analyses indicating the interaction of the drying strategy, specific energy supplied to rice and the energy used to remove 1 kg of water from rice during microwave heating

Source	Number of parameters (Nparm)	Degrees of freedom	Sum of Squares	F Ratio	Prob > F
Drying Strategy	2	2	27403949	194.5057	<.0001*
Specific Energy (kJ/kg-grain)	5	5	906914231	2574.812	<.0001*
Drying Strategy*Specific Energy (kJ/kg-grain)	10	10	36473541	51.7758	<.0001*

*Statistically significant (p<0.05)

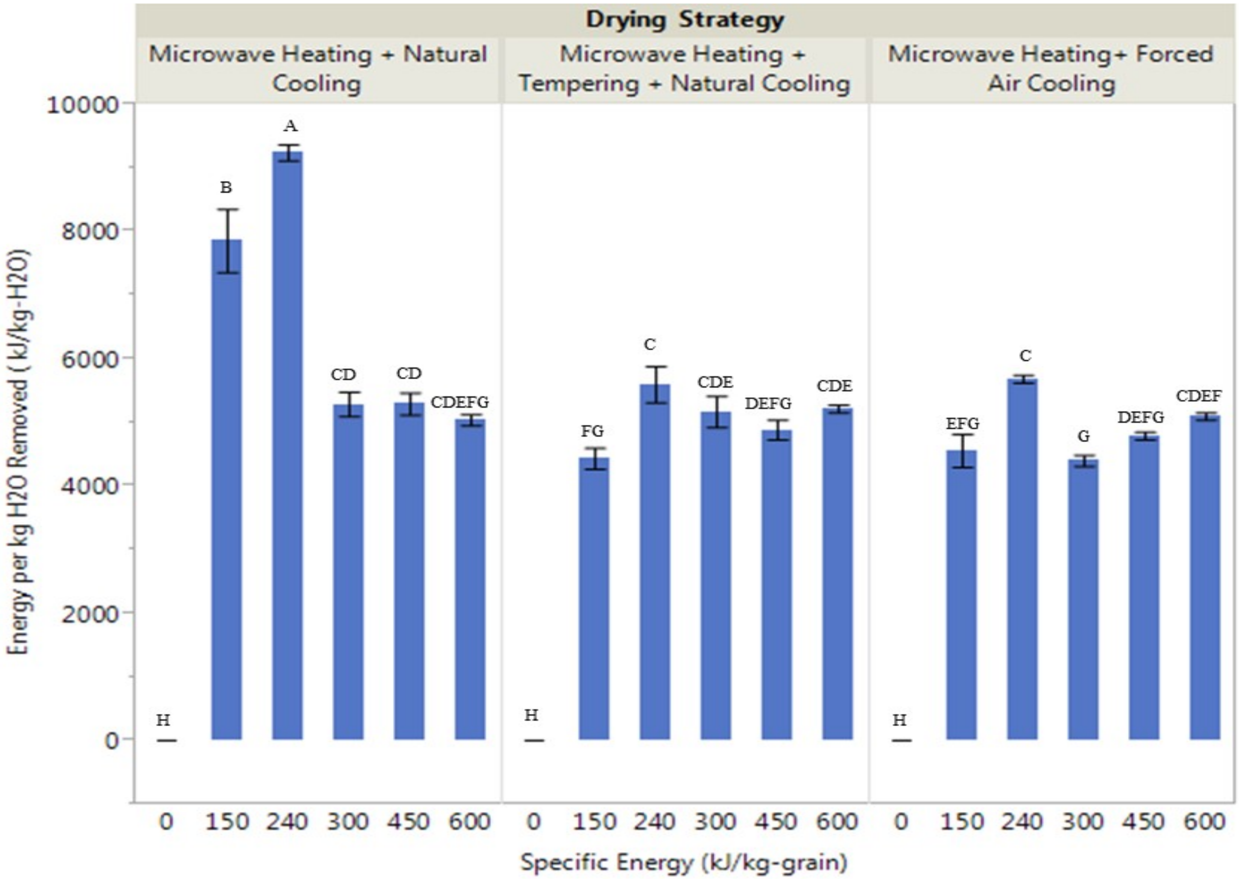
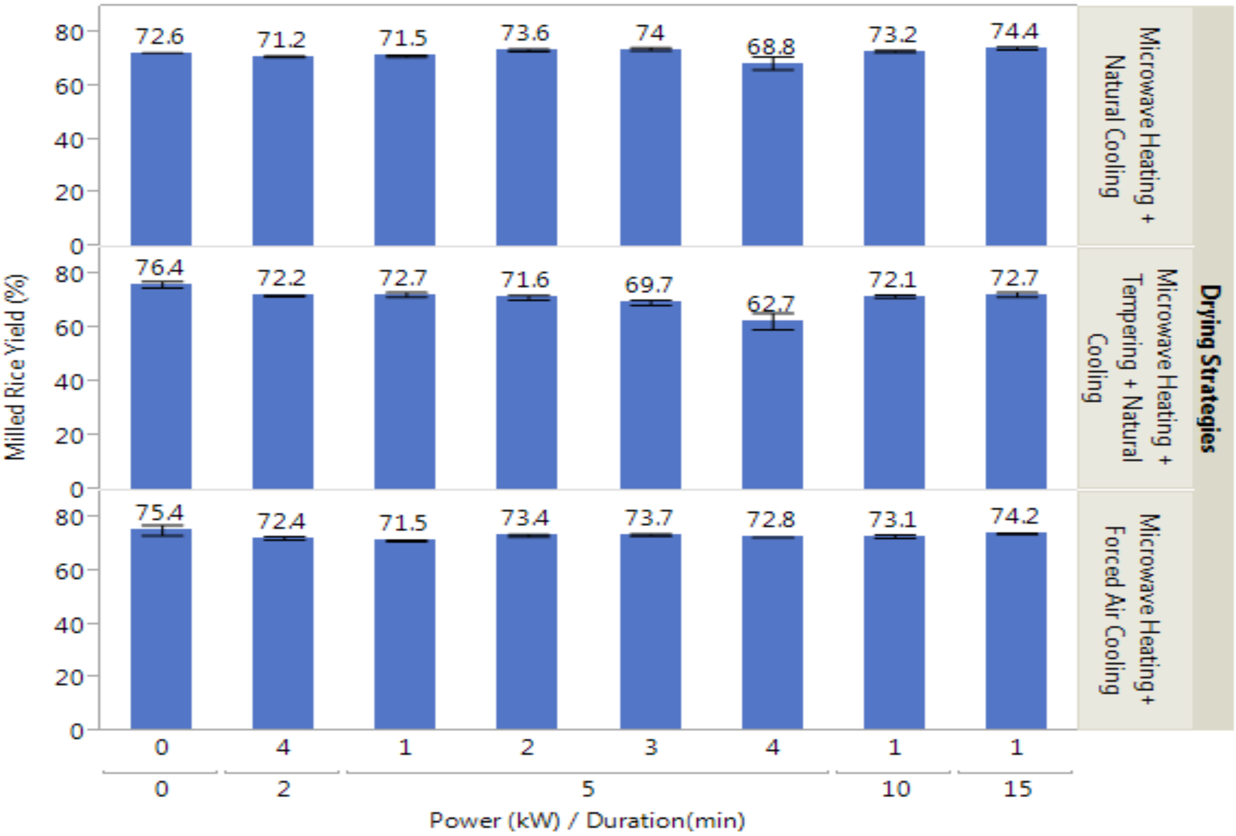


Figure 2.6: Energy required to remove water from rough rice during microwave heating with different drying strategies. The initial moisture content and the surface temperature of rice was at 23.5±0.5% (w.b.) and 17.5±0.5°C, respectively. Each error bar is constructed using 1 standard error from the mean. Means with the same type of letters are not significantly different at α = 0.05.

Milling and head rice yields

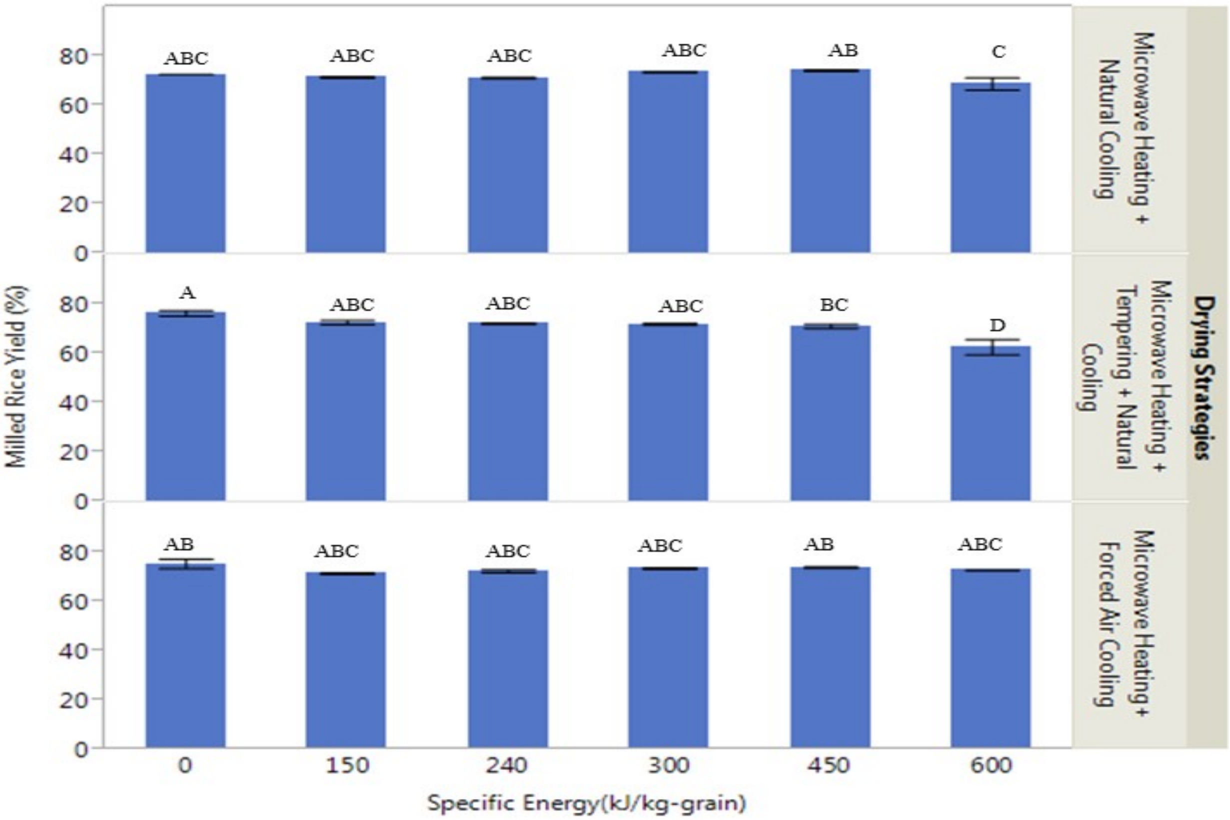
Figures 2.7 (a) and 2.7(b) show the MRY after treatment of rice at different power levels and treatment durations and at different specific energies, respectively. A one-way fixed effects analysis of variance (ANOVA) was conducted to determine if there was any difference in the MRY based on microwave energy supplied. There was a statistically significant difference between at least two energy levels ($p < .0001$). Tukey’s HSD post hoc analysis was then conducted to determine where the differences occurred and the results are presented in figure 2.7

(b). There was a statistically significant interaction between drying strategy and specific energy (*p* < .0001).



(a)

Figure 2.7a: Milled rice yields after treatment with microwave at various power levels and heating durations



(b)

Figure 2.7b: Effect of specific heat energy supplied during microwave heating on milled rice yields. Each error bar is constructed using 1 standard error from the mean; means with the same letters are not significantly different at $\alpha = 0.05$.

The HRY is often the most important quality parameter to millers since the HRY is linked to payment received for rice delivered at milling facilities. Figure 2.8 shows the HRY obtained following microwave treatment of rice with different power levels and treatment durations. The horizontal x-axis contains two parameters namely the heating duration which ranged from 1 to 4 minutes, and treatment power levels 2, 5, 10 and 15 kW. The HRY are shown on the y-axis for the three employed drying strategies. For example, the first column of bar graphs represent the HRY for treatment with 0 kW for 1 minutes, and the last column of the bar graphs represents results for treatment with 5 kW for 4 minutes. At a given power, the longer the treatment, the lower was the HRY and at a given heating duration, the higher the power, the lower was the HRY. For instance, when microwave energy of 5 kW was used the HRY reduced from 68.8% to 65.8% for 1 minute and 4 minutes heating durations, respectively, for the process involving microwave heating followed by tempering and natural air cooling; However, the corresponding HRY reduction was 67.8% to 23.4% and 65.2% to 23.8% in the case of microwave heating followed by natural cooling and microwave heating followed by forced air cooling, respectively. Overall, tempering of rice after microwave heating helped to maintain the HRY to levels comparable to the control conditions.

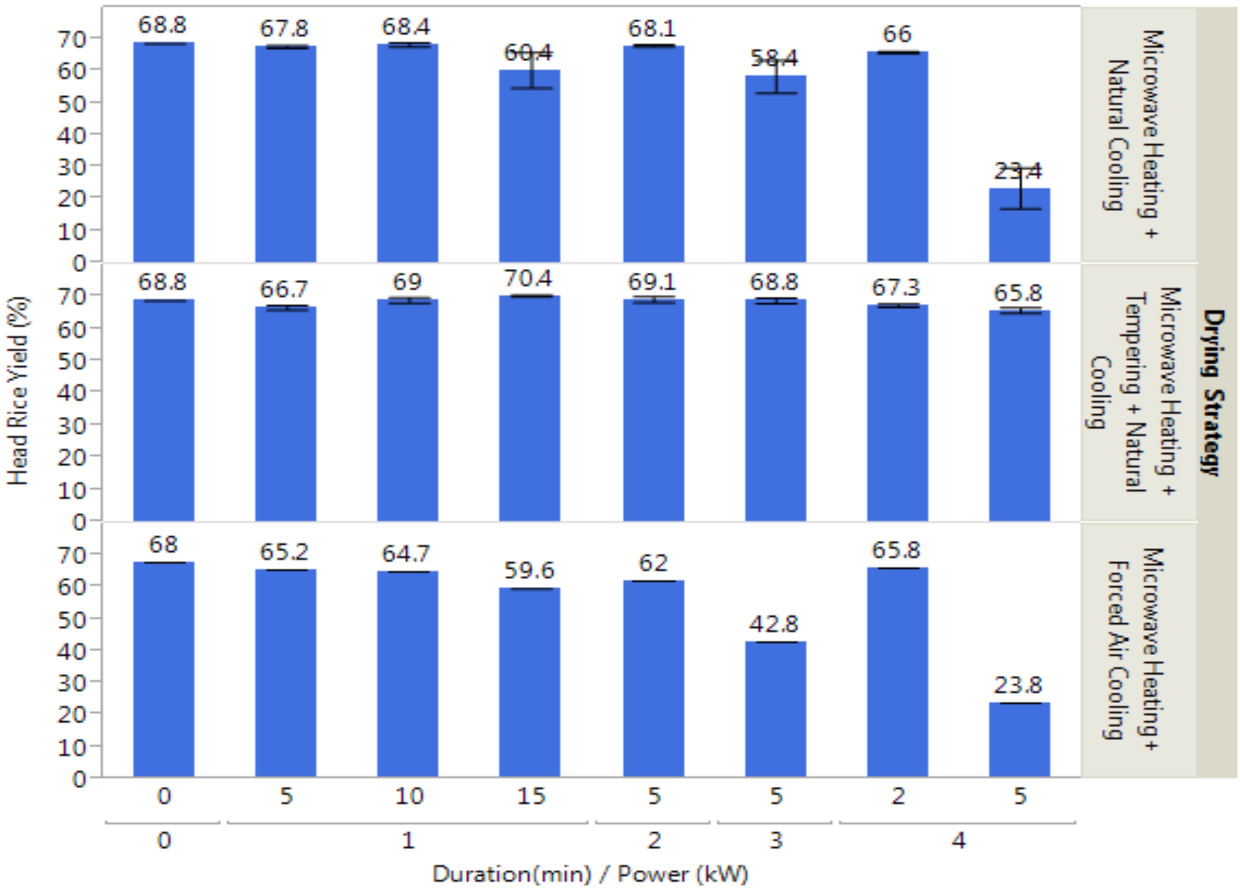


Figure 2.8: Effect of microwave treatment power and heating duration on head rice yield. Each error bar is constructed using 1 standard error from the mean.

Statistical analyses were performed to determine if there were significant differences in HRY based on the quantity of microwave energy supplied to the grain and the interactions with the drying strategy (Table 2.5). There was a statistically significant interaction between drying strategies and microwave energy supplied ($p < .0001$) on the resulting HRYs. Tukey's HSD post hoc analysis was then conducted to determine where the differences occur; the differences are shown in figure 2.9. Supplying microwave energy in the range of 0 to 240 kJ/kg-grain did not result in statistically significant differences in the HRY compared to that of the control sample when the three strategies were compared. When the specific energy supplied exceeded 300 kJ/kg-grain, a very noticeable reduction in the HRY commenced, especially for strategies that did not incorporate a tempering step. For instance, the HRY dropped below 50% when the energy exceeded 500 kJ/kg-grain for microwave heating with natural cooling and microwave heating with forced air cooling. The need to introduce a tempering step in the process was, therefore, crucial at high microwave energy, especially above 500 kJ/kg-grain. The negative impact of conditions without tempering are due to differential stresses resulting from moisture and temperature gradients which cause fissuring of rice. The tempering process allows natural equilibration within the rice kernel which may reduce the tensile and compressive stress during cooling thereby reducing fissuring and breakage of the rice kernel.

Table 2.5: Statistical analyses indicating the interaction of the drying strategy, specific energy supplied to rice and the head rice yield for rice during microwave heating

Source	**Number of parameters (Nparm)**	**Degrees of freedom**	**Sum of Squares**	**F Ratio**	**Prob > F**
Drying Strategy	2	2	1606.1410	40.7580	<.0001*
Specific Energy (kJ/kg-grain)	5	5	6559.3460	66.5809	<.0001*
Drying Strategy*Specific Energy (kJ/kg-grain)	10	10	2986.9858	15.1598	<.0001*

*Statistically significant ($p<0.05$)

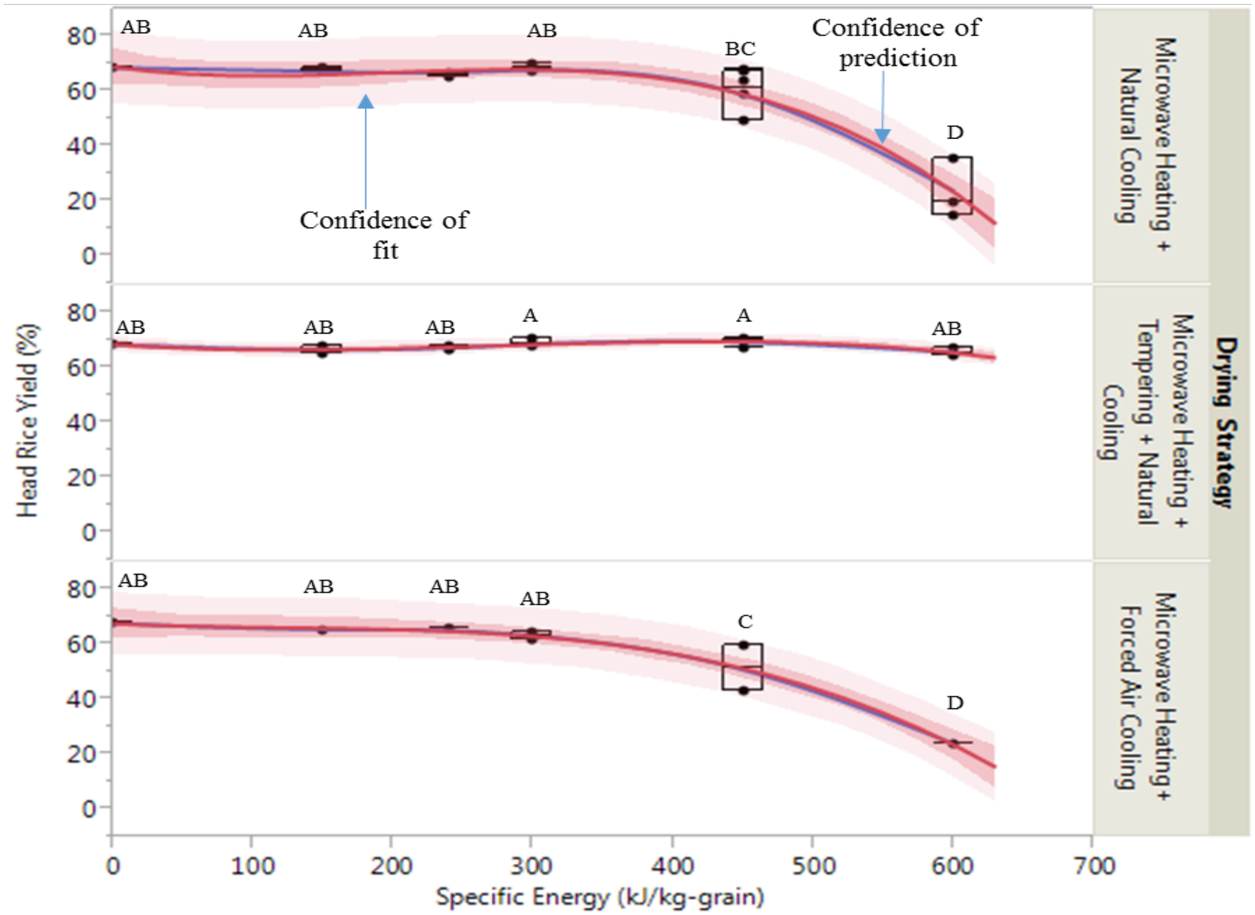


Figure 2.9: Effect of energy supplied during microwave treatment on head rice yield. The solid lines of fit are bounded by the confidence of fit and confidence of prediction. Means with the same type of letters are not significantly different at α = 0.05.

Three models of cubic, quadratic and linear degrees were fitted to the data of HRY versus the specific energy. Table 6 contains the model equations; root mean square errors (RMSE) and the R^2 values. Based on the results, the cubic model best fitted the correlation of specific energy input and the HRY for rice at IMC of 23.5±0.5% and surface temperature 17.5±0.5° and microwave heating with specific energy input in the range of 0 to 600 kJ/ kg-grain. The R^2 associated with the cubic, quadratic and linear models are shown in Table 2.6.

Table 2.6: Relationship between the head rice yield (HRY, %) and microwave specific energy input ($E_{s,}$ kJ /kg of rice) during microwave treatment of rice[††].

Drying Strategy	**Mode Type**	**Equation**	**Root Mean Square Error (% HRY)**	**R^2**
Microwave Heating + Natural Cooling	Cubic	$HRY= 69.08-0.06921E_s+ 0.000452E_s^2 - 7.715 \times 10^{-7}E_s^3$	5.56	0.889
	Quadratic	$HRY= 65.15+0.08227E_s-0.000239E_s^2$	7.05	0.812
	Linear	$HRY= 79.25-0.06137E_s$	11.14	0.509
Microwave Heating + Tempering + Natural Cooling	Cubic	$HRY= 68.74-0.03551E_s+ 0.000184E_s^2 - 2.215 \times 10^{-7}E_s^3$	1.19	0.597
	Quadratic	$HRY= 67.62+0.007981E_s-1.451\times10^{-5}E_s^2$	1.74	0.095
	Linear	$HRY= 68.47-0.000744E_s$	1.78	0.006
Microwave Heating + Forced Air Cooling	Cubic	$HRY= 67.81-0.02281E_s+ 0.000134E_s^2- 3.64 \times 10^{-7}E_s^3$	4.70	0.911
	Quadratic	$HRY= 65.96+0.04869E_s-0.000192E_s^2$	5.05	0.892
	Linear	$HRY= 77.30-0.06688E_s$	8.60	0.673

[††] The initial moisture content and the surface temperature of rice were 23.5±0.5% (w.b.) and 17.5±0.5°C, respectively.

CONCLUSION

The effectiveness of using an industrial-type 915 MHz microwave system to achieve one-pass drying of rice while maintaining the head rice yield was investigated. The implication of integrating rice tempering, natural air cooling and forced air cooling to help improve the drying process and rice quality were evaluated for medium-grain rice (*cv.* Jupiter). Models for describing the kinetics of the drying and HRY for the processes were produced. Based on the findings of this feasibility study, there is potential to scale up microwave treatment of rice to achieve one-pass drying. Supplying microwave energy of up to 600 kJ/kg-grain to the medium-grain rice at IMC of 23% to 24% MC, and incorporating an additional 4 h tempering step at 60^{o}C dried rice to final MC of 14% to 16%, depending on rate of energy supply, with HRY not significantly different from gently dried (natural air at 25°C and relative humidity of 65%) control samples. The MC reduction and the HRY resulting from microwave heating followed by natural air cooling and microwave heating followed by forced air cooling were inferior compared to the strategy which incorporated tempering. Without tempering step, microwave heating with energy input less than 300 kJ/kg-grain (at 23% to 24% MC) is recommended to obtain HRY comparable to the control samples. It was possible to dry freshly-harvested, high MC medium-grain rice in one-pass with microwave heating to remove significant percentage points of moisture content.

The microwave heating process could be optimized to achieve one-pass rice drying with the potential to maintain the HRY. The challenge, however, remains in scaling up the process to achieve commercially viable throughput. It is also vital that future studies be done to access the drying characteristics of long-grain rice and evaluate the impacts of the treatments on other quality indices including rice color, viscous properties, flavor profiles, and assess potential to reduce microbial activity on rice.

FUTURE WORK

Demand to dry rice at peak harvest escalates tremendously and annually, but the rice-harvesting "window" remains relatively short and is also characterized by warm and humid conditions that favor the proliferation of microbes and pests within the grain-storage ecosystem. Development in rice-harvesting technology has also increased the speed at which rice can be harvested. Larger and faster grain carts, trucks, and trailers for transporting rice from combines to driers result in a much greater rice-delivery rate to driers. Unfortunately, the rice-drying infrastructure has not grown at the same rate as that of delivery at commercial drying facilities. Temporary "wet holding" (delayed drying) of rice has become inevitable; this poses many challenges, particularly for rice coming in at high moisture content (Atungulu, 2015).

Rice harvests drying times for conventional drying methods can range from multiple hours to multiple weeks depending on the temperature of the drying air. In order to maximize MW drying to avoid bottlenecks at peak harvest times future studies will involve determining the implications of varying rice bed thicknesses on rice quality parameters. Information on non-uniformity of temperature, milled rice and functional qualities on rice of increasing rice bed thickness will give insight on the feasibility of drying at the industrial level.

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Implications of Microwave Drying Using 915 MHz Frequency on the Temperature Distribution Profiles in Multiple Rice Bed Thicknesses

ABSTRACT

Microwave (MW) drying offers great promise to achieve simultaneous rice drying and decontamination of mycotoxin-producing molds. However, high heat fluxes and temperature non-uniformity, which take place during microwave processing, can cause defects and non-homogeneity in the final product. These defects greatly alter the milled rice yields as well as rice physicochemical properties. To avoid such defects, the heating process needs to be optimized to avoid non-uniform heating so that the rice quality is not compromised. In this study, temperature rise and non-uniformity during the microwave drying of medium grain rice beds of thicknesses 5, 10 and 15 cm was investigated. Freshly harvested medium grain rough rice samples at an initial moisture content of 24% w.b. were treated using a 915 MHz Industrial microwave dryer at power levels of 5, 10 and 15 kW and heating durations of 4, 6 and 8 minutes. The rice beds were contained in a modified tray that accommodated up to 9 kg of rice separated by thin fiberglass mesh in 3 kg increments. Each layer of rice was fitted with fiber optic sensors connected to a real time data logger during MW treatments. It was determined that specific energy has significant effects on the rice surface temperature rise ($p < 0.0001$). Rice beds of 5 cm thicknesses treated with MW specific energy of 133.33 kJ/kg-grain had a surface temperature of 57.29°C. By contrast, a specific energy of 800.00 kJ/kg-grain at the same thickness resulted in a surface temperature of 113.03 °C. There was disparity in the final surface temperatures within rice beds as a result of increasing thicknesses. Rice bed middle layers had surface temperatures greater than the top and bottom layers as a consequence of the limited airflow and mass transfer *at the middle. Additionally, the top rice bed layer had a much lower surface temperature than the middle and bottom layers as a result of evaporative cooling occurring at the top. This non-uniformity must be taken into consideration while developing MW processing systems for the grain drying industry.*

Keywords: Average temperature; Rice drying; Maximum temperature; Microwave dryer; Non-uniformity of heating, microwave drying, energy, temperature distribution

INTRODUCTION

Microwave (MW) processing has found various applications for home cooking and is widely used in many industrial applications including meat tempering, potato chips processing and bacon cooking (Gamble & Rice, 1987). Most of the reports found in literature agree to the fact that MW treatment accords high thermal efficiency and shorter drying durations compared to conventional hot air drying (Prabhanjan et al., 1995; Maskan, 2001; Kaasová et al., 2002; Vadivambal and Jayas, 2007). Unfortunately, researchers are still concerned with apparent quality and sensory degradation in MW-processed foods as a result of temperature non-uniformity. These heterogeneities in heat energy penetration greatly alter the properties of the final product especially the rice milling quality and physiochemical properties. Uniformity of rice heating is crucial to quality characteristics following the drying process.

Unlike convective heating, MW processing generates heat from within the material being treated in a phenomenon known as MW volumetric heating. This is the MW's ability to penetrate uniformly throughout the volume of the rice kernel delivering energy evenly throughout (Bih, 2003). In high MC agricultural materials such as rough rice, the internal heat generation creates a moisture driving potential from the center outward thus leading to faster heating rates and shorter processing times when compared to convective heating methods (Oliveira, 2002). Additionally, the superior control offered by MW systems contributes to higher quality by making product temperature much easier to regulate.

While uniform heating is expected with the use of MWs, the sinusoidal wave pattern propagated develops hot and cold spots within the bulk of the grain. Additionally, researchers are concerned with MWs' limited penetration depth. Past research on the use of an industrial MW to dry rough rice has indicated that using a 2450-MHz MW with power levels in the range of 90 to 500 W was effective at drying a rough rice lot in 6 to 56 min (Kaasová et al., 2002). However, a major drawback of 2450-MHz MW power is the limited penetration depth of the MW field into the heated product causing non-uniform heating and temperature gradient formation which negatively impacted the rice milling and physiochemical properties.

It is suggested that industrial MWs with a frequency of 915-MHz penetrate to a greater depth than does the 2450-MHz frequency making the use of industrial MWs with 915 MHz frequencies potentially suitable for large-scale rice-drying applications and possibly commercialization (Wang et al., 2003). To ensure the efficient use of an industrial MW system and to tailor it for application in the rice milling industry, a sound knowledge of temperature distribution profiles within the rice bed layer is essential.

In this study temperature rise and non-uniformity of heating medium grain rice in multiple rice bed layers using a 915 MHz Industrial MW were investigated. Temperature distribution profiles were tracked using fiber optic temperature sensors (OMEGA Engineering, INC., Stamford, CT 06907) connected to a real time data logger that was placed between rice bed layers during MW treatments.

OBJECTIVES

This study investigated the implications of MW specific energy and varying rice bed thicknesses on temperature rise and non-uniformity within drying rice beds of increasing thicknesses.

The specific objectives of this research were to determine:

1. The impacts of increasing MW specific energy on rice beds' final surface temperature.
2. The impacts of varying rice bed thicknesses on rice beds' final surface temperature.
3. The impacts of increasing MW intensity and heating durations on the surface temperature of the individual rice bed layers during treatments.

Knowledge of temperature rise and non-uniformity with the use of industrial MWs to heat and dry grain at different bed thicknesses is crucial to the design of a scaled up MW drying system for rough rice for applications in the grain industry. This information would be helpful to select power levels and treatment durations optimal for temperature and rice quality homogeneity.

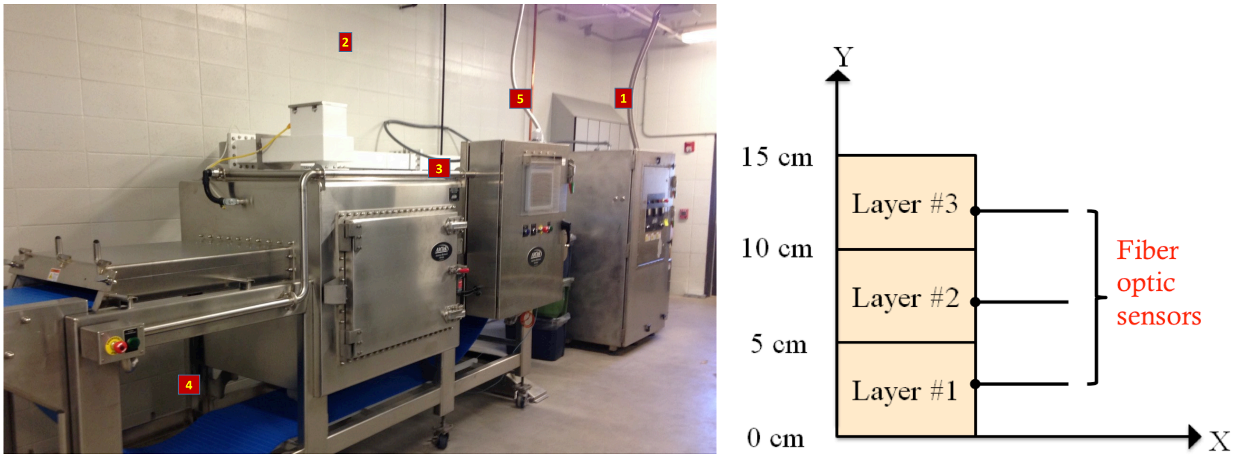
MATERIALS AND METHODS

Rice samples

Freshly harvested, medium-grain rice samples (cv. Jupiter) at initial MC of 23.5% (wet basis) were used in this study. The samples were cleaned using a dockage equipment (MCi Kicker Dockage Tester, Mid-Continent Industries Inc., Newton, KS). The equipment used a series of small sized sieves to provide a fast, accurate and consistent way of separating shrunken, broken, scalped material, broken kernels, splits and dust from rice. The cleaned rice was stored in a laboratory cold room set at 4°C. At the beginning of the experiments, the samples were retrieved from the cold room and allowed to equilibrate with room conditions (25^{o}C) overnight before conducting any experiments. The MCs of the samples reported in this study were determined using an AM 5200 Grain Moisture Tester (PERTEN Instruments, Hägersten, Sweden) which was calibrated using the ASABE standard (Jindal and Siebenmorgen, 1987). The MC of each sample was measured by placing 15 g duplicate samples into a 130°C conduction oven (Shellblue, Sheldon Mfg., Inc., Cornelius, OR) set at 130^{o}C for 24 h, followed by cooling in a desiccator for at least half an hour (Jindal and Siebenmorgen, 1987). All reported MCs are on wet basis (w.b).

Microwave equipment

An industrial MW system (AMTek, Applied Microwaves Technology Inc., Cedar Rapids, IW) was used in this study. The system (Fig. 3.1a) consists of a transmitter, a wave guide, and the MW heating zone (oven) and operates at a frequency of 915 MHz. The transmitter is a high-powered vacuum tube that works as a self-excited MW oscillator. It is used to convert high-voltage electric energy to MW radiation. The waveguide consists of a rectangular or cylindrical metal tube or pipe through which the electromagnetic field propagates lengthwise. It is used to couple MW power from the magnetron into the lab oven. The lab oven is the internal cavity of the MW that provides uniform temperatures throughout while in use.



(a) (b)

Figure 3.1a: Diagram of microwave system showing the transmitter (1), heating zone (2), wave guide (3), conveyor belt (4), and control panel (5), **Figure 3.1b:** Diagram of 9 kg of rice in 3 stackable microwave blind trays fitted with fiber optic cables in each layer

Experimental Design

MW specific energy (kJ/kg) is defined as the MW energy transferred per unit mass of product being treated and is calculated as follows;

$$SE = \frac{P \times T}{M} \quad (1)$$

Where,

SE is the microwave specific energy (kJ/kg)

P is the microwave power (kW)

T is the microwave heating duration (s)

M is the mass of product being treated (kg)

Based on a feasibility study it was determined that changes in MW specific energy have statistically significant ($p < 0.05$) effects on the rice surface temperature, final moisture content, milled rice and physiochemical properties and that optimum responses occurred at or around 600 kJ/kg-grain. Additionally, treatments over 900 kJ/kg-grain resulted in the rice burning and popping, and that specific energies of 600 kJ/kg-grain gave the best milled rice and head rice yields. Accordingly, future experimentation will involve exploration of MW specific energies of 533.33, 600, 800 and 900 kJ/kg. MW treatments were done in batch with power levels of levels of 5, 10 and 15 kW and heating durations of 4, 6 and 8 minutes for rice beds of thicknesses 5, 10 and 15 cm which translate to masses of 3, 6 and 9 kg and the experimental design is shown in Table 3.1.

Table 3.1: Rice bed thicknesses, microwave power levels and heating durations used in the rice drying experiments

Rice Bed Thickness (cm)	Microwave Power (kW)	Heating Duration (min)
15	10	8
5	5	6
10	10	6
10	15	4
15	15	6
5	5	8
5	10	4
10	10	8
15	15	8
10	15	6

Microwave Treatments

The implications of MW intensity and heating duration on treatments of rice beds of different thicknesses (5, 10 and 15 cm were studied. For each layer a sample of 3000 g rice was massed out and placed into MW safe trays (Fig. 3.1b) for the treatment. Each tray was stackable allowing for a total of up to 9000 g of rice to be treated at once. The outsides of the trays were made of polypropylene with a Teflon coated fiberglass mesh at the bottom to hold the samples. The trays with rice sample were set in the oven on the belt and treated at various power levels and durations (Table 3.1). The temperature of rice during MW heating was measured using fiber optic temperature sensors (OMEGA Engineering, INC., Stamford, CT 06907). After MW treatments, the samples were separated by layer then transferred immediately after to glass jars and sealed air tight. A HOBO sensor (Onset Computer Corporation, Bourne, MA) was placed in the jars to determine the changes in temperature and relative humidity inside the jars. The jars were placed in an environmental chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 60°C and relative humidity of 65%. The rice was tempered for 4 h. After the tempering, the rice was spread uniformly on individual trays, transferred to an EMC chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 25°C and relative humidity of 65%.

Statistical Analysis

Statistical analyses were performed with statistical software (JMP version 11.0.0, SAS Institute). A one-way fixed effects analysis of variance (ANOVA) and Tukey's honest significant difference (HSD) test were performed to determine significant differences within and among samples. All test were considered to be significant when $p < 0.05$.

Response surface methodology was then used to geometrically describe the relationship between a response and one or more factors. Response surface methodology is a collection of mathematical and statistical techniques based on the fit of a polynomial equation to the experimental data, which must describe the behavior of a data set with the objective of making statistical provisions. It can be well applied when a response or a set of responses of interest are influenced by several variables. By evaluating the responses, the set of operating conditions for making the product with the overall best response can be determined. This set of operating conditions is called the optimum condition for the process. The optimum condition for the response is represented by a function. The desirability of response is weighted by an importance value when it is considered against the goals of the other responses during optimization. The importance value is usually set when defining the responses.

RESULTS AND DISCUSSION

Implications of Microwave specific energy on rice surface temperature

Analyses were performed to investigate the correlation of the supplied MW specific energy with the rice bed surface temperature. Increasing specific energy supplied to the rice bed resulted in statistically significant ($p < 0.0001$) increases in rice bed surface temperature from an initial temperature of 17.5°C. Rice beds of 5 cm thicknesses treated with MW specific energy of 133.33 kJ/kg-grain had a surface temperature of 57.29°C. By contrast, at the highest specific energy of 800.00 kJ/kg-grain, for rice beds at the same thickness resulted in a surface temperature of 113.03 °C. Maximu surface temperatures and the corresponding MW specific energies can be seen in Table 3.2. Tukey's HSD test was done to identify where the differences were and are also indicated. Means with the same letter are not significantly different.

Table 3.2: Maximum surface temperatures and corresponding microwave specific energies

Specific Energy (kJ/kg-grain)	Maximum Temperature (^{o}C)	Tukey Grouping
133.33	57.29	G
200	99.79	F
266.67	101.93	E
300	103.25	D
400	111.87	C
533.33	122.23	B
600	135.83	A
800	133.03	A

Figure 3.2 shows the trend of data fitted to a cubic model. The solid line of fit is bounded by the confidence of fit and confidence of prediction.

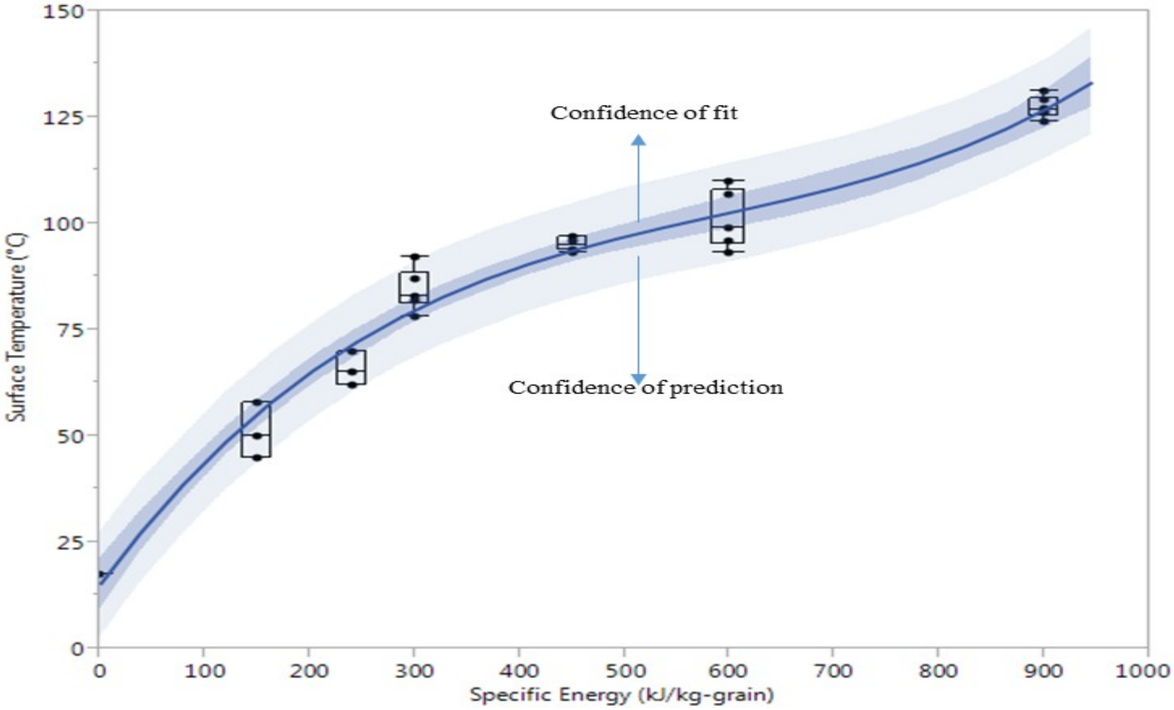


Figure 3.2: Relationship between rice surface temperature and specific energy input during microwave heating fitted to a cubic model

Implications of Rice Bed Thickness Variation on Rice Surface Temperature

The rice milling industry requires large throughputs for their drying operations to avoid drying bottlenecks at peak harvest times. Consequently, information is needed on the implications of increasing MW specific energy and rice bed thickness variation on the surface temperatures of medium grain rough rice. Due to the size limitations of the equipment, the rice beds studied in this experiment were 5, 10 and 15 cm, which corresponds to loading masses 3, 6 and 9 kg. It was determined that the effects of increasing MW specific energy and rice bed layer thickness both have a statistically significant ($p < 0.0001$) effect on the rice surface temperature as indicated by the effect test table in Table 3.3. However, it was determined that increasing

MW specific energy have more of an effect as indicated by the higher F ratio and lower p-value. This table shows the source of the effect, the number of parameters (n), the degrees of freedom (n-1), the sum of squares, F ratio and probability value. F ratio is the statistic used to test the hypothesis that the response means are significantly different from one another. A larger F ratio indicates a decreased likelihood that the observed difference in treatment means is due to chance. A small p-value (≤ 0.05) indicates strong evidence against the null hypothesis that increasing MW specific energy and rice bed thicknesses would not have a statistically significant effect on the mean surface temperatures.

Table 3.3: Effect test table showing the effects of increasing microwave specific energy and rice bed layer thickness

Source	**Number of Parameters**	**DF**	**Sum of Squares**	**F Ratio**	**Prob > F (p-value)**
Layer	3	2	692685	474.39	<.0001
Specific Energy (kJ/kg-rice)	8	7	16357744	3200.77	<.0001

Figure 3.3 shows the effect of increasing specific energy on the surface temperature of rice bed layers 1, 2 and 3. If the 15 cm rice bed was placed on an x-y plane, layer 1 (bottom layer) would represent the 0 to 5 cm layer, layer 2 (middle layer) would represent the 5 to 10 cm layer and layer 3 (top layer) would represent the 10 to 15 cm layer. These results provide insight on the uniformity of heating throughout a drying rice bed. It was observed that surface temperatures increased with increasing specific energy up until a certain temperature then began to decline with continued heating. Additionally, surface temperatures throughout the three rice

layers were more distant at lower specific energies. For example, at the specific energy of 133.33 kJ/kg-grain, layer 1 and layer 3 had a difference in surface temperature of approximately 40°C. By contrast at the specific energy of 400.00 kJ/kg that temperature difference was reduced by roughly half. This data indicates that higher specific energies are necessary for a more uniform heating.

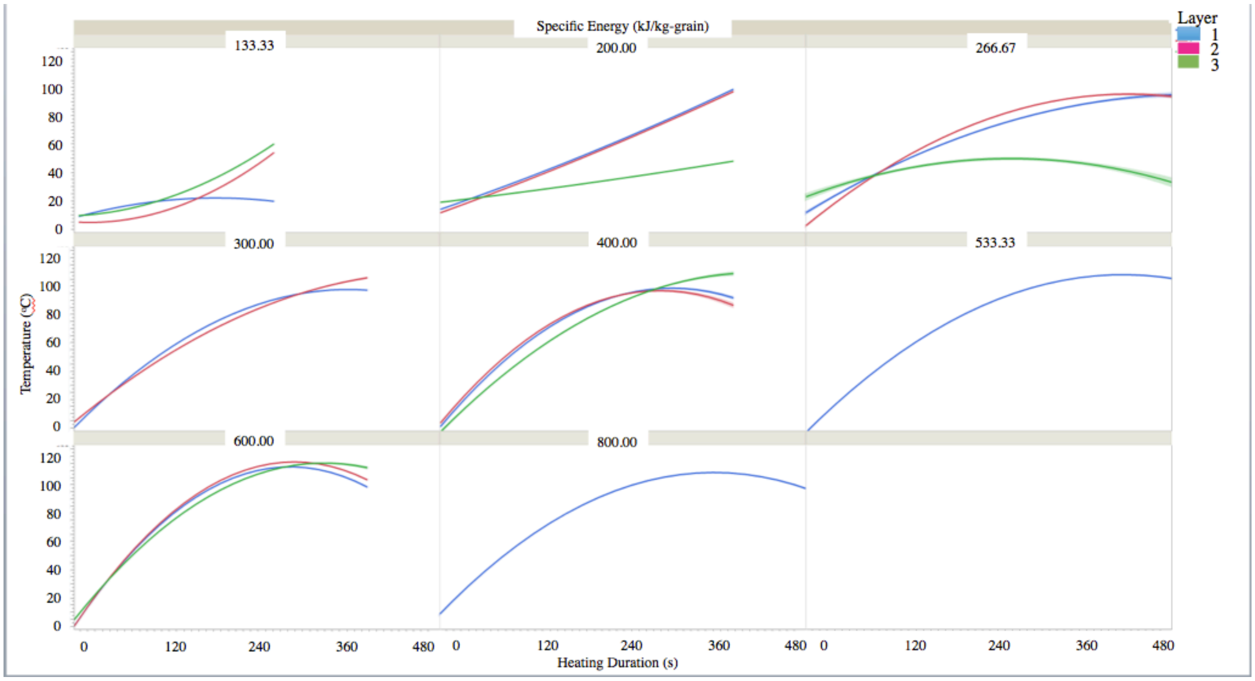


Figure 3.3: Effect of increasing microwave specific energy on the surface temperature of rice layers in a 15 cm thick rice bed

A surface plot was used to explore the relationship between the two predictor variables, specific energy and rice bed thickness, and response variable, rice bed surface temperature (Figure 3.4). The predictor variables are displayed on the x- and y-axis and the response variable is located on the z-axis. It should be noted that layer 2 had surface temperatures greater than layer 3 and layer 1. For example, at layer 2 the average surface temperature was 70.53°C while the layer on the top and bottom was 69.47 and 61.05°C respectively.

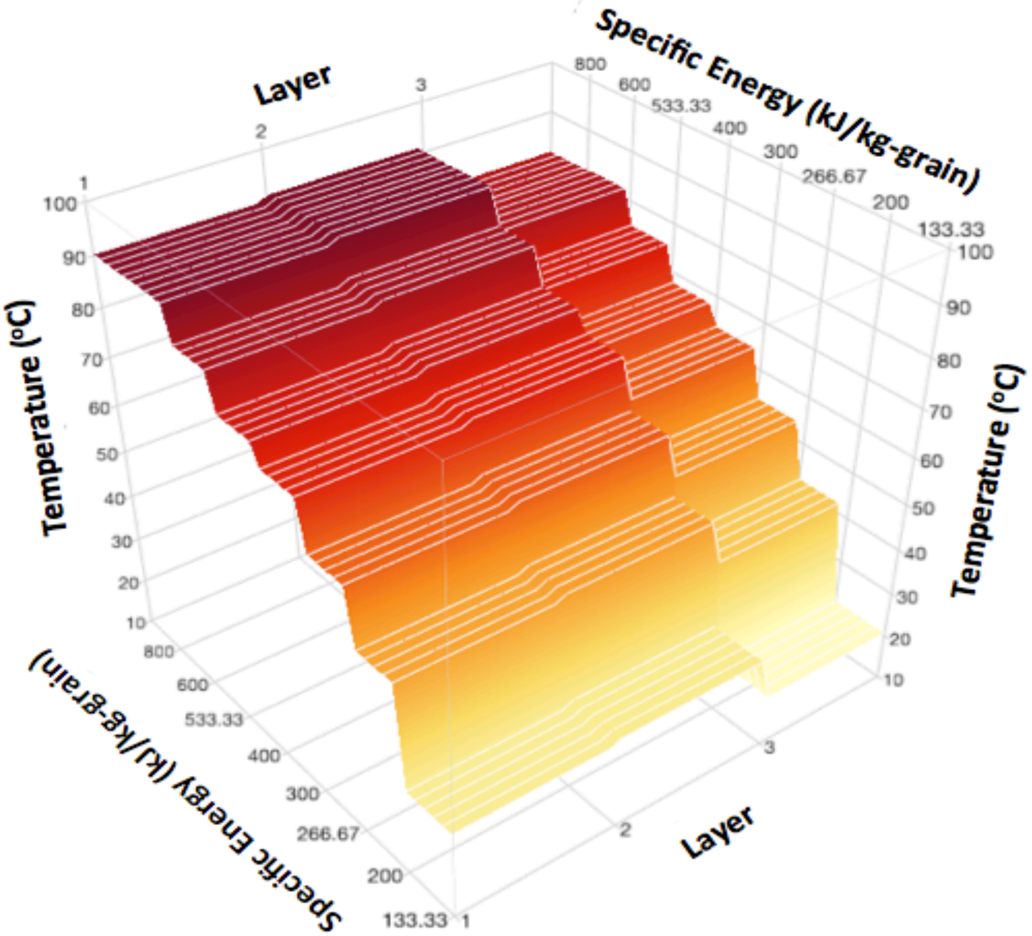


Figure 3.4: Surface profile showing the surface temperature (°C) of medium grain rough rice at increasing microwave specific energies and rice bed layer thicknesses

The data in Figure 3.4 suggests that there was not enough airflow at the middle layer to assist in removing heat. This resulted in the layer over heating. By contrast, the top and bottom layers did have considerably more air flow or mass transfer. As a result, the surface temperatures at these layers were much lower than the surface temperatures at the middle. Additionally, the top layer had a much lower surface temperature than the bottom. This was due to evaporative cooling. Evaporative cooling is the reduction in temperature resulting from the evaporation of a liquid, which removes latent heat from the surface from which evaporation takes place. Further evidence supporting this postulation is provided by Gunasekaran, S. (1990) who found that due to moisture evaporating continuously from the grain surface lowers the surface temperature because of the evaporative cooling effect. Average surface temperatures and the corresponding rice bed layer can be seen in Table 3.4. Tukey's HSD test was done to identify where the differences were and are also indicated. Means with the same letter are not significantly different.

Table 3.4: Average surface temperatures and corresponding Tukey grouping

Layer	Mean temperature (^{o}C)	Tukey Grouping
1	69.47	B
2	70.53	A
3	61.05	C

CONCLUSION

In the current investigation, non-uniform temperature distribution during the MW drying of medium grain rice was investigated. It was determined that increasing MW specific energy and increasing rice bed layer thickness have a statistically significant effect on the rice surface temperature. Increasing MW specific energy resulted in notable increases in the rice surface temperature. Additionally, higher specific energies are preferred for more uniform heating between rice bed layers.

There was a disparity in the final surface temperatures within rice beds as a result of increasing rice bed thicknesses. Rice bed middle layers had surface temperatures greater than the top and bottom layers as a consequence of the limited airflow and mass transfer at the middle.

Additionally, the top rice bed layer had a much lower surface temperature than the bottom rice bed layer as a result of evaporative cooling occurring at the top.

Commercial dryers that use convectively heated air operate at temperatures around 60°C and use multiple passes through the dryer (Wadsworth, 1994). In this study, it was observed that supplying MW energy greater than 250 kJ/kg-grain caused the rice surface temperature to exceed 60°C. The MW heating process is volumetric and leads to high-energy water molecules rapidly drifting through the rice kernel to the surface where they desorb. The volumetric heating at the high-energy fluxes afforded by MWs may allow the use of higher drying temperatures in short durations, compared to convective hot air heating. Additionally, knowledge of temperature rise and non-uniformity would be beneficial to rice millers as it would allow for the setting of optimal MW power, heating duration and rice throughput that would provide the optimal surface temperatures necessary for the necessary MC reduction while minimizing temperature non-uniformity within the drying rice beds.

FUTURE WORK

Research indicates that reductions in HRY are correlated with increased surface temperatures. This indicates that there is an upper limit to rice bed surface temperatures that should not be exceeded without significantly lowering the HRY (Stipe, Wratten, & Miller, 1972). Additionally, agricultural products experience case-hardening due to rapid drying at elevated temperatures. As drying progresses, the rate of water evaporation is faster than the rate of water diffusion to the product surface. Consequently, the outer skin becomes dry and acts as a water barrier, thus slowing down moisture removal and incurring quality degradation.

In order to optimize the MW process to rapidly dry freshly harvested rice to safe storage conditions without negatively affecting the milled rice and functional qualities future studies will involve determining the implications of increasing rice bed surface temperatures as a result of increasing MW specific energies on milled rice yields and physiochemical properties for increasing rice bed thickness; this will give insight on the feasibility of MW drying process at an industrial level.

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Implications of Specific Energy Supplied During Drying Of Medium Grain Rice by a 915 MHz Industrial Microwave on Rice Moisture Content and Milling Yields

ABSTRACT

This study aims to determine the effectiveness of utilizing a 915 MHz industrial microwave (MW) to achieve one pass rice drying with minimal implications on rice milling quality characteristics, especially the head rice yield (HRY). Medium-grain rough rice (cv. CL721) at initial moisture content (MC) of 23% (w.b.) was dried using a 915 MHz industrial MW set to transmit energy at power levels 5, 10, and 15 kW for 4, 6, and 8 minutes and rice bed thicknesses 5, 10 and 15 cm. Increasing MW specific energy had statistically significant effects ($p < 0.0001$) on all of the responses studied. Increasing specific energy caused increases in rice final surface temperature (FST) and drying rate. Conversely, increasing specific energies caused decreases in rice final moisture content (FMC), HRY, and milled rice yield (MRY). There was a statistically significant ($p < 0.05$) disparity in HRY as a result of increasing rice bed thicknesses. Highest HRY were observed at the top, followed by the middle and bottom layer. Increasing rice bed thicknesses did not result in any significant changes in the rice FMC or drying rate, and there was no disparity in these responses between any of the rice bed layers. The implications of rice FST, FMC and drying rate on HRY and MRY were determined. Increasing FST and drying rates and decreasing FMC resulted in significantly ($p <0.05$) lower MRY and HRY. Optimization analyses suggest that a power of 15 kW, a loading mass of 7.33 kg and a heating duration of 4 min are preferred for optimum MRY and HRY. These factor levels translate into a thickness of 4.40 cm and an optimized specific energy of 439.80 kJ/kg-grain. This study proves that the volumetric heating associated with MW technology can reduce MC and temperature gradients within individual rice *kernels resulting in MRYs and HRYs not significantly different from rice gently dried to an MC of 12.50% w.b. Additionally, the high heat fluxes associated with the MW heating results in one-pass drying of rough rice, from harvest MCs to safe storage MC (12.50%). Optimization of the MW drying technology to achieve rapid drying of high MC rice and superior rice quality would benefit the rice to reduce processing durations, improve HRY and attain an environmentally friendly drying method.*

Keywords: Rice temperature, rice bed thickness, microwave heating, milling yields, rice quality, microwave specific energy

INTRODUCTION

Rice kernel fissuring as a result of temperature and moisture content (MC) gradients negatively impacts the rice milling yield which, in large part, is quantified by the head rice yield (HRY) (USDA-GIPSA, 2010 and Kunze, 1979). The presence of fissures on a rice kernel makes it more susceptible to breakage during subsequent hulling and milling processes thus reducing the head HRY (Ban, 1971; Kunze & Choudhury, 1972; Kunze, 1979). HRY is the current standard in the rice industry to measure rice milling quality and is defined as the weight percentage of rough rice that remains as head rice (kernels that are at least three-fourths of the original kernel length) after complete milling. Preventing HRY reduction during drying is very critical and bears significant economic importance to the rice industry (Cnossen and Siebenmorgen, 2000). Under ideal conditions, a perfect HRY recovery would be about 70% of the total rough rice produced after the rice hulls and bran are removed. However, with current conventional rice drying methods, HRY recovery averages only about 58%, and can be even lower depending on other pre-harvest and post-harvest factors (USDA, 2014; Atungulu et al., 2015).

Conventional rice drying methods utilize either natural air or convectively heated air to dry grain. Air is forced up through the grain with fans until the grain MC is sufficiently reduced. Unlike microwave (MW) drying, heat is applied to the surface of the rice kernel instead of volumetrically. As a result, moisture is removed from the surface faster than at the center of the kernel creating a moisture gradient. The development of moisture gradients causes differential stresses within the rice kernel leading to an overall weakening of the rice mechanical properties resulting in the formation of fissures.

MWs are electromagnetic radiations with wavelengths ranging from 1 mm to 1000 mm in free space with a frequency between 300 GHz to 300 MHz, respectively. In microwave drying, heat is generated by directly transforming electromagnetic energy into molecular kinetic energy causing heat to be generated from within the material to be dried. The relatively high-energy flux and volumetric heating phenomenon resulting from microwave heating hold the potential to dry rough rice with reduced inter-kernel gradients of temperature and MC, thereby minimizing rice fissuring thus improving HRY. Also, the high and rapid heat fluxes provided by microwave drying hold the potential to inactivate harmful microorganisms especially harmful aflatoxigenic mold spores such as *Aspergillus flavus*. Preventing the proliferation of such mold spore will thusly reduce incidences of aflatoxin contamination and spoilage of rice.

MW drying offers great promise to achieve one-pass rice drying with improved milled rice quality. Atungulu et al. found that supplying MW specific energies of up to 600 kJ/kg-grain to medium grain rough rice at initial MC of 23% to 24%, and incorporating an additional 4 h tempering step at 60^{o}C dried rice resulted in dried rice with final MC of 14% to 16% with HRY not significantly different from gently dried (natural air at 25°C and relative humidity of 65%) control samples. The challenge, however, remains in scaling up the process to achieve commercially viable throughput.

The rice milling industry requires large throughputs for their drying operations to avoid drying bottlenecks at peak harvest times. Therefore, with increasing demand for higher throughputs and higher milled rice quality and for efficient operations, the drying operation and its control for minimizing product degradation is a current challenge for rice drying.

In this study, the effect of increasing MW specific energy on medium grain rice in multiple rice bed layers using a 915 MHz Industrial MW system was investigated. Insight on disparities in rice layer surface temperatures and drying rates and effects on milled rice yields and quality as a result of increasing rice bed thicknesses will allow for the tailoring of a MW drying system for application in the rice milling industry.

OBJECTIVES

This study investigated the effects of increasing microwave specific energy on the milling quality of medium grain rough rice. Additionally, this research aims to investigate disparities in rice bed milling quality as a result of temperature non-uniformity and increased drying rates between rice beds of increasing thicknesses. The specific objectives of this research were to investigate the implications of the following:

1) Increasing MW specific energy on rice milling quality in terms of milled rice yield and head rice yield.
2) Increasing microwave specific energy on the rice final surface temperature, final moisture content, and rice-drying rate.
3) Increasing rice bed layer thicknesses on rice milling quality in terms of MRY, HRY, rice final MC, final surface temperature (FST), and rice-drying rate.

Additionally, analyses were done using statistical software (JMP version 11.0.0, SAS Institute) to optimize the microwave drying process and determine optimal settings for power, loading mass (and equivalent rice bed thickness), and duration by setting desirability goals to maximize HRY and MRY and minimize the rice's final MC to safe storage conditions (12.50% w.b.).

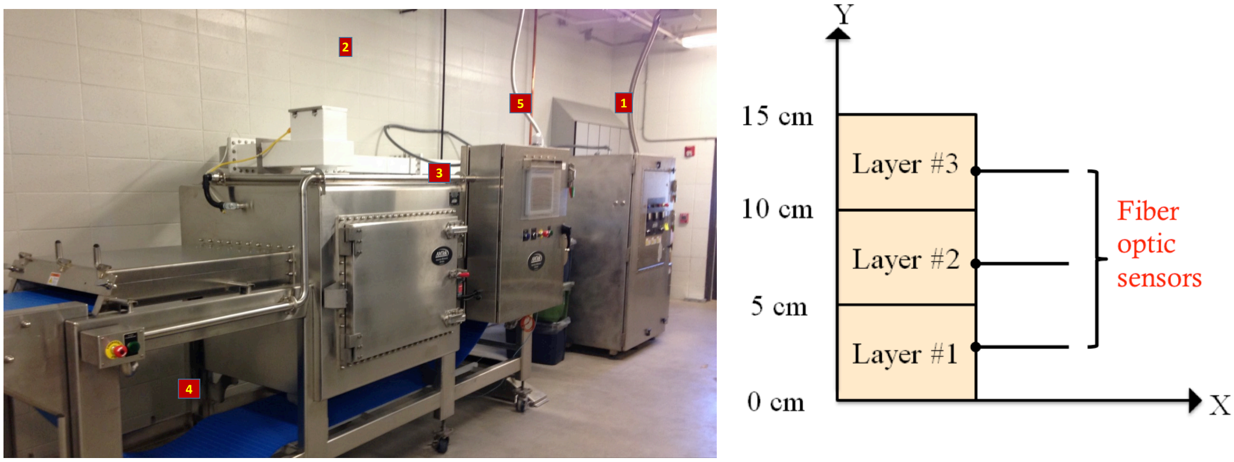
MATERIALS AND METHODS

Rice samples

Freshly-harvested, medium-grain rice samples (cv. Jupiter) at initial MC of 23.5% (wet basis) were used in this study. The samples were cleaned using a dockage equipment (MCi Kicker Dockage Tester, Mid-Continent Industries Inc., Newton, KS). The equipment used a series of small sized sieves to provide a fast, accurate and consistent way of separating shrunken, broken, scalped material, broken kernels, splits and dust from rice. The cleaned rice was stored in a laboratory cold room set at 4°C. At the beginning of the experiments, the samples were retrieved from the cold room and allowed to equilibrate with room conditions (25^{o} C) overnight before conducting any experiments. The MCs of the samples reported in this study were determined using an AM 5200 Grain Moisture Tester (PERTEN Instruments, Hägersten, Sweden) which was calibrated using the ASABE standard (Jindal and Siebenmorgen, 1987). The MC of each sample was measured by placing 15 g duplicate samples into a 130°C conduction oven (Shellblue, Sheldon Mfg., Inc., Cornelius, OR) for 24 h, followed by cooling in a desiccator for at least half an hour (Jindal and Siebenmorgen, 1987). All reported MCs are on wet basis.

Microwave equipment

An industrial microwave system (AMTek, Applied Microwaves Technology Inc., Cedar Rapids, IW) was used in this study. The system (Fig. 4.1a) consists of a transmitter, a wave guide, and the microwave heating zone (oven) and operates at a frequency of 915 MHz. The transmitter is a high-powered vacuum tube that works as a self-excited microwave oscillator. It is used to convert high-voltage electric energy to microwave radiation. The waveguide consists of a rectangular or cylindrical metal tube or pipe through which the electromagnetic field propagates lengthwise. It is used to couple microwave power from the magnetron into the lab oven. The lab oven is the internal cavity of the microwave that provides uniform temperatures throughout while in use.



(a) (b)

Figure 4.1a: Diagram of microwave system showing the transmitter (1), heating zone (2), wave guide (3), conveyor belt (4), and control panel (5), **Figure 4.1b:** Diagram of 9 kg of rice in 3 stackable microwave blind trays fitted with fiber optic cables in each layer

Experimental Design

The experimental conditions were determined based on a feasibility study. It was determined that MW treatments over 800 kJ/kg-grain result in the rice burning and popping. Consequently, for this research specific energies above 800 kJ/kg-grain were omitted. MW treatments were done in batch with power levels of levels of 5, 10 and 15 kW and heating durations of 4, 6 and 8 minutes for rice beds of thicknesses 5, 10 and 15 cm which translates to loading masses of 3, 6 and 9 kg. The experimental design is shown in Table 4.1.

Table 4.1: Rice bed thicknesses, microwave power levels and heating durations used in the rice drying experiments

Rice Bed Thickness (cm)	Microwave Power (kW)	Heating Duration (min)
5	5	4
5	5	6
5	5	8
5	10	4
10	5	4
10	5	6
10	5	8
10	10	4
10	10	6
10	10	8
10	15	4
15	5	4
15	5	6
15	5	8
15	10	4
15	10	6
15	10	8
15	15	4
15	15	6
15	15	8

Microwave Treatments

The implications of MW intensity and heating duration on treatments of rice beds of different thicknesses (5, 10 and 15 cm) were studied. For each layer a sample of 3000 g rice was massed out and placed into MW safe trays (Fig. 4.1 b) for the treatment. Each tray was stackable allowing for a total of up to 9000 g of rice to be treated at once. The outsides of the trays were made of polypropylene with a Teflon coated fiberglass mesh at the bottom to hold the samples. The trays with rice sample were set in the oven on the belt and treated at various power levels and durations (Table 4.1). The temperature of rice during MW heating was measured using fiber optic temperature sensors (OMEGA Engineering, INC., Stamford, CT 06907). After MW treatments, the samples were separated by layer then transferred immediately after to glass jars and sealed air tight. A HOBO sensor (Onset Computer Corporation, Bourne, MA) was placed in the jars to determine the changes in temperature and relative humidity inside the jars. The jars were placed in an environmental chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 60°C and relative humidity of 65%. The rice was tempered for 4 h. After the tempering, the rice was spread uniformly on individual trays, transferred to an EMC chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 25°C and relative humidity of 65%.

Drying Rate Calculation

Drying rate is defined by the loss of moisture from the wet solid per unit time. A general temperature and RH independent equation was created to estimate drying rates and can be found in equation 1;

$$\boldsymbol{Drying\ rate} = \left(\frac{\boldsymbol{kg.water\ removed}}{\boldsymbol{second}}\right) = \frac{(\boldsymbol{m_w - m_d})}{\boldsymbol{t}} \qquad \textbf{(1)}$$

Where;

m_w = Mass of rice before drying (kg)

m_d = Mass of rice after drying (kg)

t = Heating duration (s)

Rice Milling

Triplicate, 150 g sub samples of rough rice, obtained from each sample dried to 12.50% MC, were dehulled using a laboratory huller (Satake Rice Machine, Satake Engineering Co., Ltd., Tokyo, Japan), milled for 30 s using a laboratory mill (McGill #2 Rice Mill, RAPSCO, Brookshire, TX) and aspirated for 30 s using a seed blower (South Dakota Seed Blower, Seedboro, Chicago, IL). MRY was calculated as the mass proportion of rough rice that remains including head rice and broken, after milling. Head rice was then separated from broken kernels using a double tray sizing machine (Grainman Machinery Manufacturing Corp., Miami, FL). Head rice are considered as kernels that remain at least three-fourths of the original kernel length after complete milling (USDA-GIPSA 2010). HRY was calculated as the mass proportion of rough rice that remains as head rice after complete milling.

Statistical Analysis

Statistical analyses were performed with statistical software (JMP version 11.0.0, SAS Institute). A one-way fixed effects analysis of variance (ANOVA) and Tukey's honest significant difference (HSD) test were performed to determine significant differences within and among samples. All tests were considered to be significant when $p < 0.05$.

Response surface methodology (RSM) was then used to geometrically describe the relationship between a response and one or more factors. RSM is a collection of mathematical and statistical techniques based on the fit of a polynomial equation to the experimental data, which describe the behavior of a data set with the objective of making statistical inferences. It can be well applied when a response or a set of responses of interest are influenced by several variables. By evaluating the responses, the set of operating conditions for making the product with the overall best response can be determined. This set of operating conditions is called the optimum condition for the process. The optimum condition for the response is represented by a function. The desirability of response is weighted by an importance value when it is considered against the goals of the other responses during optimization. The importance value is usually set when defining the responses.

Optimization Factors

Based on a feasibility study it was determined that changes in MW specific energy have statistically significant ($p < 0.05$) effects on the rice in terms of surface temperature, final MC, milled rice and physiochemical properties and that optimum responses occurred at or around 600 kJ/kg-grain. Accordingly, future experimentation involved exploration of microwave specific of 533.33, 600 and 800 kJ/kg.

MW specific energy (kJ/kg) is defined as the microwave energy transferred per unit mass of product being treated and is calculated as follows;

$$SE = \frac{P \times T}{M} \quad (2)$$

Where:

SE is the microwave specific energy (kJ/kg)

P is the microwave power (kW)

T is the microwave heating duration (s)

M is the mass of product being treated (kg)

Minute changes in MW power, heating durations or product loading mass exact changes in the magnitude of MW specific energy. For example, an increase in product mass will cause a decrease in MW specific energy and vice versa. Therefore the factors of importance for this study are the factors that lead to changes in MW specific energy.

Response Variables

Variables of interest in an experiment (those that are measured or observed) are called response or dependent variables. The response variables that will be optimized in this experiment are MRY, HRY, and FMC. These response variables and their response goals were determined as most important based on a literature review and are presented in Table 2.

Head Rice Yield And Milled Rice Yield

Preventing HRY reduction during drying is very critical and bears significant economic importance to the rice industry. Hence, HRY and MRY were given the highest importance (3) because they hold the most economic importance for the rice milling industry. The response goal was set to maximize responses.

Final Moisture Content

High MC rice is susceptible to spoilage especially from the proliferation of fungal spores inherent in the rice production and harvesting systems. Drying rough rice below harvest MCs to that necessary for safe storage conditions (12.50% w.b) is the most effective and widely used method to preserve the microbial quality of rice. The introduction of a one-pass drying system that can dry rough rice lots from harvest conditions to a MC of 12.50 -13.00% w.b in one pass with HRY comparable or better than conventional drying methods will translate into a large cost savings for the rice milling industry. To that end, rice FMC was also given an importance of 3. The response goal was set to minimize responses (Table 4.2).

Table 4.2: Experimental responses, response goals, and importance

Response Name	Response Goal	Importance
Milled Rice Yield (%)	Maximize	3
Head Rice Yield (%)	Maximize	3
Final Moisture Content (%)	Minimize	3

RESULTS AND DISCUSSION

Implications of Increasing Microwave Specific Energy on milled rice yield and head rice yield

Control samples constituted medium-grain rough rice (cv. CL721) at initial (MC) of 23% w.b. that were not treated with MW but gently dried to a MC of 12.50% w.b. in an EMC chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 25°C and relative humidity of 65%. The least square means of the control MRY and HRY were 70.35 and 63.13 %, and standard deviations were 3.02 and 4.38 respectively.

The effect of increasing MW specific energy was found to be significant for both the MRY and HRY responses as indicated by the effect test tables (Tables 3 and 4). This table shows the source of the effect, the degrees of freedom (n-1), the sum of squares, and mean square, F ratio, and probability value. F ratio is the statistic used to test the hypothesis that the response means are significantly different from one another. A larger F ratio indicates a decreased likelihood that the observed difference in treatment means is due to chance. A small p-value ($\leq$ 0.05) indicates strong evidence against the null hypothesis. It should be noted that the MRY response had a much smaller F ratio with reference to the HRY response. This indicates that the HRY response was more sensitive to the effects of increasing MW specific energy than the MRY.

Milled rice is rice that remains once the brown rice has been milled to remove the germ and a specified amount of the bran; this fraction includes both broken and intact kernels (Webb, 1991). As a result, the variation between milled rice yields is not expected to be large and is usually around 70% representing the removal of 30% of the rice kernel in the form of the hull and bran.

Table 4.3: Effect test table showing the effects of increasing microwave specific energy on the milled rice yield

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	890.5752	111.322	3.5734
Error	111	3457.9457	31.153	**Prob > F**
C. Total	119	4348.5209		0.0010*

Table 4.4: Effect test table showing the effects of increasing microwave specific energy on the head rice yield

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	7114.573	889.322	5.9472
Error	111	6190.106	55.767	Prob > F
C. Total	119	13304.679		<.0001*

Milled Rice Yield

The implications of increasing specific energy on the MRY and HRY were determined and are displayed in Figure 4.2. Tukey's HSD test was done to identify where the differences were and are indicated on the graph. Means with the same letter are not significantly different. The effect of increasing MW specific energy was determined to have statistically significant effects on the MRY. As MW specific energy increased, the MRY increased to a peak response at 300 kJ/kg-grain after which the MRY decreased. At this specific energy rice samples had least square means of 79.27% and standard deviation of 2.34. It should be noted, however, that the MRY for rice samples treated with MW were statistically similar to the MRY of control samples gently dried with natural air.

Head Rice Yield

The effect of increasing MW specific energy was determined to have statistically significant effects on the HRY (Fig. 4.2). As MW specific energy increased, the HRY increased to a peak response at 300 kJ/kg-grain. At this specific energy rice samples had least square means of 67.89% and standard deviation of 3.12. As MW specific energy increased, the HRY increased to a peak response at 300 kJ/kg-grain after which the HRY decreased. This slight reduction can be attributed to the increasing specific energy. Higher MW specific energies have been shown to induce larger surface temperatures causing the formation of fissures. The presence of fissures on a rice kernel makes it more susceptible to breakage during subsequent hulling and milling processes.

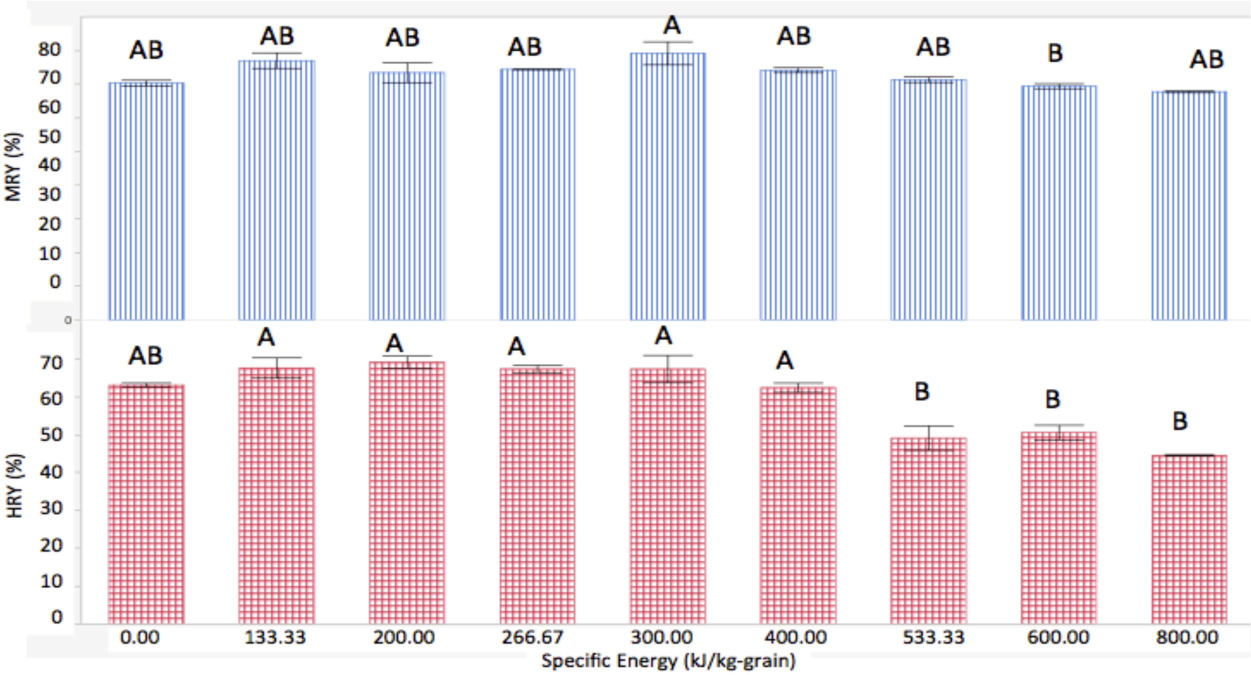


Figure 4.2: Effect of increasing microwave specific energy on the milled rice yield and head rice yield of medium grain rice. Means with the same type of letters are not significantly different at $\alpha = 0.05$.

Implications Of Rice Bed Thickness Variation

The effects of increasing MW specific energy and rice bed layer thickness (1, 2 and 3 which correspond to 5.00 10.00 and 15.00 cm) were determined for the MRY and HRY. Tables 4.5 and 4.6 show the effect summary table for the MRY and HRY responses respectively. The tables list the model effects, sorted by ascending *p*-values. Smaller p-values indicate higher significance to the model. Data suggests that increasing rice bed layer thickness was only significant for the HRY response as indicated by the corresponding p-value.

Table 4.5: Effect summary table showing the effects of increasing microwave specific energy and rice bed layer thickness on the milled rice yield response

Source	P Value
Layer	0.9352
Specific Energy (kJ/kg-rice)	0.0014*

Table 4.6: Effect summary table showing the effects of increasing microwave specific energy and rice bed layer thickness on the head rice yield response

Source	P Value
Layer	0.01399
Specific Energy (kJ/kg-rice)	0.02873

Milled Rice Yield

The implications of increasing rice bed thicknesses on the rice MRY and HRY were determined and are displayed in Figure 4.3. Tukey's HSD test was done to identify where the differences were and are indicated on the graph. Increasing the rice bed layer thickness resulted in a disparity in responses between layers. The top layer (Layer 3) had MRY higher than the middle (Layer 2) and bottom layers (Layer 1). At this layer, the samples had MRY with a least square mean of 72.99 and standard deviations of 0.71. The bottom layer had MRY higher than the middle layer. In rice beds of 15 cm thickness, it was observed that middle rice bed layers tend to reach higher surface temperatures compared to the top and bottom layers which resulted in lower MRY. Top layers experienced evaporative cooling resulting in lower surface temperatures and thusly-higher MRY. It should be noted that there was no statistical difference in MRY between the rice bed layers.

Head Rice Yield

Increasing the rice bed layer thickness resulted in a disparity in responses between layers (Fig. 4.3). The top layer (Layer 3) had HRY higher than the middle (Layer 2) and bottom layers (Layer 1). At this layer, the samples had HRY with a least square mean of 64.52 and standard deviations of 0.71. The bottom and middle layers had statistically similar mean HRYs that were lower than the top layer.

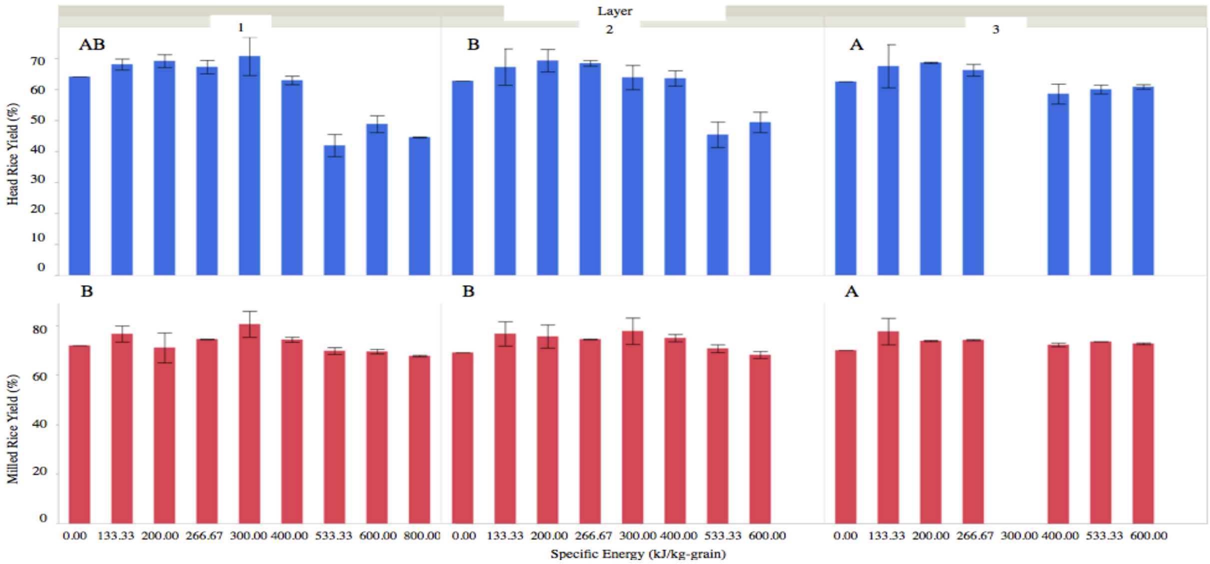


Figure 4.3: Effect of increasing microwave specific energy and rice bed thicknesses on the milled rice yield and head rice yield of medium grain rice. Means with the same type of letters are not significantly different at $\alpha = 0.05$.

Implications of Increasing Microwave Specific Energy on final moisture content and drying rate

The implications of MW specific energy on the rice FMC, and drying rate were determined and are displayed in Figure 4.4. The effect of increasing MW specific energy was found to be statistically significant ($p < .0001$) for both the FMC and drying rate responses as indicated by the effect test shown in Tables 4.7 and 4.8.

Final Moisture Content

The FMC decreased with increasing specific energy. The lowest FMC were seen at the specific energy of 800 kJ/kg. The responses of FMC had least mean square of 13.50 and standard deviation of 1.02.

Drying Rate

The effect of increasing specific energy was found to be statistically significant (p> 0.0001) on the drying rate response. The drying rate increased with increasing specific energy until a slight drop at the specific energy of 800 kJ/kg-grain. At this specific energy, the response of drying rate had least square mean of 0.0007 and standard deviation of 0.0001.

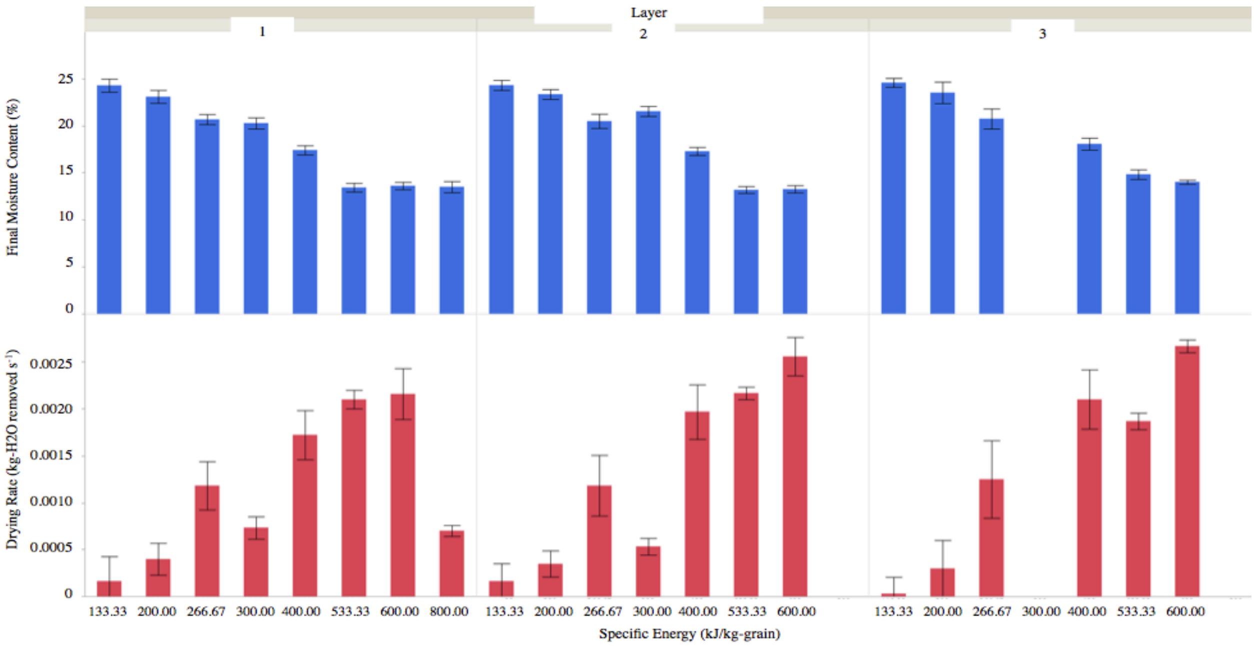


Figure 4.4: Effect of increasing microwave specific energy on the final moisture content and drying rate of medium grain rice. Means with the same type of letters are not significantly different at $\alpha = 0.05$.

Table 4.7: Effect test table showing the effects of increasing microwave specific energy on the rice final moisture content

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	1663.6751	207.959	98.1859
Error	108	228.7458	2.118	**Prob > F**
C. Total	116	1892.4209		<.0001*

Table 4.8: Effect test table showing the effects of increasing microwave specific energy on the rice drying rate

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	0.00007095	8.8684e-6	17.2607
Error	108	0.00005549	5.1379e-7	**Prob > F**
C. Total	116	0.00012644		<.0001*

Implications of rice bed thickness variation on Final Surface Temperature

The rice milling industry requires large throughputs for their drying operations to avoid drying bottlenecks at peak harvest times. Consequently, information is needed on the implications of increasing MW specific energy and rice bed thickness variation on the surface temperatures of medium grain rough rice. It was determined that the effects of increasing MW specific energy and rice bed layer thickness both have a statistically significant ($p < 0.0001$) effect on the rice surface temperature as indicated by the effect test table in Table 4.9. The FST decreased with increasing specific energy. The highest FST was seen at the specific energy of 800 kJ/kg. At this specific energy, the response of FST had least square means of 122.50^{o}C and standard deviation of 5.50 ^{o}C. However, it was determined that increasing MW specific energy have more of an effect as indicated by the higher F ratio and lower p-value.

Table 4.9: Effect test table showing the effects of increasing microwave specific energy and rice bed layer thickness on the rice final surface temperature

Source	**Number of Parameters**	**DF**	**Sum of Squares**	**F Ratio**	**Prob > F (p-value)**
Layer	3	2	692685	474.39	<.0001
Specific Energy (kJ/kg-rice)	8	7	16357744	3200.77	<.0001

Figure 4.5 shows the effect of increasing specific energy on the surface temperature of rice bed layers 1, 2 and 3. If the 15 cm rice bed was placed on an x-y plane, layer 1 would represent the 0 to 5 cm layer, layer 2 would represent the 5 to 10 cm layer and layer 3 would represent the 10 to 15 cm layer. These results provide insight on the uniformity of heating throughout a drying rice bed. It was observed that surface temperatures increased with increasing specific energy up until a certain temperature then began to decline with continued heating. Additionally, surface temperatures throughout the three rice layers were more distant at lower specific energies. For example, at the specific energy of 133.33 kJ/kg-grain, layer 1 and layer 3 had a difference in surface temperature of approximately 40^{o}C. By contrast at specific energy of 400.00 kJ/kg that temperature difference was reduce by approximately half. This data indicates that higher specific energies are necessary for a more uniform heating.

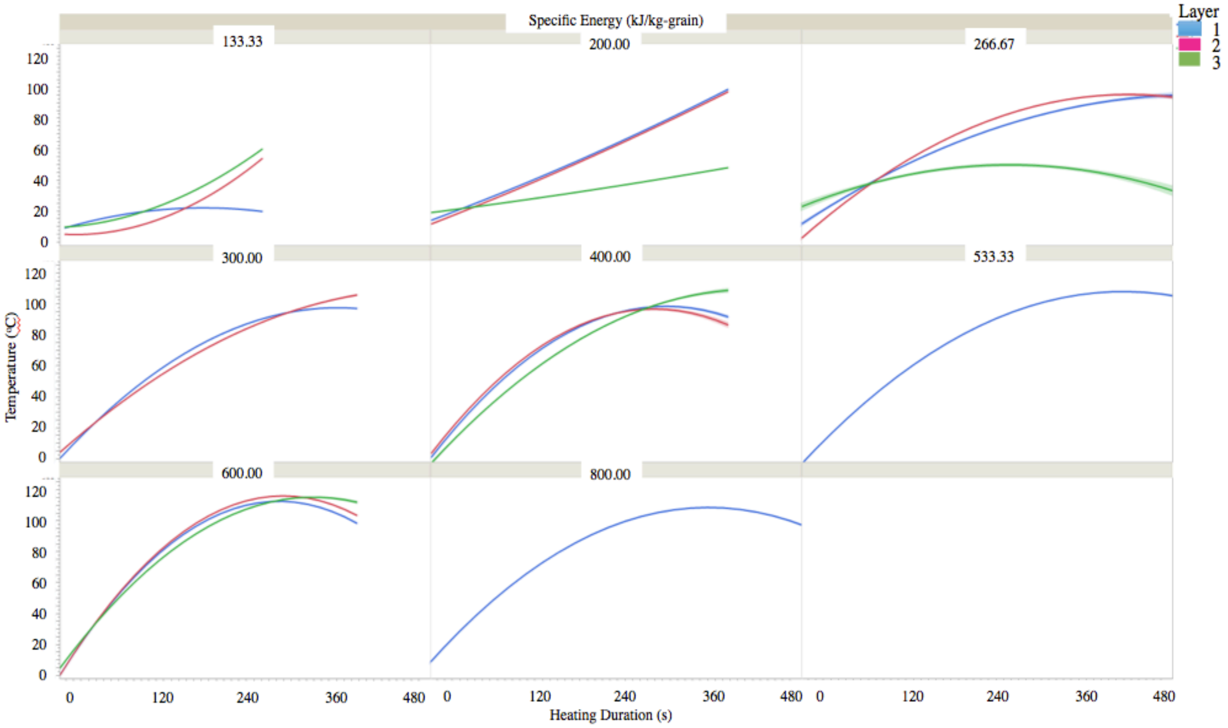


Figure 4.5: Effect of increasing microwave specific energy on the surface temperature of rice layers in a 15 cm thick rice bed

Implications of increasing rice bed thickness on final moisture content and drying rate

The factor of rice bed thicknesses was not significant for the drying rate and FMC responses (p = 0.15 and p = 0.57). Increasing the rice bed layer thickness did not result in any changes in FMC, FST or drying rate and there was no disparity in these responses between any of the layers.

Implications of final moisture content, final surface temperature and drying rate on milled rice quality

Analyses were conducted to determine the implications of the FMC, FST and drying rate effects on the MRY and HRY. Tables 4.10 and 4.11 list the model effects, sorted by ascending *p*-values for the FMC, FST and drying rate effects for the MRY and HRY responses.

Milled Rice Yield

For the response of MRY, of the 3 factors analyzed it was determined that FMC had the most effect on MRY ($p = 0.009$). This means that the effect of decreasing FMC lead to a significant decrease in MRY. The effects of FST and drying rate did not have any significant statistical effect on the MRY as indicated by their p-values of $p = 0.56$ and $p = 0.81$ respectively. This shows that increases in FST and drying rate did not significantly affect the sample MRY.

Table 4.10: Effect summary table showing the effects of rice final moisture content, final surface temperature and drying rate on the milled rice yield response

Source	P Value
Final moisture content (%)	0.00886
Final surface temperature (^{o} C)	0.56131
Drying rate (kg/s)	0.81446

Head Rice Yield

It was determined that FMC had the most significant effect on the HRY ($p < 0.0001$). Decreasing FMC leads to a significant decrease in HRY. The effects of FST also had an effect on the HRY. Higher final surface temperatures resulted in low HRY. Drying rate did not have any significant statistical effect on the HRY ($p = 0.89$).

For the response of HRY, of the 3 factors analyzed, it was determined that FMC have the most effect on HRY ($p < 0.0001$) (Table 12). This means that the effect of decreasing FMC lead to a significant decrease in HRY. The effects of FST also had a significant ($p = 0.05$) effect on the HRY. Increasing FST resulted in significantly lower HRY. This result was corroborated by Wadsworth (1993), who postulated that increased surface temperatures are correlated with decreases in HRY. Drying rate did not have any significant (p = 0.89) effect on the HRY. It should be noted, however, that the HRY for rice samples treated with MW were statistically similar or higher than the HRY of control samples gently dried with natural air.

Table 4.11: Effect summary table showing the effects of rice final moisture content, final surface temperature and drying rate on the head rice yield response

Source	PValue
Final moisture content (%)	0.00000
Final surface temperature (^{o}C)	0.04506
Drying rate (kg/s)	0.88557

Optimization

Specific energy is calculated using the variables of microwave power, treatment duration, and loading mass of the treated sample and can be obtained by using many different combinations of these variables. For example, a specific energy of 600 kJ/kg-grain can be obtained using the following combinations of power, loading mass, and duration in Table 4.12 below;

Table 4.12: Possible power, loading mass and treatment durations necessary to achieve a microwave specific energy of 600 kJ/kg-grain

Power (kW)	Mass (kg)	Treatment Duration (min)
10.00	6.00	6.00
15.00	6.00	4.00
15.00	9.00	6.00

Due to the combinatorial nature of MW specific energy, the process must be optimized to determine the best combinations of power, mass and heating durations necessary to achieve the greatest responses in terms of physical characteristics of the end product. Typically in the analysis of industrial data, there are many response variables to be investigated. The problem arises when all of these responses are under investigation at the same time. The experimenter must decide which responses are most important, usually at the expense of other responses. To overcome this problem, optimization was carried out using RSM.

Prediction Profiler was used to set desirability goals, which in this study was to maximize MRY and HRY and to minimize the FMC. This was done to find optimal settings for the factors of power, mass, and duration. According to the prediction profiles (Figure 4.6) it was determined that maximum MRY and HRY and minimum FMC is obtained at factor settings found in Table 4.13.

Table 4.13: Optimized parameter settings for milled rice yield, head rice yield and final moisture content

Factor	Optimized settings
Power (kW)	15
Loading Mass (kg)	7.33
Duration (min)	4

Table 4.14: Optimized parameter responses for milled rice yield, head rice yield and final moisture content

Response	Optimized response
Milled rice yield (%)	71.91
Head rice yield (%)	57.79
Final moisture content (%)	14.97

Of the possible power (5, 10 and 15 kW), loading mass (3, 6 and 9 kg) and treatment duration (4, 6 and 8 mins) combinations, it was determined that a power of 15 kW, mass of 7.33 kg and a duration of 4 min provides optimal MRY (71.91 %), HRY (57.59 %) and FMC (14.97 %). It should be noted that a mass of 7.33 kg translates into a thickness of 4.40 cm and that the optimized factor settings translate into a specific energy of 439.80 kJ/kg-grain.

In addition to the determination of the optimal factor levels, the prediction profiler also gives insight to the significance of impact a factor has on the performance parameter in question. A steep slope indicates that an operational parameter has a significant impact on the given performance parameter, whereas a shallow slope indicates little or no effect on a performance parameter.

The Desirability Profile

The last row of plots shows the desirability trace for each factor. The numerical value beside the word 'Desirability' on the vertical axis is the geometric mean of the desirability measures. This row of plots shows both the current desirability and the trace of desirability that result from changing one factor at a time. A desirability of 0.81 indicates that approximately 80.86 % of the goals to optimize milled rice quality responses were reached.

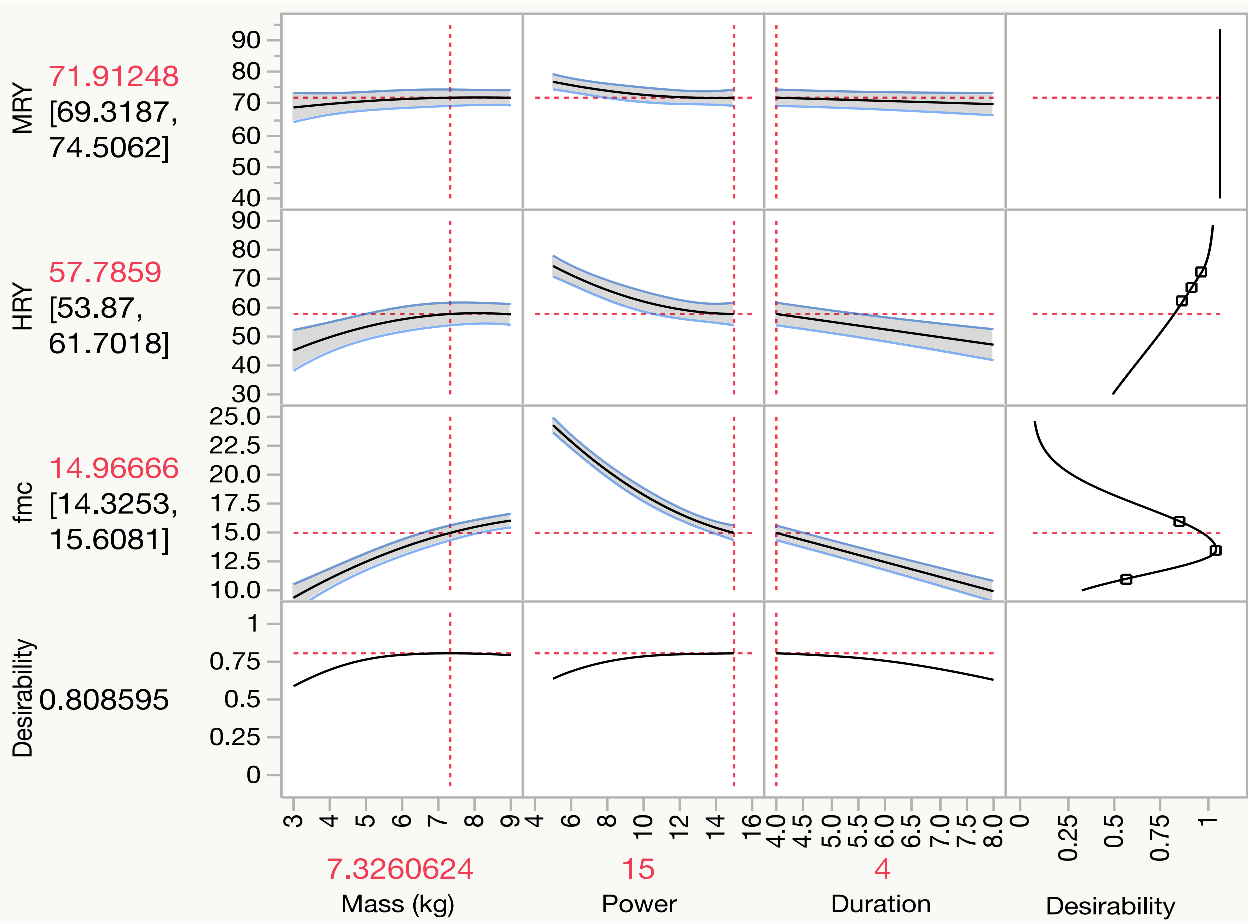


Figure 4.6: Prediction profile for the milled rice yield (MRY), head rice yield (HRY) and final moisture content (fmc) responses with parameter settings power, loading mass and heating duration

Table 4.15 shows the effect summary table for responses MRY, HRY and FMC. The tables list the model effects, sorted by ascending *p*-values. Smaller p-values indicate higher significance to the model. It was determined that the effect of increasing MW power was the only effect that caused statistically significant changes on the MRY response as indicated by the p-value.

The effects of increasing power and treatment duration were determined to be most significant for the HRY response as indicated by the p-values. The effect of increasing rice bed mass or thicknesses did not have a statistical effect on the HRY response.

There was high significance for the power, mass, and duration effects for the FMC response.

Table 4.15: Effect summary table showing the effects of power, loading mass and heating duration on the milled rice yield, head rice yield and final moisture content responses

Source	**Response P-Value**		
	Milled Rice Yield (%)	Head Rice Yield (%)	Final Moisture Content (%)
Power (kW)	0.00014	< 0.0001	<0.0001
Mass (kg)	0.14730	0.45921	<0.0001
Duration (min)	0.77727	< 0.0001	<0.0001

Validation

Using optimization analyses, it was determined that 15.00 kW, 7.33 kg, and a 4.00 minute heating duration provide the optimal response in terms of MRY and HRY. These factor levels translate into a thickness of 4.40 cm and an optimized specific energy of 491.13 kJ/kg-grain. Predicted data for MRY and HRY was compared to experimental data. At 533.33 kJ/kg-grain, specific energy experimental MRY and HRY were 71.29 and 56.37 % respectively. These levels which are well within the range of the predicted data.

CONCLUSION

This work showed that MW drying of rough rice holds promise as a rapid drying method once the parameter settings of power, mass and duration are optimized to produce the most desirable products in terms of HRY and MRY.

Increasing MW specific energy had statistically significant effects ($p < 0.0001$) on all of the responses studied. Increasing specific energy caused increases in rice FST and drying rate. Conversely, increasing specific energies caused decreases in rice FMC, HRY, and MRY. There was a statistically significant ($p < 0.05$) disparity in HRY as a result of increasing rice bed thicknesses. Highest HRY were observed at the top, followed by the middle and bottom layer. Increasing rice bed thicknesses did not result in any significant changes in the rice FMC or drying rate, and there was no disparity in these responses between any of the rice bed layers. The implications of rice FST, FMC and drying rate on HRY and MRY were determined. Increasing FST and drying rates and decreasing FMC resulted in significantly ($p <0.05$) lower MRY and HRY. Analyses were done to determine the statistical significance of applied MW power, loading mass, and treatment duration to the overall fit of models for MRY, HRY and FMC. The analysis indicated high significance for the power factor only in the MRY model. This means that increasing power had more of an effect on the MRY response than the other factors. High significance was seen for the power and duration factors in the HRY response model. This means that increasing power and duration had more of an effect on the HRY response than the other factor of mass. High significance was seen for power, mass, and treatment duration on the FMC response. This means that all factors had a significant effect on the FMC.

Optimization analyses suggest that a power of 15 kW, a mass 7.33 kg and a heating duration of 4 min are preferred for optimum MRY and HRY. These factor levels translate into a thickness of 4.40 cm and an optimized specific energy of 439.80 kJ/kg-grain. This study proves that the volumetric heating associated with MW technology can reduce MC and temperature gradients within individual rice kernels resulting in MRYs and HRYs not significantly different from rice gently dried to an MC of 12.50% w.b. Additionally, the high heat fluxes associated with the MW heating results in one-pass drying of rough rice, from harvest moisture contents to safe storage MC (12.50%).

Optimization of the microwave drying technology to achieve rapid drying of high MC rice and superior rice quality would benefit the rice industry by saving energy, considerably reducing processing durations, improving HRY and accord environmentally friendly drying.

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Implications of Microwave Drying Using 915 MHz Frequency on Rice Physiochemical Properties

ABSTRACT

Rice, in any of its many prepared forms, provides more than one-fifth of the total calories consumed by the world's population. Its kernels are processed and used in a vast variety of dishes including cereals, desserts, and bread. The quality and consumer acceptability of the final food product are vital factors to consider in any drying process. Microwave (MW) drying offers great promise to achieve simultaneous rice drying and decontamination of mycotoxin-producing molds. However, the heating process needs to be optimized so that the rice quality is not compromised. The objective of this study was to investigate the effects of utilizing an industrial MW to rapidly dry high moisture content (MC) rice on the physiochemical properties. Medium-grain rough rice (cv. CL721) at initial MC of 24% (w.b.) was dried using a 915 MHz industrial MW set to transmit energy at power levels 5, 10, and 15 kW for 4, 6, and 8 minutes and rice bed thicknesses 5, 10 and 15 cm. Near-infrared (NIR) spectroscopy and a rapid visco-analyzer (RVA) were used to assess the milled rice protein content, surface lipid content (SLC), total color difference (TCD) and rice peak and final viscosities (cP). The effect of increasing MW specific energy was statistically significant ($p < 0.0001$) for all of the responses studied. Increasing MW specific energy resulted in an increase in measures rice surface lipid content (SLC), protein content and final and peak viscosities. Responses increased to a maximum then decreased at specific energies over 800 kJ/kg-grain. The opposite profile was true for rice total color difference. TCD decreased as a result of increasing MW specific energy to its lowest point at 533.33 kJ/kg-grain then increased at specific energies over 600 kJ/kg-grain. The effect of *varying rice bed thicknesses was not statistically significant. There was no disparity in any of the rice physiochemical properties across rice bed thicknesses of up to 15 cm. Statistical analyses to determine optimal settings for the MW drying with least impact on the rice physiochemical properties indicated the settings of MW power, rice bed thickness and MW treatment duration to be at 10.95 kW, 10.90 cm, 5.80 min, respectively. These factor levels translate to an optimized specific energy of 582.66 kJ/kg-grain.*

Keywords: Microwave drying, energy, protein content, surface lipid content, milled rice color, peak viscosity and final viscosity

INTRODUCTION

Rice is one of the most important grains concerning human nutrition and caloric intake (Food and Agricultural Organization of the United Nations, 2004). More than 3.5 billion people depend on rice for more than 20% of their daily calories. As an ingredient, milled rice or its flour is incorporated into a vast variety of dishes including cereals, bread, desserts and as thickeners for sauces.

The cooking and eating quality of rice is defined by its physiochemical properties. These properties can affect rice's functionality and subsequently the quality of the final food product. (Noomhorm et al., 1997; Lyon et al., 1999; Perdon et al., 1999). Therefore, it is important that the physiochemical properties are not negatively affected by the drying method used.

MW processing has found various applications for home cooking and is widely used in many industrial applications including meat tempering, potato chips processing and bacon cooking (Gamble & Rice, 1987). Most of the reports found in literature agree to the fact that

MW treatment accords high thermal efficiency and shorter drying durations compared to conventional hot air drying (Cho et al. 1990; Prabhanjan et al., 1995; Maskan, 2001; Kaasová et al., 2002; Vadivambal and Jayas, 2007). However, researchers are still concerned with apparent quality and sensory degradation in MW processed foods as a result of the high heat fluxes. Walde et al. (2002) reported that although MW drying was effective at reducing the power consumption in wheat milling industries, the use of a MW was found not to be suitable for the long run as products made from the MW treated wheat were hard in texture. Additionally, it was found that the flours of corn dried by MWs had decreased viscosity compared to control samples processed by conventional convective methods (Velu et al. 2006). Current research suggests that the reduction in viscosity was as a result of the alteration in the structure of starch and protein within the flour. However, there is insufficient research on the effect of MW intensity on the physiochemical properties of medium grain rice. At the industrial level, the demand for high drying throughputs necessitates the need to investigate the implications of MW heating on the physiochemical properties of rice dried at elevated levels of MW specific energy.

OBJECTIVES

This study examined the implications of increasing MW specific energy on the physiochemical properties of medium grain rough rice. Additionally, this research aims to investigate the implications of rice bed thickness variation on disparities in rice bed physiochemical properties throughout the entire bed. The specific objectives of this research were to investigate the implications of the following:

1) Increasing MW specific energy on rice physiochemical properties including protein content, surface lipid content and milled rice total color difference

2) Increasing MW specific energy on rice peak and final viscosities
3) Disparity of rice protein content, surface lipid content milled rice total color difference and peak and final viscosities across rice beds of increasing thicknesses.

Additionally, analyses were done using statistical software (JMP version 11.0.0, SAS Institute) to optimize the MW drying process and determine optimal settings for power, loading mass (equivalent rice bed thickness) and treatment duration by setting desirability goals to optimize these responses. Optimization of the MW drying technology to achieve rapid drying of high MC rice and superior rice quality would benefit the rice industry. This study provides insight into the effect of increasing MW intensities on the rice physiochemical properties.

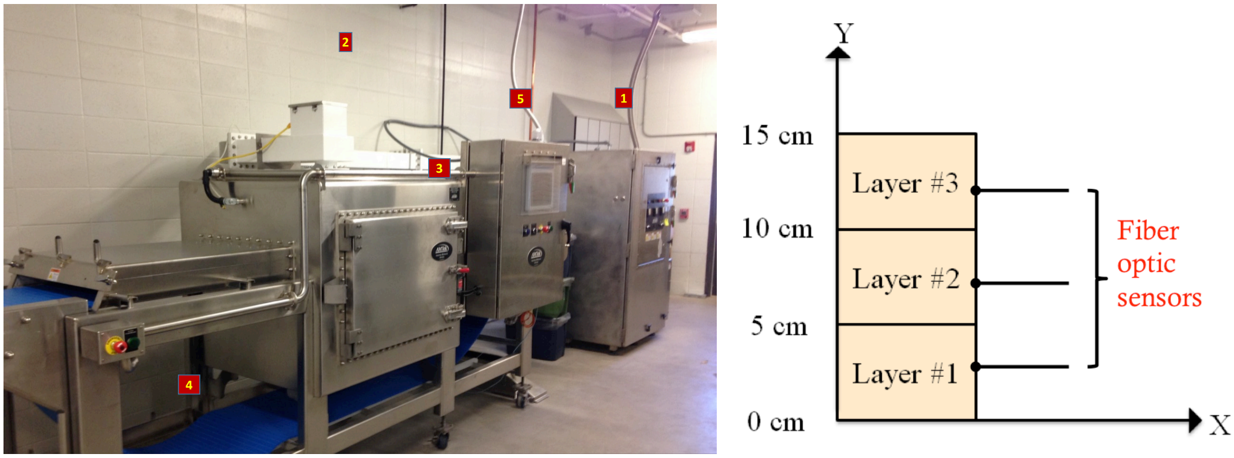
MATERIALS AND METHODS

Rice samples

Freshly harvested, medium-grain rice samples (cv. Jupiter) at initial MC of 23.5% (wet basis) were used in this study. The samples were cleaned using a dockage equipment (MCi Kicker Dockage Tester, Mid-Continent Industries Inc., Newton, KS). The equipment used a series of small sized sieves to provide a fast, accurate and consistent way of separating shrunken, broken, scalped material, broken kernels, splits and dust from rice. The cleaned rice was stored in a laboratory cold room set at 4°C. At the beginning of the experiments, the samples were retrieved from the cold room and allowed to equilibrate with room conditions (25°C) overnight before conducting any tests. The MCs of the samples reported in this study were determined using an AM 5200 Grain Moisture Tester (PERTEN Instruments, Hägersten, Sweden) which was calibrated using the ASABE standard (Jindal and Siebenmorgen, 1987). The MC of each sample was measured by placing 15 g duplicate samples into a conduction oven (Shellblue, Sheldon Mfg., Inc., Cornelius, OR) set at 130^{o}C for 24 h, followed by cooling in a desiccator for at least half an hour (Jindal and Siebenmorgen, 1987). All reported MCs are on wet basis.

Microwave equipment

An industrial MW system (AMTek, Applied Microwaves Technology Inc., Cedar Rapids, IW) was used in this study. The system (Fig. 5.1a) consists of a transmitter, a wave guide, and the MW heating zone (oven) and operates at a frequency of 915 MHz. The transmitter is a high-powered vacuum tube that works as a self-excited MW oscillator. It is used to convert high-voltage electric energy to MW radiation. The waveguide consists of a rectangular or cylindrical metal tube or pipe through which the electromagnetic field propagates lengthwise. It is used to couple MW power from the magnetron into the lab oven. The lab oven is the internal cavity of the MW that provides uniform temperatures throughout while in use.



(a) (b)

Figure 5.1a: Diagram of microwave system showing the transmitter (1), heating zone (2), wave guide (3), conveyor belt (4), and control panel (5), **Figure 5.1b:** Diagram of 9 kg of rice in 3 stackable microwave blind trays fitted with fiber optic cables in each layer

Experimental Design

The experimental conditions were determined based on a feasibility study. It was determined that MW treatments over 900 kJ/kg-grain resulted in the rice burning and popping and that specific energy of 600 kJ/kg-grain gave the best milled rice and head rice yields. Consequently, for this research specific energies between 533 and 900 kJ/kg-grain were chosen. MW treatments were done in batch with power levels of levels of 5, 10 and 15 kW and heating durations of 4, 6 and 8 minutes for rice beds of thicknesses 5, 10 and 15 cm which translates to loading masses of 3, 6 and 9 kg. The experimental design is shown in Table 5.1.

Table 5.1: Rice bed thicknesses, microwave power levels and heating durations used in the rice drying experiments

Rice Bed Thickness (cm)	**Microwave Power (kW)**	**Heating Duration (min)**
15	10	8
5	5	6
10	10	6
10	15	4
15	15	6
5	5	8
5	10	4
10	10	8
15	15	8
10	15	6

Microwave Treatments

The implications of MW intensity and heating duration on treatments of rice beds of different thicknesses (5, 10 and 15 cm) were studied. For each layer a sample of 3000 g rice was massed out and placed into MW safe trays (Fig. 5.1 b) for the treatment. Each tray was stackable allowing for a total of up to 9000 g of rice to be treated at once. The outsides of the trays were made of polypropylene with a Teflon coated fiberglass mesh at the bottom to hold the samples. The trays with rice sample were set in the oven on the belt and treated at various power levels and durations (Table 5.1). The temperature of rice during MW heating was measured using fiber optic temperature sensors (OMEGA Engineering, INC., Stamford, CT 06907). After MW treatments, the samples were separated by layer then transferred immediately after to glass jars and sealed air tight. A HOBO sensor (Onset Computer Corporation, Bourne, MA) was placed in the jars to determine the changes in temperature and relative humidity inside the jars. The jars were placed in an environmental chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 60°C and relative humidity of 65%. The rice was tempered for 4 h. After the tempering, the rice was spread uniformly on individual trays, transferred to an EMC chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 25°C and relative humidity of 65%.

Rice Milling

Triplicate, 150 g sub samples of rough rice, obtained from each sample dried to 12.5% MC, were dehulled using a laboratory huller (Satake Rice Machine, Satake Engineering Co., Ltd., Tokyo, Japan), milled for 30 s using a laboratory mill (McGill #2 Rice Mill, RAPSCO, Brookshire, TX) and aspirated for 30 s using a seed blower (South Dakota Seed Blower, Seedboro, Chicago, IL). Milled rice yield was calculated as the mass proportion of rough rice that remains including head rice and broken, after milling. Head rice was then separated from broken kernels using a double tray sizing machine (Grainman Machinery Manufacturing Corp., Miami, FL). Head rice are considered as kernels that remain at least three-fourths of the original kernel length after complete milling (USDA-GIPSA 2010). Head rice yield was calculated as the mass proportion of rough rice that remains as head rice after complete milling.

Crude protein determination

Crude protein was measured by scanning 50 g of white rice kernels using NIR reflectance (NIR, DA7200, Perten Instrument, Hagersten, Sweden) following AACCI Approved Method (39-25.01) for whole-grain. Before NIR analysis, the instrument was calibrated using the AACCI Approved Method 46-16.01. The resulting equation for calibration is shown in equation 1:

$$CP = 0.747 \times CP_{NIR} + 1.893 \qquad (1)$$

where, CP denotes crude protein content using approved method, CP_{NIR} denotes crude protein determined using NIR method. The crude protein was reported as a mass percentage of protein in wet basis relative to the mass of white rice.

Surface lipid content determination

Head rice surface lipid content, also known as fat content, was determined as an indicator of the degree of milling using the previously described NIR system. The NIR was calibrated with AACCI Approved Method 30-25.01, and the resulting calibration curve is presented equation 2 (Matsler & Siebenmorgen, 2005; Saleh et. al., 2008):

$$SLC = 0.871 \times SLC_{NIR} - 0.092 \qquad (2)$$

SLC: surface lipid content (approved method) (%)

SLC_{NIR}: surface lipid content (NIR method)

Color values determination

The milled rice color indices (L*, a*, and b*) were measured using a colorimeter (Hunter Associates Laboratory, Reston, VA). This was done by placing the measuring arm of the hand-held equipment in contact with and on top of the milled head rice. Before each test, the colorimeter was calibrated using a reference white plate provided by the manufacturer. The instrument measures color indices, specified by the International Commission on Illumination (CIE). The parameters L* describes the lightness from 100 (light) to 0 (dark), parameter a* describes red-green color with +a* values for redness and −a* values for greenness, and parameter b* indicates yellow-blue color with +b* values for yellowness and −b* values for blueness. The a* and b* parameters are chromatic components ranging from −120 to 120 (Khir et al., 2014). The TCD (eqn. 3) is a combination of all the CIE parameters that indicates the total color difference of the rice kernel after treatment:

$$\mathrm{TCD} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad (3)$$

ΔL^*, Δa^*, and Δb^* represent the difference in L*, a* and b* values between conventionally dried rice samples and MW treated rice, respectively.

Pasting properties determination

The pasting properties of each of the samples were measured using Rapid Visco Analyzer-Super (RVA) (Newport Scientific Pty. Ltd., Warriewood, NSW, Australia). To determine the pasting viscosity profiles, triplicate, 20 g head rice sub-samples were ground into flour using a cyclone mill with a 0.5 mm sieve (model 2511, Udy Corp., Fort Collins, CO). The

MC of the flour was determined by drying triplicate, 2.5 g samples in a convection oven at 130°C for 1 h (Jindal and Siebenmorgen, 1987). Flour samples were prepared for viscosity analysis by mixing 3 ± 0.01g of flour (at approximately 12% MC) with 25 ± 0.05 mL deionized water. Water corrections were made to account for the samples being above or below 12% MC. Rapid Visco Analyzer-Super 4 (Newport Scientific Pty. Ltd., Warriewood, NSW, Australia) was used to determine the peak and final viscosity of the rice flour. Setback viscosity was calculated as the difference between final and peak viscosities. The RVA was set up on a 12.5 min routine (1.5 min at 50°C, heating to 95°C at 12°C/min, 2.5 min at 95°C, cooling to 50°C at 12°C/ min, and held for 1 min at 50°C) according to AACC Methods (1996). Peak and final viscosities were recorded in centipoises (1 RVA unit = 10 cP). Observations in changes to pasting properties will be used to determine changes in rice functionality.

Statistical Analysis

Statistical analyses were performed with statistical software (JMP version 11.0.0, SAS Institute). A one-way fixed effects analysis of variance (ANOVA) and Tukey's honest significant difference (HSD) test were performed to determine significant differences within and among samples. All test were considered to be significant when $p < 0.05$.

Response surface methodology was then used to geometrically describe the relationship between a response and one or more factors. Response surface methodology is a collection of mathematical and statistical techniques based on the fit of a polynomial equation to the experimental data, which describe the behavior of a data set with the objective of making statistical inferences. It can be well applied when a response or a set of responses of interest are influenced by several variables. By evaluating the responses, the set of operating conditions for making the product with the overall best response can be determined. This set of operating conditions is called the optimum condition for the process. The optimum condition for the response is represented by a function. The desirability of response is weighted by an importance value when it is considered against the goals of the other responses during optimization. The importance value is usually set when defining the responses.

Optimization Factors

Based on a feasibility study it was determined that changes in MW specific energy had statistically significant ($p < 0.05$) effects on the rice in terms of surface temperature, final moisture content, milled rice and physiochemical properties and that optimum responses occurred at or around 600 kJ/kg-grain. Accordingly, experimentation involved exploration of MW specific energies of 533.33, 600, 800 and 900 kJ/kg.

MW specific energy (kJ/kg) is defined as the MW energy transferred per unit mass of product being treated and is calculated as follows:

$$SE = \frac{P \times T}{M} \quad (4)$$

Where:

SE is the microwave specific energy (kJ/kg)

P is the microwave power (kW)

T is the microwave heating duration (s)

M is the mass of product being treated (kg)

Minute changes in MW power, heating durations or product loading mass exact changes in the magnitude of MW specific energy. For example, an increase in product mass will cause a decrease in MW specific energy and vice versa. Therefore the factors of importance for this study are the factors that lead to changes in MW specific energy.

RESPONSE VARIABLES

Variables of interest in an experiment (those that are measured or observed) are called response or dependent variables. The response variables that will be optimized in this experiment were protein content, TCD and peak and final viscosity. These response variables and their response goals were determined as most important based on a literature review (Table 2).

The physiochemical properties of the white rice kernel were determined to be the response of second most importance. Although these properties are not as high in terms of economic importance as milled rice yield (MRY) and head rice yield (HRY), they are still critical. Rice consumers represent one of the most demanding cereal markets with regards to product quality (IRRI, 2002; Coats, 2003, Ondier et al. 2010). For this reason, any change in the rice physiochemical properties as a result of changes in drying methods must be minimized. Based on literature it was determined that rice's physiochemical properties were determined largely by protein content and pasting properties; color plays a major role in sensory characterization.

Protein Content

Research has provided ample support for the assertion that the starch, protein and the interaction between the two components affect rice eating and cooking properties. Medium grain rice is reported to have four types of proteins found in rice, albumins, globulins, prolamin and glutelin the total of which is approximately 8.3% (+/- .2%) of the total kernel mass. Albumins and globulins exist in the aleurone layer, which is the outermost layer of the rice endosperm, however, this layer is usually removed during the process of milling leaving mostly the prolamin and glutelin proteins (Lim et al., 1999). These protein fractions have recently attracted interest as being a starch granule-associated protein (SGAP) (Udaka et al., 2000). SGAPs are proteins that are located in and on starch granules. Baldwin (2002) indicated the importance of the small but measurable quantities of SGAP in research and stated that the removal of protein from rice granules caused small but consistent changes in starch gelatinisation temperatures. Similarly, pasting characteristics of rice starch were highly dependent on the residual protein content, and protein removal imparted an increase in RVA paste viscosity and a decrease in pasting temperature (Lim et al., 1999).

Medium grain rice was found to have total protein contents of 8.30% +/- 0.02%. Based on the literature review we might reasonably expect rice functionality to be affected if there are changes in protein content after drying. To that end, rice protein content was given an importance of 2. The response goal was set to target a range of 7.5 to 8.5 %.

Surface Lipid Content

SLC is the mass percentage of lipid remaining on the surface of a rice kernel after milling. SLC affects the stability, quality, appearance, and end-use functionality of rice (Chen et al. 1997). The majority of the rice's lipids are concentrated in the bran, making it subject to rancidification. As a result, bran is often separated from the rice kernel before storage in a process called milling. As milling progresses, the degree of milling (DOM) is said to increase and the SLC decreases (Hogan and Deobald 1961; Pomeranz et al. 1975; Miller et al. 1979). Consequently, rice SLC is often used as a parameter to indicate DOM. Industrial milling practice for rough rice targets a degree of milling (DOM) that has a resultant SLC of 0.4% for optimal HRY recovery and better storability. Therefore the response goal was to set target response to 0.4%. SLC response was given an importance of 2.

Total Color Difference

The visual appearance of any food is of great importance. There are many theories as to what causes rice discoloration, microbial contamination, high respiration rates (Schroeder, 1963), and elevated water activity, temperature, and carbon dioxide content (Bason et al., 1990). Grain drying temperatures and drying durations have also been associated with changes in rice kernel color (Bunyawanichakul et al., 2007). It was suggested that longer drying duration and high initial MCs, accelerate the Maillard reaction that may lead to kernel discoloration (Inprasit and Noomhorm, 2001).

Due to the high heat fluxes accorded by the use of an industrial MW, changes in color that may negatively effect the rice's sensory perception is entirely possible. Analyses were conducted to determine what MW specific energies cause these changes and to minimize these responses. Research suggests that a total color difference below 13 units is negligible in terms of human visual perception (Atungulu et al., 2004). As a result, the response goal was set to minimize responses with an upper threshold limit of 13 units. Like the other physiochemical responses, the total color difference was given an importance of 2.

Pasting Properties

Rapid visco analysis (RVA) of starch is a method that measures and records the viscosity during hydration and subsequent gelatinization of starch granules during heating and stirring in excess water (Almeida-Dominguez et al., 1997). Early in the pasting process, the starch granules absorb a significant amount of water and swell resulting in an increase in viscosity. After peak viscosity is reached the slurry is held at the maximum temperature. This peak temperature occurs at the equilibrium point between swelling and polymer leaching. During a hold period (typically

95°C) the slurry is continuously stirred resulting in shear thinning as a result of the starch molecules' reorientation. Due to shear thinning the viscosity declines to its lowest point. This is the tough viscosity (holding strength). The difference between peak and trough viscosity is termed breakdown viscosity, and a low value indicates shear-force stability under heated conditions. As the starch mixture is subsequently cooled, the viscosity increases to a final viscosity, with the difference between the final and trough viscosities being termed the setback viscosity. This phase of the pasting curve involves retrogradation or re-ordering of the starch molecules. The final viscosity is the most commonly used parameter to define the quality of a particular starch sample.

These starch-viscosity properties (peak, trough, final, breakdown and setback viscosity) help predict the functionality of food products. Each of these properties has an influence on the cooking quality of rice. For example, higher peak viscosities were found to enhance the grain quality resulting in cooked rice that is soft and glutinous in texture while increased final viscosity has been correlated to flour thickness. For the purpose of this experiment, the pasting properties that were highlighted and optimized are peak and final viscosities. Peak and final viscosities were given an importance of 2. The response goal was set to maximize responses.

Table 5.2: Experimental responses, response goals, and importance

Response Name	Lower Limit	Upper Limit	Response Goal	Importance
Surface Lipid Content	.35	.45	Match Target	2
Protein Content	7.5	8.5	Match Target	2
Total Color Difference	0	13	Match Target	2
Peak Viscosity (cP)			Maximize	2
Final Viscosity (cP)			Maximize	2

RESULTS AND DISCUSSION

Control samples and responses

The least square mean SLC, Protein content, total color difference, peak and final viscosity of control samples and their standard deviations are presented in Table 5.3. All parameter levels were well within the ranges found in the literature. A TCD of 2.69 indicates that rice samples before MW treatments had a fair amount of discoloration. However, this level is well below the human visual perception threshold. Further analyses was used to compare control samples with samples treated with increasing MW specific energies in varying rice bed thicknesses.

Table 5.3: Surface lipid content, protein content and total color difference of control samples

Response	Mean	Standard Deviation
Surface Lipid Content (%)	0.47	0.10
Protein Content (%)	5.70	1.10
Total Color Difference	2.69	1.07
Peak Viscosity (cP)	3183.33	472.24
Final Viscosity (cP)	2745.33	342.23

The effects of increasing specific energy on the SLC, protein content and the total color difference are displayed in Figure 2.

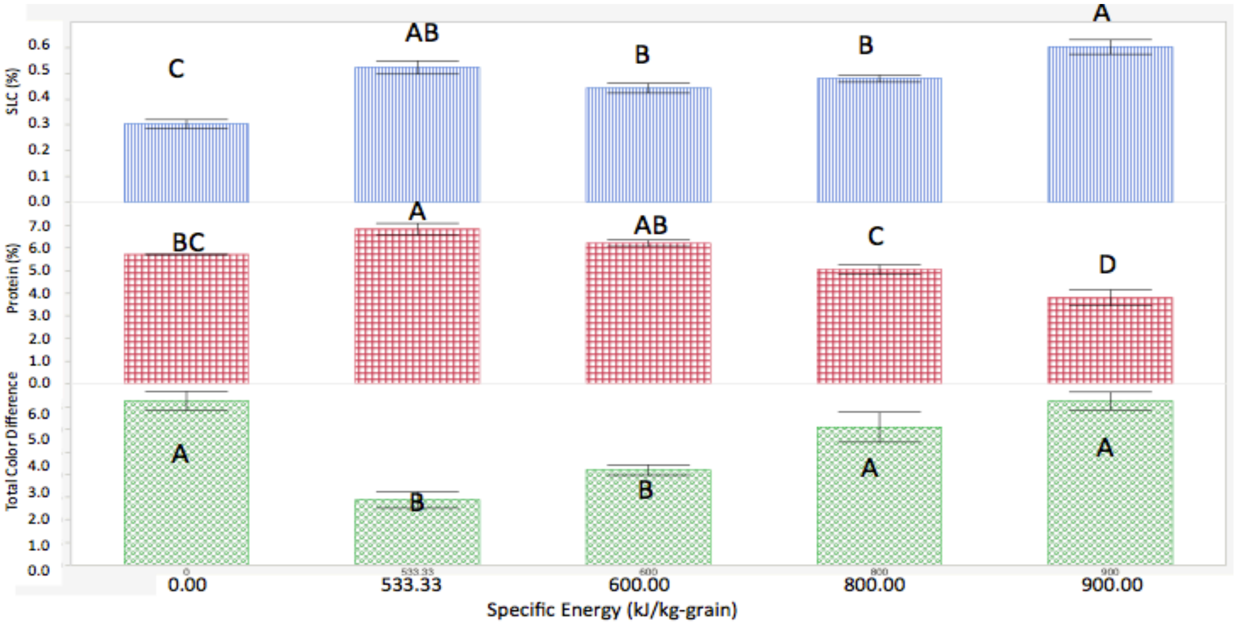


Figure 5.2: Effects of increasing microwave specific energy on the surface lipid content (SLC), protein content and the total color difference (TCD) of medium grain rice. Means with the same type of letters are not significantly different at $\alpha = 0.05$.

Implications of Increasing Microwave Specific Energy on SLC, Protein, and Total Color Difference

The implications of increasing MW specific energy on the SLC, protein content and TCD of medium grain rough rice were investigated. It was determined that increasing MW specific energy had a statistically significant ($p < 0.0001$) effect on all of the responses in question as indicated by the effect test table (Table 5.4). Table 5.4 shows the source of the effect, the degrees of freedom (n-1), the sum of squares, mean square, F ratio and probability value. F ratio is the statistic used to test the hypothesis that the response means are significantly different from one another. A larger F ratio indicates a decreased likelihood that the observed difference in treatment means is due to chance. A small p-value (≤ 0.05) indicates strong evidence against the null hypothesis.

Table 5.4: Effect test table showing the effects of increasing microwave specific energy on the surface lipid content, protein content and the total color difference of medium grain rice

Response	Source	DF	Sum of Squares	Mean Square	F Ratio
Surface Lipid Content (%)	Model	4	0.22	0.05	12.0746
	Error	47	0.21	0.00	**Prob > F**
	C. Total	51	0.43		<.0001*
Protein Content (%)	Model	4	39.16	9.79	18.4464
	Error	46	24.41	0.53	**Prob > F**
	C. Total	50	63.57		<.0001*
Total Color Difference	Model	4	22.95	5.74	8.6591
	Error	37	24.51	0.66	**Prob > F**
	C. Total	41	47.46		<.0001*

The implications of increasing MW specific energy on the peak and final viscosity of medium grain rough rice were investigated. It was determined that increasing MW specific energy have a statistically significant ($p < 0.0001$) effect on both responses as indicated by the effect test table (Table 5.5).

Table 5.5: Effect test table showing the effects of increasing microwave specific energy on the peak and final viscosity of medium grain rice

Response	Source	DF	Sum of Squares	Mean Square	F Ratio
Peak Viscosity (cP)	Model	4	20570073	5142518	7.5091
	Error	37	25338913	684835	**Prob > F**
	C. Total	41	45908986	-	0.0002*
Final Viscosity (cP)	Model	4	17979000	4494750	12.6866
	Error	37	13108732	354290	**Prob > F**
	C. Total	41	31087733	-	<0.0001*

Surface Lipid Content

The effect of increasing MW specific energy supplied to the rice resulted in statistically significant ($p < 0.05$) increases in rice SLC. Tukey's HSD test was done to identify where the differences were and are indicated on the graph in Figure 5.2. Means with the same letter are not significantly different. The highest SLC was seen at specific energies of 900 kJ/kg and had least square means of 0.60% and standard deviations of 0.07. This is an SLC increase of 127.66% compared to control samples.

Industrial milling practice for rough rice targets a degree of milling (DOM) that has a resultant SLC of 0.4% for optimal HRY recovery and better storability. However, milling equipment is metered to obtain this SLC based on characteristics of rice dried using conventional drying methods. An excessively high SLC for rice kernels dried using MW indicates considerable kernel hardening resulting in less surface lipid being removed after 30 s of milling.

This data indicates that it is necessary to reconsider milling durations that give similar SLC for MW drying operations.

Protein

Figure 5.2 shows the effect of increasing MW specific energy on protein content. It was observed that increasing MW specific energy caused statistically significant ($p < 0.05$) increases in protein content up until its peak at 533.33 kJ/kg-grain specific energy, after which the graph leveled out then decreased. The lowest protein content was seen at specific energies of 900 kJ/kg and had least square means of 3.80 % and standard deviations of 0.79. This is a decrease in protein content of 33.33 % compared to the control.

During the process of drying and milling, denaturation and changes of the functionality of the rice proteins can take place that may influence overall rice quality. Research on rice proteins extracted from defatted rice flour suggests that the two major rice proteins (globulin and glutelin) progressively denatured upon heat treatments from 45^{o}C to 80^{o}C for 10 min and leveled off from 80^{o}C to 95 ^{o}C for 10 min (Ju, Hettiarachchy & Rath, 2001). The high energy fluxes afforded by the use of an industrial MW is capable of heating rice to surface temperatures over 120^{o}C (Atungulu et al., 2015). Increasing specific energies resulted in increasing final surface temperatures and consequently an increase in the denaturation of rice proteins.

Total Color Difference

Increasing MW specific energy had statistically significant effects on the rice kernel's color. Rice samples that had received MW specific energies less than 600.00 kJ/kg-grain had TCD significantly less than that of the control samples. Rice samples treated with MW specific energies more than 600.00 kJ/kg-grain had significant increases in TCD. At these MW specific energies, rice TCD were statistically similar to control samples. The highest TCD was seen at specific energy of 900 kJ/kg and had least square means of 6.37 and standard deviations of 0.87.

Research indicates that drying high MC rice at elevated temperatures have been implicated in rice discoloration (Christensen and Kaufmann, 1965; Mauron, 1981). Rice whiteness has been found to decrease with increasing drying temperatures and drying durations (Bunyawanichakul et al., 2007). Maillard reactions that may lead to discoloration is accelerated by longer drying durations and high initial MCs during drying (Inprasit and Noomhorm, 2001).

The high-energy fluxes afforded by increasing MW specific energies resulted in increasing final surface temperatures and consequently an increase in TCD. However, the treated samples had TCD values that were relatively low to the threshold TCD of 13 units. Although the color change was seen in some samples in comparison to the control samples, a TCD below 13 units indicates that the human visual response or perception with reference to color change is expected to be negligible (Atungulu et al., 2004).

The rice industry considers rice discoloration a serious problem and a major determinant of quality and price of milled rice. In rice grading systems, tolerance levels are established for the presence of yellow kernels (GIPSA, 2004), which may cause financial losses due to downgrading or rejection.

Implications of Increasing Microwave Specific Energy on Pasting Properties

Peak Viscosity

The effects of increasing specific energy on the rice peak and final viscosity are displayed in Figure 5.3. There was a significant increase in peak viscosity from control responses of 3183.33 cP as a result of increasing MW specific energy. The highest mean peak viscosity with a least square mean of 3619.30 cP and standard deviation of 309.15 cP was observed at MW specific energy of 533.33 kJ/kg-grain. MW specific energies over 533.33 kJ/kg-grain resulted in considerable decreases. There was no statistically ($p > 0.05$) significant difference between MW treated samples and control samples except samples treated at 900 kJ/kg-grain. At this specific energy, rice samples had the lowest mean peak viscosity with least square means of 1182.60 cP and standard deviation of 137.38 cP.

Final Viscosity

There was a significant increase in final viscosity from control responses of 2745.33 cP as a result of increasing MW specific energy. The highest mean final viscosity with a least square mean of 4034.60 cP and standard deviation of 708.79 cP was observed at MW specific energy of 800.00 kJ/kg-grain. MW specific energies over 800.00 kJ/kg-grain resulted in considerable decreases. There was no statistically ($p > 0.05$) significant difference between MW treated samples and control samples except samples treated at 600 and 800 kJ/kg-grain where responses were higher. At 900 kJ/kg-grain MW specific energy, rice samples had the lowest mean final viscosity with least square means of 1930.30 cP and standard deviation of 269.06 cP.

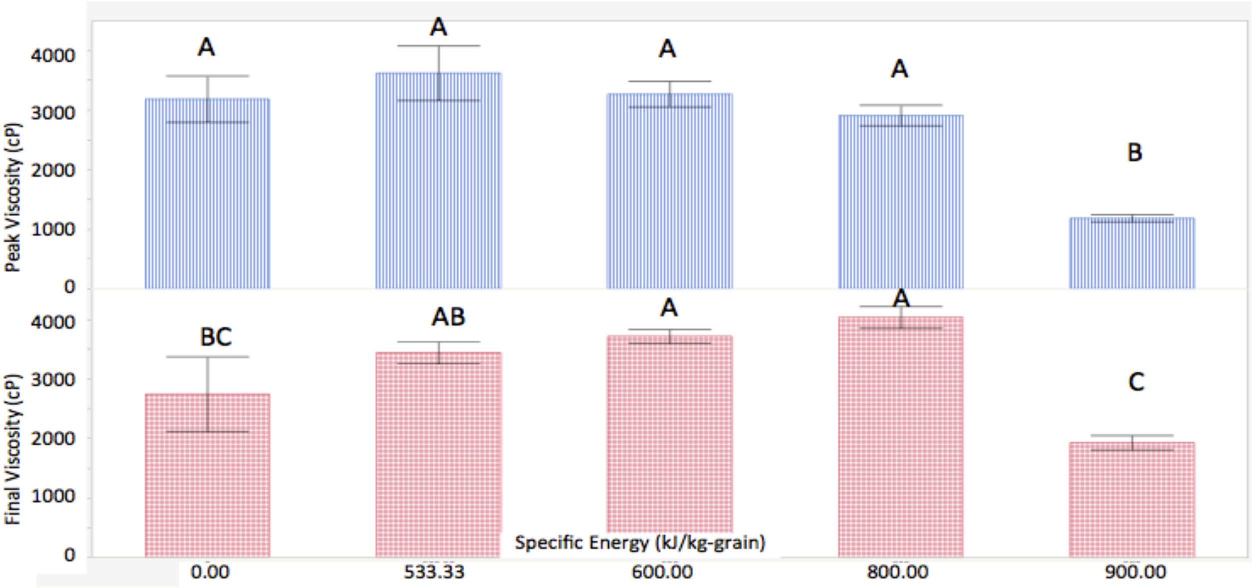


Figure 5.3: Effect of increasing microwave specific energy on the peak and final viscosity of medium grain rice. Means with the same type of letters are not significantly different at $\alpha = 0.05$.

Implications of Rice Bed Thickness Variation

The implications of varying rice bed thicknesses were determined. The rice milling industry requires large throughputs for their drying operations to avoid drying bottlenecks at peak harvest times. Consequently, information is needed on any variation in physiochemical properties throughout the rice bed layer as a result of increasing rice bed thicknesses. Due to the size limitations of the equipment, the rice beds studied in this experiment were 5, 10 and 15 cm, which corresponds to loading masses 3, 6 and 9 kg.

Surface lipid content, protein content and the total color difference

The implications of varying rice bed layer thickness (1, 2 and 3 which correspond to 5.00 10.00 and 15.00 cm) were determined for the SLC, protein content and the total color difference of medium grain rough rice (Figure 5.4). It was noted that specific energy had a statistically significant effect ($p > 0.0001$) on the responses in question. However, the factor of rice bed thicknesses was not significant for any of the responses.

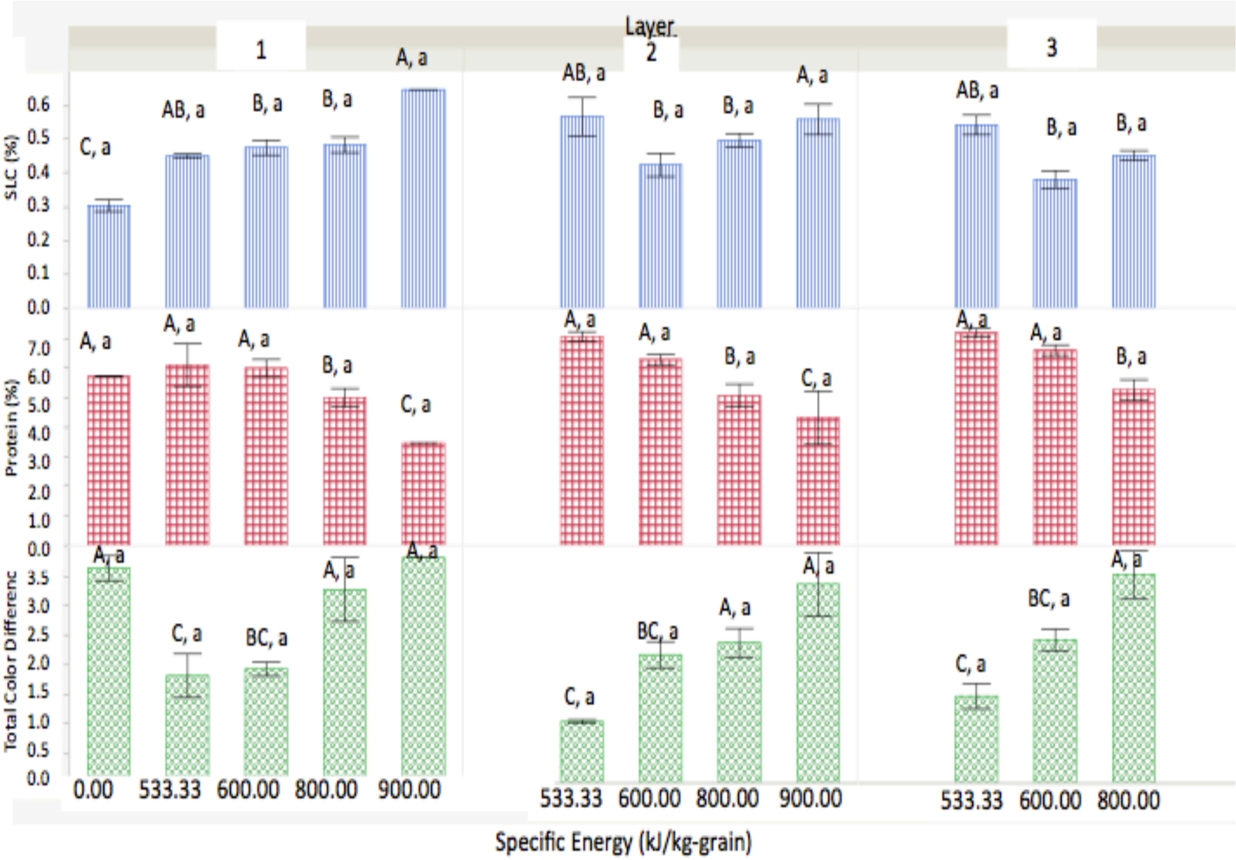


Figure 5.4: Effect of increasing microwave specific energy and rice bed layer thicknesses (1, 2 and 3 which correspond to 5.00 10.00 and 15.00 cm) on the surface lipid content (SLC), protein content and the total color difference (TCD) of medium grain rice. Means with the same type of letters are not significantly different at $\alpha = 0.05$.

Peak and Final Viscosity

The effects of increasing specific energy and rice bed layer thickness (1, 2 and 3 which correspond to 5.00 10.00 and 15.00 cm) were determined for the peak and final viscosity of the rice flour (Figure 5.5). It was noted that increasing the specific energy supplied to the rice resulted in a significant effect ($p > 0.0001$) on the peak and final viscosity of the rice flour. However, the factor of rice bed thicknesses was not significant for either peak or final viscosity ($p = 0.2306$ and $p = 0.2708$). There was no disparity in peak and final viscosities among the layers.

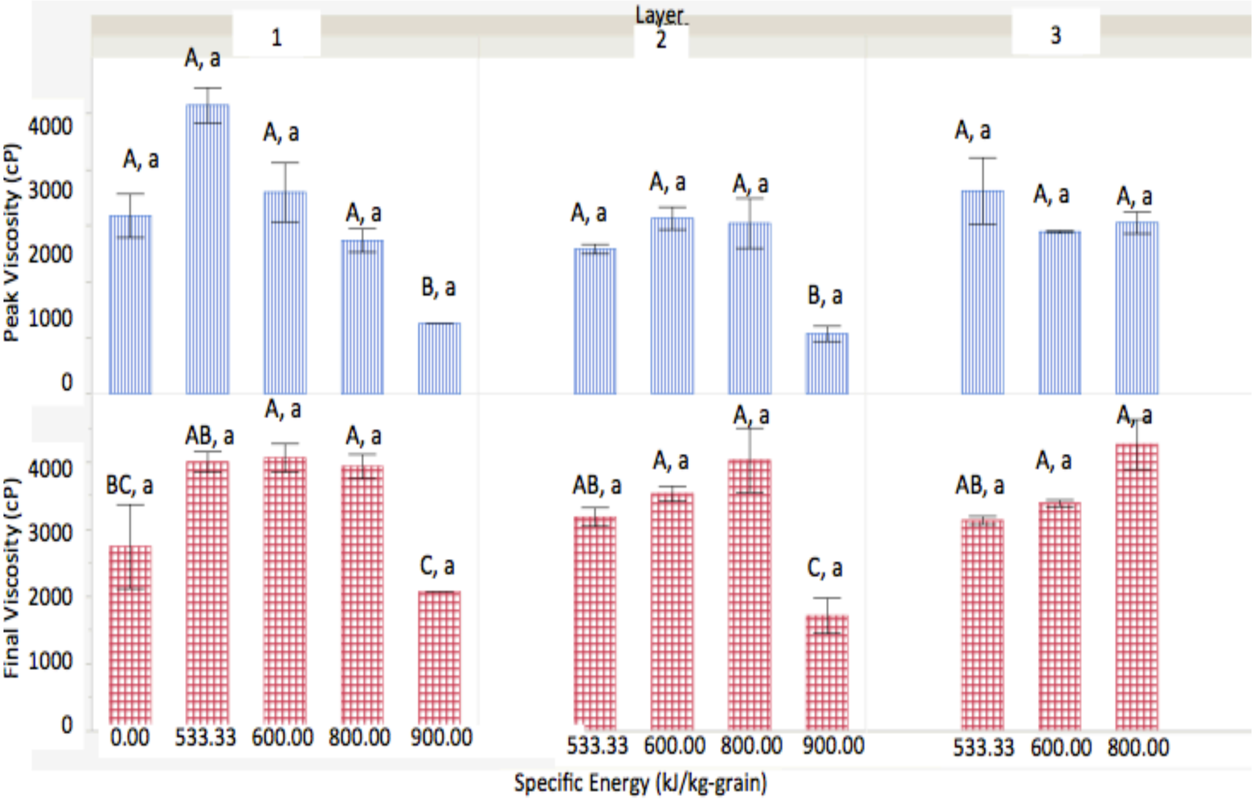


Figure 5.5: Effect of increasing microwave specific energy and rice bed layer thicknesses (1, 2 and 3 which correspond to 5.00 10.00 and 15.00 cm) on the peak and final viscosity of medium grain rice. Means with the same type of letters are not significantly different at α = 0.05.

Optimization

Specific energy is calculated using the variables of MW power, the treatment duration and mass of the treated sample and can be obtained by using many different combinations of these variables. For example, a specific energy of 600 kJ-kg-grain can be obtained using the following combinations of power, mass and duration in Table 6 below;

Table 5.7: Possible power, loading mass and treatment durations necessary to achieve a microwave specific energy of 600 kJ/kg-grain

Power (kW)	Mass (kg)	Duration (min)
10.00	6.00	6.00
15.00	6.00	4.00
15.00	9.00	6.00

Due to the combinatorial nature of MW specific energy, the process must be optimized to determine the best combinations of power, mass and heating durations necessary to achieve the greatest responses in terms of physiochemical properties of the end product. Typically in the analysis of industrial data, there are many response variables to be investigated. The problem arises when all of these responses are under investigation at the same time. The experimenter must decide which responses are most important, usually at the expense of other responses. To overcome this problem, optimization was carried out using response surface methodology (RSM).

Optimization of surface lipid content, protein content and total color difference

Table 5.8 shows the effect summary tables for responses SLC, protein content and TCD. The tables list the model effects, sorted by ascending *p*-values. Smaller p-values indicate higher significance to the model. It was determined that for all the responses in question there were statistically significant main effects ($p < 0.05$). For the SLC response, the main effect was duration only. However, for protein and TCD responses, the statistically significant main effects were power and duration. It was also determined that there were statistically significant quadratic effects ($p < 0.05$). Mass had a quadratic effect on the SLC response, duration had a quadratic effect on the protein response, and both mass and duration had quadratic effects on the TCD response. This means that if the relationship between responses and the factor in question were represented by a graph, the graph would be a curve and the optimal factor level would not be at the extremes of the experimental region but inside it.

Table 5.8: Effect summary table showing the effects of microwave power, loading mass and heating duration on the surface lipid content, protein content and total color difference responses

Response	Source	P Value
Surface Lipid Content (%)	Duration (min)	0.00087
Protein (%)	Mass (kg)*Mass (kg)	0.00105
	Power (kW)	< 0.0001
	Mass (kg)	< 0.0001
	Duration (min)*Duration (min)	< 0.0001
Total Color Difference	Duration (min)	0.00012
	Mass (kg)	< 0.0001
	Power (kW)	0.00001
	Mass (kg)*Mass (kg)	0.00033
	Duration (min)*Duration (min)	0.02872

Table 5.9 shows the effect summary table for responses Peak Viscosity and Final Viscosity. It was determined that for all the responses in question there were statistically significant main effects ($p< 0.05$) of mass, power, and duration. It was also determined that

power had a statistically significant quadratic effect (p = 0.00054) on the peak and final viscosity response.

Table 5.9: Effect summary table showing the effects of microwave power, loading mass and heating duration on the peak and final viscosity responses

Source	P Value
Power (kW)	0.00003
Power (kW)*Power (kW)	0.00054
Mass (kg)	0.00132
Duration (min)	0.00483

Prediction Profiler

To achieve the optimal processing with regard to product SLC, protein content and the total color difference a prediction profiler was used to set desirability goals. This was done to find optimal settings for the factors of mass, power, and duration. According to the prediction profiles located in Figures 5.6 and 5.7, it was determined that desirable levels of SLC, protein content and the total color difference is obtained at the factor settings found in Table 5.10, the corresponding responses and prediction profiles are located in Table 5.11 and figure 5.8 respectively.

Of the possible power (5, 10 and 15 kW), Mass (3, 6 and 9 kg) and duration (4, 6 and 8 mins) combinations it was determined that 11 kW, 6.60 kg, and a 5.96 minute heating duration provide the optimal response in terms of SLC, Protein and total color difference. It should be noted that a mass of 6.60 kg translates into a thickness of 11.00 cm and that the optimized factor settings translate into a specific energy of 596.00 kJ/kg-grain.

Table 5.10: Optimized parameter settings for rice surface lipid content, protein content and total color difference

Parameter	Optimized Parameter Setting
Power (kW)	11.00
Mass (kg)	6.60
Duration (min)	5.96

Table 5.11: Optimized parameter responses for rice surface lipid content, protein content and total color difference

Response	Optimized Response	Minimum	Maximum
Surface lipid content (%)	0.50	0.35	0.66
Protein (%)	6.77	7.50	8.50
Total Color Difference	1.65	0.00	13.00

In addition to the determination of the optimal factor levels, the prediction profiler also gives insight to the significance of impact a factor has on the performance parameter in question. A steep slope indicates that an operational parameter has a significant impact on the given performance parameter, whereas a shallow slope indicates little or no effect on a performance parameter. The operational parameters of duration, power and mass were determined to be the most significant performance parameters for the SLC, protein and TCD responses respectively as indicated by the steepness of the slopes in the graphs. This indicates that the effect of increasing duration, power and mass contributed the most change to the SLC, protein and TCD responses, respectively.

The Desirability Profile

The last row of plots shows the desirability trace for each factor. The numerical value beside the word ‘Desirability’ on the vertical axis is the geometric mean of the desirability measures. This row of plots shows both the current desirability and the trace of desirability that result from changing one factor at a time. A desirability of 0.7552 indicates that approximately 75.52 % of the goals to optimize rice physiochemical properties were achieved.

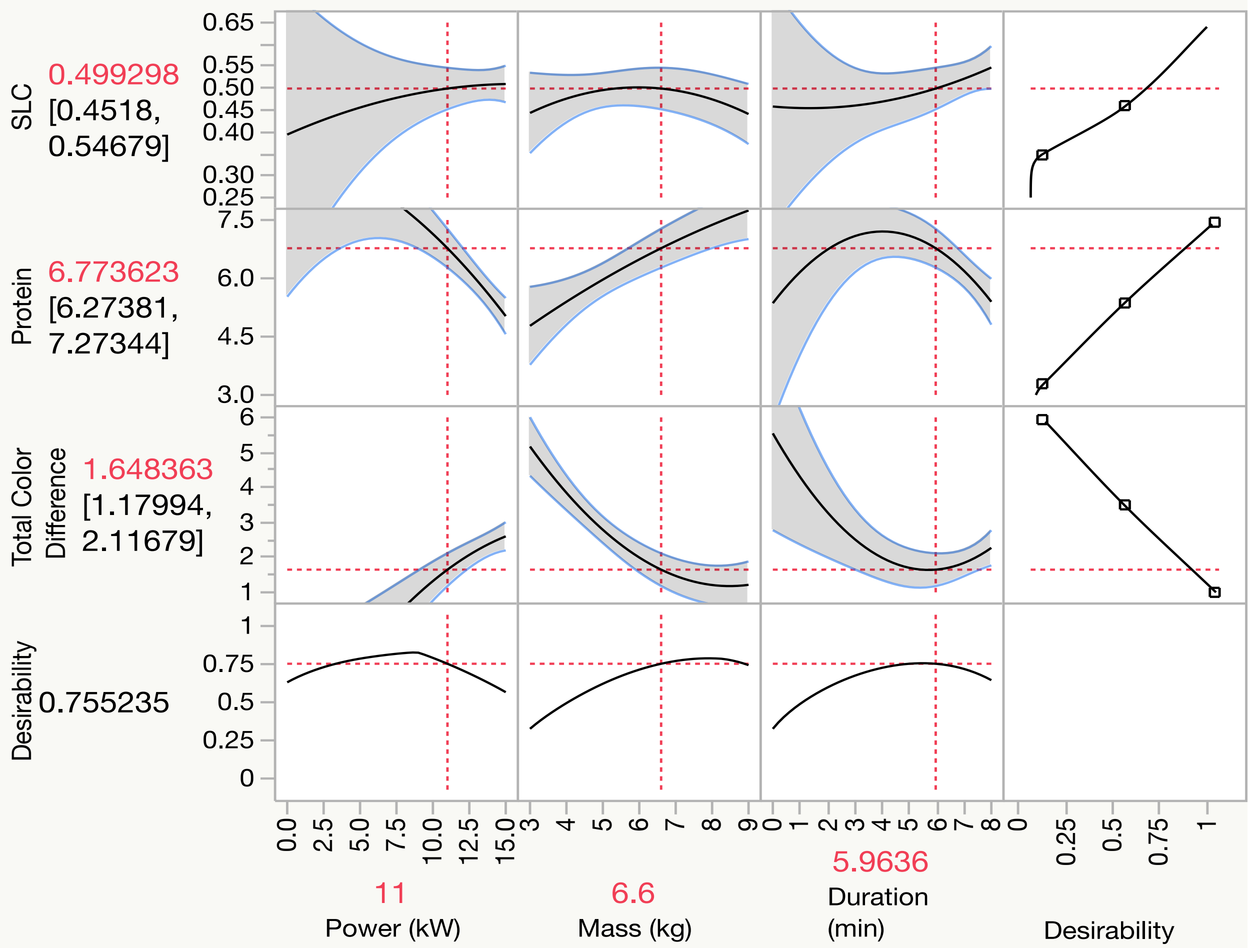


Figure 5.6: Prediction profile for surface lipid content (SLC), protein content and the total color difference (TCD) responses with parameter settings power, loading mass and duration

Optimization of Peak and Final Viscosity

Prediction Profiler was used to maximize the peak viscosity and final viscosity responses. This was done to find optimal settings for the factors of mass, power, and duration. According to the prediction profile located (Fig. 5.7) it was determined that maximum peak and final viscosities is obtained at the factor settings found in Table 5.12, the corresponding prediction profiles are located in Figure 5.7.

Table 5.12: Optimized parameter settings for rice peak and final viscosity

Parameter	Optimized Parameter Setting
Power (kW)	10.89
Mass (kg)	6.47
Duration (min)	5.64

Of the possible power (5, 10 and 15 kW), mass (3, 6 and 9 kg) and treatment duration (4, 6 and 8 mins) combinations it was determined that moderate levels of each were optimal and a specific energy of 653.40 kJ/kg-grain provides the optimal response in terms of peak and final viscosity. The optimal responses are located in Table 5.13. It should be noted that a mass of 6.47 kg translates into a thickness of 10.78 cm and that the optimized factor settings translate into a specific energy of 569.58 kJ/kg-grain.

Table 5.13: Optimized parameter responses for rice peak and final viscosity

Response	Optimized Response
Peak Viscosity (cP)	3807.62
Final Viscosity (cP)	3840.03

The operational parameter of power was determined to be the most significant performance parameter for both responses as indicated by the steepness of the (Fig. 5.7). This indicates that the effect of increasing power contributed the most change to the peak and final viscosity responses.

The Desirability Profile

The last row of plots shows the desirability trace for each factor. A desirability of 0.6058 indicates that approximately 60.58 % of the goals to optimize milled rice pasting properties were achieved.

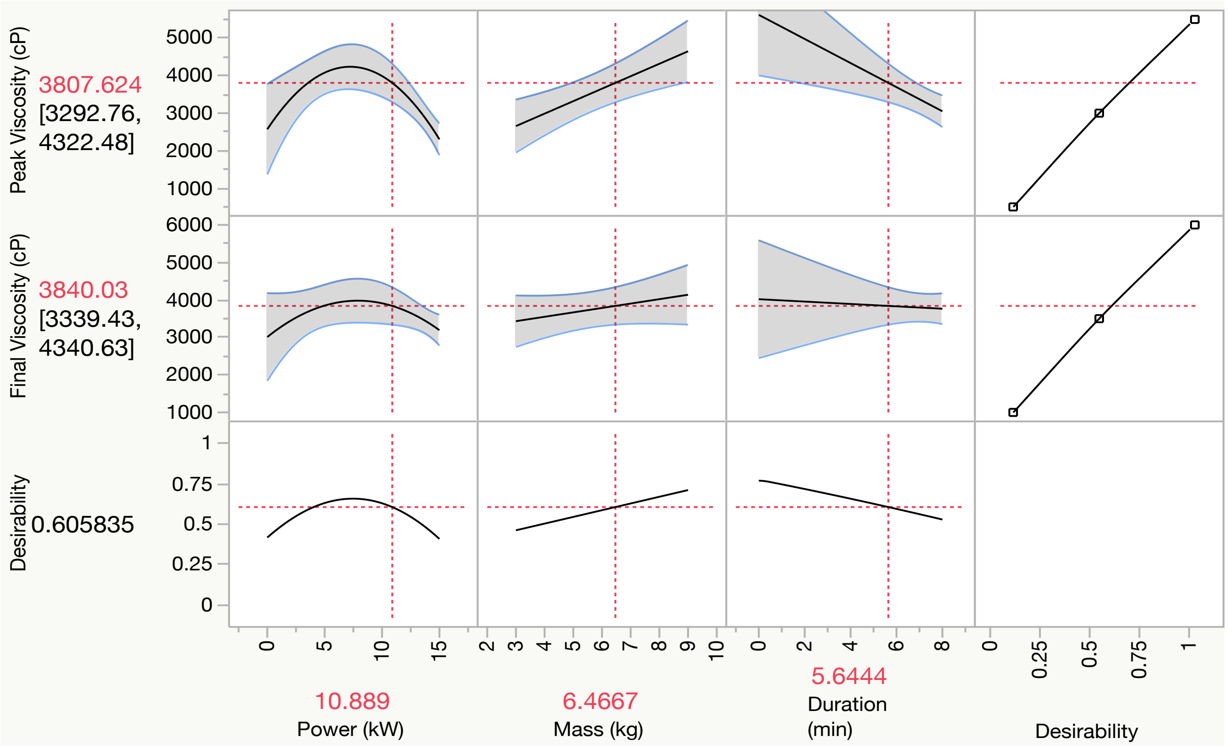


Figure 5.7: Prediction profile for peak and final viscosity responses with parameter settings power, loading mass and duration

Validation

Using optimization analyses, it was determined that 11 kW, 6.60 kg, and a 5.96 minute heating duration provides the optimal response in terms of SLC, protein, and total color difference. These factor levels translate to a thickness of 11.00 cm and an optimized specific energy of 596.00 kJ/kg-grain. Predicted data for SLC, protein and total color difference was compared to experimental data. At 600.00 kJ/kg-grain specific energy, experimental SLC, protein content and total color difference were 0.59%, 6.23% and 2.13% respectively. These levels were well within the range of the predicted data.

For the peak and final viscosity responses, it was determined that a power of 10.89 kW, a mass of 6.47 kg and a heating duration of 5.64 min be preferred for optimum rice peak and final viscosity. These factor levels translate into a thickness of 10.78 cm and an optimized specific energy of 569.58 kJ/kg-grain. At 600.00 kJ/kg-grain, specific energy experimental peak and final viscosity were well within the range of the predicted data.

CONCLUSION

This work showed that MW drying of rough rice holds promise as a rapid drying method once the parameter settings of power (kW), mass (kg) and duration (min) are optimized to produce the most desirable products in terms of physiochemical properties. It was determined that specific energy had highly significant effects on all of the responses studied ($p < 0.0001$). However, there was no such significance for varying rice bed layer thickness up to 15 cm. Optimization analyses suggest that a power of 10.95 kW, a mass of 6.54 kg and a heating duration of 5.80 min are preferred for optimum rice physiochemical and pasting properties. These factor levels translate to a thickness of 10.90 cm and an optimized specific energy of 582.66 kJ/kg-grain.

Optimization of the MW drying technology to achieve rapid drying of high MC rice and superior rice quality would benefit the rice industry by saving energy, considerably reducing processing durations, improve HRY, and provide an environmentally friendly drying method.

FUTURE WORK

Research indicates that rice physiochemical properties are correlated with microbial loads. Bacterial contamination of rice can lead to active respiration of the grain during storage leading to yellowing of the rice grain as a result of heat build up in the paddy; depletion of the nutrition reserves that the seed uses to germinate or sprout and economic losses to producers from a lowered head rice yield caused by dry matter loss.

MW drying, compared to conventional convective natural and hot-air heating, is known to have higher heat fluxes. These heat fluxes hold the potential to inactivate harmful mold spores that cause aflatoxin contamination as well as the contamination of other spoilage bacteria. The volumetric heating phenomenon afforded by the use of MW heating offers accelerated temperature rise at the interior of the kernel (Gowen, Abu-Ghannam, Frias, & Oliveira, 2006; Vadivambal & Jayas, 2007). This volumetric heating also offers the possibility to inactivate the fungal spores of aflatoxin-producing molds on the surface as well as inside of rice kernels.

To maximize the decontamination potential of the MW drying process, future studies will involve determining the implications of increasing MW specific energies and rice bed thicknesses on the rice microbial community.

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RICE MICROBIAL COMMUNITY RESPONSES TO DRYING BY INDUSTRIAL MICROWAVE

ABSTRACT

The typical convective natural and heated air-drying methods for rice are not metered to inactivate harmful fungal spores that produce mycotoxins. Some mycotoxins such as aflatoxin are highly toxic and present health hazards to grain consumers. The objective of this study was to investigate the effectiveness of utilizing microwaves (MW) to achieve rapid decontamination, especially of aflatoxigenic fungal spores. Medium-grain rough rice (cv. CL721) at initial moisture content (MC) of 23% (w.b.) was dried using a 915 MHz industrial MW set to transmit energy at power levels 5, 10, and 15 kW for 4, 6, and 8 minutes and for rice bed thicknesses 5, 10 and 15 cm. Inactivation of the aflatoxigenic fungal spore of Aspergillus flavus and that of other bacteria across the rice bed thickness was studied. Increasing MW specific energy resulted in statistically significant (p<0.0001) decreases in rice microbial loads. At the highest specific energy (900 kJ/kg-rough rice), which corresponded to setting processing conditions to 15 kW power level and 6 minute heating duration for a 10 cm thick rice bed, the reduction of the aerobic bacterial and aflatoxigenic fungal loads was 4.56 and 2.93 Log (CFU/g-grain), respectively. The disparity of microbial inactivation across the entire rice bed was statistically insignificant (p = 0.28) for the A. flavus mold count (for rice bed thicknesses up to 15 cm). However, there was a disparity of microbial inactivation of significance (p = 0.02) across the entire rice bed for the aerobic bacteria count. Rice bed top layers had aerobic bacteria counts higher than the middle and bottom layers. Additionally, the middle layer had aerobic bacteria counts higher than the bottom layer. Optimization analyses suggest that a power of 12.32 kW, a *mass of 7.14 kg and a heating duration of 6.66 min provide the optimal response in terms of rice microbial bacteria load reduction. These factor levels translate into a thickness of 11.10 cm and an optimized specific energy of 689.99 kJ/kg-grain. This work showed that MW drying of rough rice holds promise as a rapid drying method with potential benefits of microbial decontamination; this may help producers combat fungi related problems such as those resulting from mycotoxin contamination.*

Keywords: Rice, Microwave drying, Moisture removal, Microbial load reduction,

INTRODUCTION

Worldwide, 10% of all harvested grain succumbs to post-harvest losses as a result of infestation by insects, rodents and spoilage microbes. Out of the total food grain losses, 5–30 % are a result of molds and mycotoxins (Rajendran 2002). Bacterial and fungal contamination of rice can lead to active respiration of the grain during storage resulting in a general yellowing of the rice grain as a result of heat build up in the paddy grain. Respiration of bacterial and fungal colonies also leads to the depletion of rice nutrients leading to dry matter losses and decreased viability resulting in economic losses to producers from a lowered head rice yield (HRY).

To avoid the proliferation of microbes on freshly harvested rice lots, rice is quickly dried to 13.5 % w.b MC then stored in conditions of lower temperature and humidity to control microbial growth on rice. However, it is often the case that rice lots are infected before harvest and already contain considerable amounts of bacteria and aflatoxin-producing molds (Méndez-Albores, A., et al. 2007). Farmers and health officials alike are especially concerned with *Aspergillus flavus,* an opportunistic pathogen of crops that is prevalent in the air.

Aspergillus flavus is a common heat tolerant pathogen of rough rice, especially prevalent under insufficient drying and inappropriate storage conditions. *A. flavus* produces aflatoxins, a potent toxin that is well known for its deleterious effects on human and animal health (Probst, Njapau, & Cotty, 2007; Reddy & Raghavender, 2007). Consumption of aflatoxin-contaminated food causes acute and chronic toxicity as a result of accumulation in the body, causing acute liver damage, liver cirrhosis, tumors, and teratogenic effects.

Conventional drying and decontamination of rice is a two step process. In convective drying methods, rice grains are exposed to relatively low air temperatures (about 43°C) to avoid lowering the rice milling quality (Kunze and Calderwood. 1985). However, these drying temperatures are below the temperature needed to be able to meet the National Advisory Committee on Microbiological Criteria for Foods (NACMCF) disinfection requirements for a 5-log reduction in the level of pathogens. Often, to achieve these requirements, some chemical application is employed. However, the prolonged chemical residual resistance on rice and the compounds discharged to water and air could be potentially hazardous to the environment, animals, and humans.

Methyl bromide is a popular fumigant of fruit and cereals and is used to control a wide variety of pests including spiders, rodents, and fungi. First registered as a pesticide in 1961, methyl bromide is a fast acting decontamination method, controlling insects in less than 48 h in closed spaces. However, the Environmental Protection Agency has restricted its use due to its harmful effect on the ozone layer. Additionally, methyl bromide dissipates rapidly to the atmosphere and its exposure to humans can cause central nervous system and respiratory system failures.

Phosphine is another commonly used method for grain decontamination. Although effective, microbes and insect populations on grain are mutating to develop phosphine resistance.

Additionally, phosphine gas is highly toxic, reactive, and potentially explosive. Because of the dangers associated with their use, phosphine fumigants have been restricted.

The application of any chemical to a crop or food raises the question of risks and benefits. Consumers are now taking personal accountability to address social and environmental issues by purchasing more sustainable and environmentally friendly food products. Accordingly, alternatives to chemical decontamination methods are being tested as replacements for methyl bromide and other harmful fumigants. Alternatives of note are physical control methods such as heating and cooling.

MW energy has been used in food processing applications due to its merits of time and energy savings, considerably reduced processing durations, fine microstructures and hence improved mechanical properties, and it is also environmentally friendly with very high heat energy transfer rates (heat fluxes) (>400°C/min) (Mullin, 1995; Thuery, 1992). These benefits are finding applications in the grain industry, making the use of industrial MW drying of rice a possible avenue to mitigate food safety concerns related to bacteria and mold contamination.

MWs are portions of the electromagnetic spectrum with wavelengths in the range 0.001–0.3 m, and frequencies between 300 MHz and 300 GHz (Oghbaei & Mirzaee, 2010). MWs generate heat in food products as a result of the absorption of energy by molecules within the food in a process called dielectric heating. Molecules such as water and fats are electric dipoles. The partial positive charge at one end and a partial negative charge at the other, when in an electric field, begin to rotate in an attempt to align themselves with the alternating fields leading to vibration and thusly heating.

MW drying, compared to conventional convective natural and hot-air heating, is known to have higher heat fluxes. These heat fluxes hold the potential to inactivate harmful mold spores that cause aflatoxin contamination as well as the contamination of other spoilage bacteria. The volumetric heating phenomenon afforded by the use of MW heating offers accelerated increase in temperature at the interior of the kernel (Gowen, Abu-Ghannam, Frias, & Oliveira, 2006; Vadivambal & Jayas, 2007). This volumetric heating also offers the possibility to inactivate the fungal spores of aflatoxin-producing molds on the surface as well as inside of rice kernels.

While uniform heating is expected with the use of MWs, the sinusoidal wave pattern propagated develops hot and cold spots within the bulk of the grain. Hot and cold spots within a rice bed can lead to fungal growth in certain spots that can then proliferate throughout the grain mass during storage. Additionally, the MW heat transfer behavior is affected by many factors including the bed thickness, kernel geometry, and dielectric properties of the grain in question. The heat capacity and dielectric properties change with MC and temperature and thus complicate the MW drying and decontamination processes.

OBJECTIVES

The objective of this study was to investigate the effectiveness of utilizing a 915 MHz industrial MW to treat medium-grain rough rice (cv. CL721) at initial MC of 23% (w.b.) in bed thicknesses of 5, 10 and 15 cm at power and heating duration combinations of 5, 10, and 15 kW and 4, 6, and 8 minutes, respectively to achieve reduction of aerobic bacteria and aflatoxigenic mold species such as *A. flavus*. The specific objectives of this research were the following:

4) Investigate the effects of MW specific energy on inactivation of aerobic bacteria and aflatoxigenic mold species such as *A. flavus*.
5) Investigate the inactivation of aerobic bacteria and aflatoxigenic mold by MW heating across rice bed layers of different thicknesses.
6) Optimize the MW drying process to determine optimal settings for power, loading mass and treatment duration for maximum reduction of aerobic bacteria and aflatoxigenic mold species.

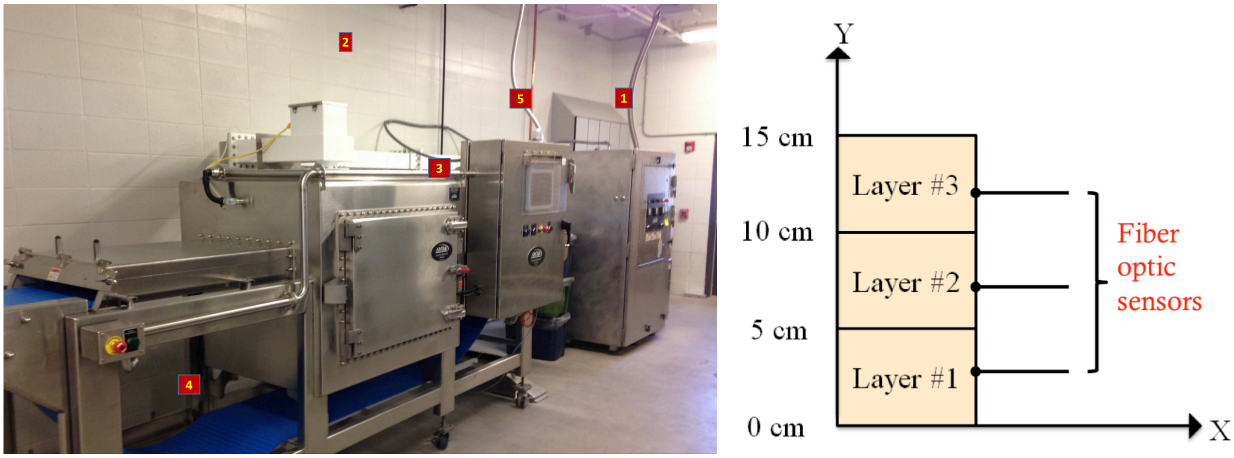
MATERIALS AND METHODS

Rice samples

Freshly-harvested, medium-grain rice samples (cv. CL271) at initial MC of 23.5% (wet basis) were used in this study. The samples were cleaned using a dockage equipment (MCi Kicker Dockage Tester, Mid-Continent Industries Inc., Newton, KS). The equipment used a series of small sized sieves to provide a fast, accurate and consistent way of separating shrunken, broken, scalped material, broken kernels, splits and dust from rice. The cleaned rice was stored in a laboratory cold room set at 4°C. At the beginning of the experiments, the samples were retrieved from the cold room and allowed to equilibrate with room conditions (25^{o} C) for one hour before conducting any experiments. The MCs of the samples reported in this study were determined using an AM 5200 Grain Moisture Tester (PERTEN Instruments, Hägersten, Sweden) which was calibrated using the American Society of Agricultural and Biological Engineers standard (Jindal and Siebenmorgen, 1987). The MC of each sample was measured by placing 15 g duplicate samples into a 130°C conduction oven (Shellblue, Sheldon Mfg., Inc., Cornelius, OR) setat 130^{o}C for 24 h, followed by cooling in a desiccator for at least half an hour (Jindal and Siebenmorgen, 1987). All reported MCs are on wet basis (w.b).

Microwave equipment and treatments

An industrial MW system (AMTek, Applied Microwaves Technology Inc., Cedar Rapids, IW) was used in this study. The system (Fig. 6.1a) consisted of a transmitter, a wave guide, and the MW heating zone (oven) and was operated at a frequency of 915 MHz. The transmitter is a high-powered vacuum tube that works as a self-excited MW oscillator. It is used to convert high-voltage electric energy to MW radiation. The waveguide consists of a rectangular or cylindrical metal tube or pipe through which the electromagnetic field propagates lengthwise. It is used to couple MW power from the magnetron into the lab oven. The lab oven is the internal cavity of the MW that provides uniform temperatures throughout while in use.



(a) (b)

Figure 6.1a: Diagram of microwave system showing the transmitter (1), heating zone (2), wave guide (3), conveyor belt (4), and control panel (5), **Figure 6.1b:** Diagram of 9 kg of rice in 3 stackable microwave blind trays fitted with fiber optic cables in each layer

The implications of MW heat intensity and heating duration on the microbial load reduction for rice beds of different thicknesses (5, 10 and 15 cm) was studied. For each layer a sample of 3000 g rough rice was massed out and placed into MW safe trays (Fig. 6.1 b) for the treatment. Each tray was stackable allowing for a total of 9000 g of rice to be treated at once for a 15 cm rice layer bed thickness. The outsides of the trays were made of polypropylene with a Teflon coated fiberglass mesh at the bottom to hold the samples. The trays with rice sample were set in the oven on the belt and treated at various power levels and durations (Table 6.1). The specific energy (kJ/kg-rough rice) was determined based on the MW power (kW), the treatment duration (min), and loading mass (kg) of the treated rice sample.

After MW treatments, the rice samples were separated by layer then transferred immediately to glass jars and sealed air tight. A HOBO sensor (Onset Computer Corporation, Bourne, MA) was placed in the jars to determine the changes in temperature and relative humidity inside the jars. The jars were placed in an environmental chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 60°C and relative humidity of 65%. The rice was tempered for 4 h. After the tempering, the rice layers were spread uniformly on individual trays, transferred to an EMC chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 25°C and relative humidity of 65%. The samples were allowed to cool naturally to 25°C. After cooling, the MC was determined using the AM 5200 Grain Moisture Tester (PERTEN Instruments, Hägersten, Sweden). After the MC of the rough rice had been determined, 10 g of treated sample were taken out for microbial analysis. Control samples constituted samples that were not treated with MW but gently dried to an MC of 12.5% in an EMC chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 25°C and relative humidity of 65%.

Table 6.1: Rice bed thicknesses, microwave power levels heating durations and resultant microwave specific energies used in the rice drying experiments. ǂ

Bed Thickness (cm)	**Microwave Power (kW)**	**Heating Duration (min)**	**Specific Energy (kJ/kg-grain)**
5	5	8	800.00
5	10	4	800.00
10	10	6	600.00
10	10	8	800.00
15	10	8	533.33
10	15	4	600.00
10	15	6	900.00
15	15	6	600.00
15	15	8	800.00

ǂ Microwave treatment power (kW), heating duration (min) and bed thicknesses (cm) combinations were chosen based on its ability to reduce rough rice MC from 24% to 12% w.b. in one pass with resultant HRY comparable to control as determined by a preliminary feasibility study. A full factorial design was not feasible because under some power levels and heating durations the rice would pop.

Microbial Analysis

Phosphate-buffered dilution water was prepared by dissolving 34 g of KH_2PO_4 in 500 mL water in a 1 L volumetric flask. The pH of the solution was adjusted to 7.2 using 1M NaOH solution. Then, a stock solution was made by adding distilled water to bring volume to 1 L in the volumetric flask. The stock solution was autoclaved at 121°C for 20 minutes. Phosphate-buffered dilution water was prepared by taking 1.25 mL of stock solution and bringing it to 1 L with distilled cold water. Dilution water was dispensed into smaller bottles and autoclaved at

121°C (AOAC methods 990.12 and 997.02). Seven dilution tubes with caps were prepared by serial dilution.

Rough rice total (ground sample) were determined. The rough rice samples were masticated at two different settings using a lab masticator (Silver Panoramic, iUL, S.A., Barcelona, Spain). A 10 g sample of rice was mixed with 90 mL phosphate-buffered dilution water in a sterile stomacher bag and masticated in the lab masticator. The masticator was set at 240 s and 0.5 strokes/s. This setting allowed the rice samples to be completely pulverized allowing for total microbial load analyses. Mixing 1 mL of the original mixture with 9 mL of phosphate-buffered dilution water in a test tube and repeating the dilution until 10^{-8} dilution was performed.

The 3M Petrifilm Aerobic Count Plates and Rose Bengal agar supplemented with the antibiotic dichloran were used to enumerate aerobic bacterial, and *A. flavus* mold counts as follows:

Aerobic Plate Counts

The count plates were placed on a flat surface and the top film carefully lifted. A P1000 micropipette (Finnpipette F2, Thermo Fisher Scientific, Inc., Vantaa, Finland) was used to pipette 1 mL of sample solution onto the center of the plate. Then, the top film was placed down onto the inoculum. After the center of spreader was aligned with the center of the plate, the center of spreader was gently pressed to distribute the inoculum evenly, and then the gel was allowed one minute to solidify. Aerobic Count Plates were incubated (VWR General Purpose Incubator 1536, Sheldon Manufacturing Inc., Cornelius, OR) at 37°C for 48 hours before counting.

Dichloran Supplemented Rose Bengal Agar

Rose Bengal Agar is a selective medium to detect and enumerate yeasts and molds in food samples. Rose Bengal agar base was liquefied by autoclaving at 121°C for 45 mins. The medium was then allowed to cool to 45°C to 50°C then supplemented with dichloran and a stock solution of streptomycin and chlortetracycline after which it was poured into sterile Petri dishes and allowed to solidify. After medium is cooled, 0.1 ml aliquots of sample solution were spread on the Petri plates using glass hockey sticks. The Rose Bengal Agar plates were incubated (Thelco Model 4, Precision Scientific Instruments, Inc., Chicago, IL) at 25°C for 120 hours before counting. After incubation, the colony forming units (CFU) on each plate was counted.

Microbial Enumeration

After incubation, the CFU on each plate were counted. The appropriate dilution factor, volume, and sample weight were taken into account to obtain the total CFU/g of each sample:

$$T_{cfu} = \frac{P_{cfu}}{D_r} \qquad (1)$$

where T_{cfu} is total colony forming units per gram of rough rice (CFU/g), P_{cfu} is colony forming units counted on plate per gram of rice (CFU/g), and D_r is dilution factor (10-3 to 10-8 times).

Statistical Analysis

Statistical analyses were performed with statistical software (JMP version 11.0.0, SAS Institute). A one-way fixed effects analysis of variance (ANOVA) and Tukey's honest significant difference (HSD) test were performed to determine significant differences within and among samples. All test were considered to be significant when $p < 0.05$.

Response surface methodology (RSM) was then used to geometrically describe the relationship between a response and one or more factors. RSM is a collection of mathematical and statistical techniques based on the fit of a polynomial equation to the experimental data, which must describe the behavior of a data set with the objective of making statistical inferences. It can be well applied when a response or a set of responses of interest are influenced by several variables. By evaluating the responses, the set of operating conditions for making the product with the overall best response can be determined. This set of operating conditions is called the optimum condition for the process. The optimum condition for the response is represented by a function ("Multiple Response Optimization Using JMP - SAS."). The desirability of response is weighted by an importance value when it is considered against the goals of the other responses during optimization. The importance value is usually set when defining the responses.

Optimization Factors

Based on a feasibility study it was determined that changes in MW specific energy had statistically significant ($p < 0.05$) effects on the rice in terms of surface temperature (ST), final MC, milled rice and physiochemical properties and that optimum responses occurred at or around 600 kJ/kg-grain. Accordingly, experimentation involved exploration of MW specific energies of 533.33, 600, 800 and 900 kJ/kg.

MW specific energy (kJ/kg) is defined as the MW energy transferred per unit mass of product being treated and is calculated as follows:

$$SE = \frac{P \times T}{M} \quad (2)$$

Where:

SE is the microwave specific energy (kJ/kg)

P is the microwave power (kW)

T is the microwave heating duration (s)

M is the mass of product being treated (kg)

Minute changes in MW power, heating durations or product loading mass exact changes in the magnitude of MW specific energy. For example, an increase in product mass will cause a decrease in MW specific energy and vice versa. Therefore the factors of importance for this study are the factors that lead to changes in MW specific energy.

Response Variables

Conventional convective heated air rice drying methods are not metered to decontaminate the harmful and heat tolerant microbes common to food products left in storage. Additionally, the specific conditions of temperature and relative humidities of storage vessels can contribute to the rapid deterioration of stored rice by promoting microbial growth (Christensen and Saucer 1992). Microbial contaminations of rice can lead to kernel discoloration, changes in chemical and nutritional characteristics, reduced germination and most importantly, lead to mycotoxin contamination (Paster et al. 1993). Although research has shown no correlation between aerobic bacterial counts with levels of pathogens they can be used as indicator organisms to assess the performance of antimicrobial interventions such as that of MW. The response goal was set to minimize responses.

RESULTS AND DISCUSSION

Aerobic bacteria colony appeared red in color on Aerobic Count Plate. Yeast colony appeared blue-green or off- white in color and had non-diffusive edges. Mold colony colors were blue, black, yellow, or green. Mold colonies tended to be larger and more diffusive than yeast colonies. The least square mean and the standard deviation of the population of aerobic bacteria and *A. flavus* of control samples are presented in Table 6.2.

Table 6.2: Aerobic bacterial and *Aspergillus flavus* mold counts of control samples

Microbe	**Mean Concentration (Log (CFU/g-grain))**	**Standard Deviation**
Aerobic Bacteria	7.25	0.75
Aspergillus flavus	4.05	0.61

Implications of Increasing Microwave Specific Energy on Microbial Loads

Analyses were performed to investigate the correlation of the supplied MW specific energy with the rice microbial loads. Increasing specific energy supplied to the rice bed resulted in statistically significant ($p < 0.0001$) decreases in both the aerobic bacteria and *A. flavus* microbial response as indicated by the effect test table in Table 6.3. This table shows the source of the effect, the degrees of freedom (n-1), the sum of squares, F ratio and probability value. F ratio is the statistic used to test the hypothesis that the response means are significantly different from one another. A larger F ratio indicates a decreased likelihood that the observed difference in treatment means is due to chance. A small p-value (≤ 0.05) indicates strong evidence against the null hypothesis.

Aerobic Bacteria Loads

The effect of increasing specific energy was found to cause statistically significant effects to the aerobic bacteria load response ($p < 0.0001$). It should be noted, however, that the F ratio for the aerobic bacteria response was higher than that of the *A. flavus* response. This indicates that the effect of increasing MW specific energy brought about more reductions in the aerobic load response than that of the *A. flavus* response. This can be explained by the hardiness of the *A. flavus* mold spores. The heat tolerant nature of *A. flavus* makes it very difficult to decontaminate; and this presents the problems related to pathogenicity in human and food systems (Yu et al., 2005).

Table 6.3: Effect test table showing the effects of increasing microwave specific energy on the aerobic bacterial populations of medium grain rice

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	50.03588	12.5090	9.5745
Error	39	50.95313	1.3065	**Prob > F**
Corrected Total	43	100.98901		<.0001*

Aspergillus flavus loads

The effect of increasing specific energy was found to cause statistically significant effects ($p < 0.0001$) on the *A. flavus* load response as indicated by the effect test table in Table 6.4.

Table 6.4: Effect test table showing the effects of increasing microwave specific energy on the *Aspergillus flavus* mold populations of medium grain rice

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	4	21.461067	5.36527	8.8344
Error	38	23.077931	0.60731	**Prob > F**
Corrected Total	42	44.538997		<.0001*

The effects of increasing specific energy on the rice microbial populations are displayed in figure 6.2. Aerobic bacteria and *A. flavus* mold count for the control samples were significantly higher than the aerobic bacteria count and *A. flavus* mold count of samples treated with MW. It was noted that increasing the specific energy supplied to the rice resulted in decreasing microbial loads for both the aerobic bacteria and the *A. flavus* mold (Fig. 6.2). Tukey's HSD test was done to identify where the differences were and are indicated on the graph. Means with the same letter are not significantly different. The lowest aerobic bacteria and *A. flavus* counts were seen at specific energies of 900 kJ/kg-grain and had least square means of 2.69 Log (CFU/g-grain) and 1.12 Log (CFU/g-grain) and standard deviations of 0.53 Log (CFU/g-grain) and 0.43 Log (CFU/g-grain) respectively. Higher heat fluxes are seen at higher specific energies. At 900 kJ/kg-grain, the rice bed layers experienced higher temperatures and thusly-higher microbial decontamination than rice treated at lower specific energies.

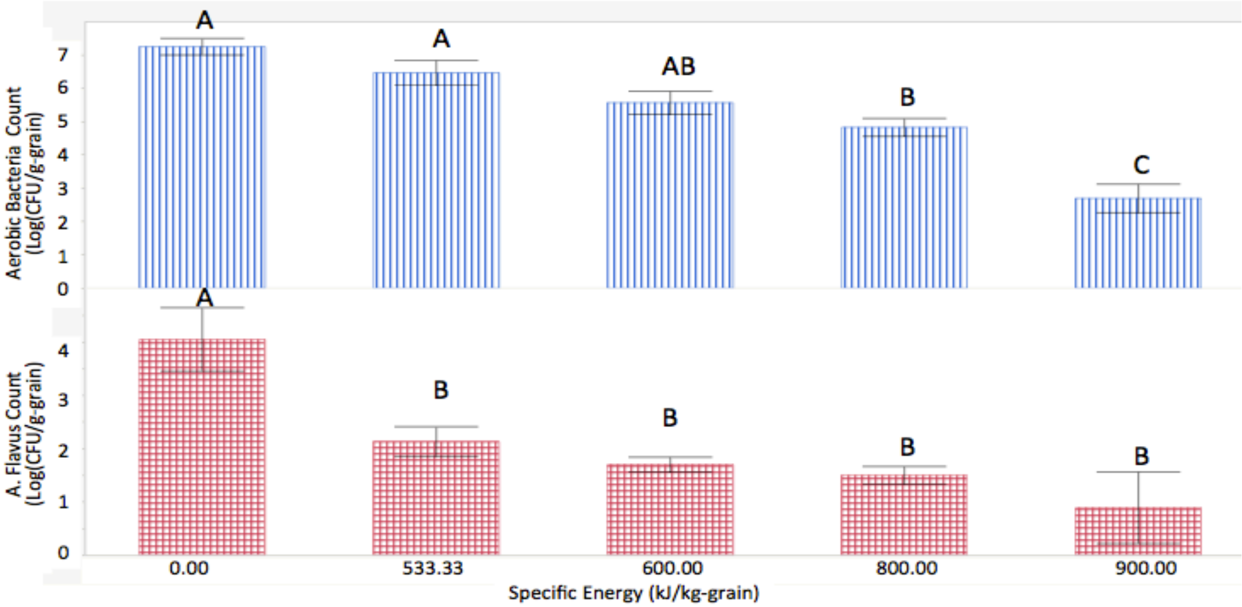


Figure 6.2: Effects of increasing microwave specific energy on the aerobic bacterial and *Aspergillus flavus* populations on medium grain rice. Means with the same type of letters are not significantly different at $\alpha = 0.05$.

Implications of rice bed thickness variation

The impacts of varying rice bed thicknesses were determined. The rice milling industry requires large throughputs for their drying operations to avoid microbial decontamination bottlenecks at peak harvest times. Consequently, information is needed on any variation in STs throughout the rice bed layer as a result of increasing rice bed thicknesses. Due to the size limitations of the equipment, the rice beds studied in this experiment were 5, 10 and 15 cm, which correspond to loading masses 3, 6 and 9 kg.

The effect of increasing specific energy was found to be statistically significant ($p = 0.0245$) for the aerobic bacteria load response only. Increasing the rice bed layer thickness resulted in a disparity of aerobic bacteria counts between the top and bottom layers. Rice at the top layers had aerobic bacteria counts higher than the middle and bottom layers. Additionally, the middle layers had aerobic bacteria counts higher than the bottom layer. This level of significance was not seen for the *A. flavus* decontamination ($p = 0.2801$). There was no disparity in decontamination of *A. flavus* between any of the layers. The lowest aerobic bacteria counts were seen at specific energies of 900 kJ/kg-grain and at layer 1 which corresponds to the 0 to 5 cm thickness. In rice beds of 15 cm thickness, it was observed that bottom rice bed layers tend to reach higher STs compared to top layers. Top layers experienced evaporative cooling resulting in lower STs and this likely reduced decontamination effectiveness. At 900 kJ/kg-grain, the responses of aerobic bacteria and *A. flavus* counts had least square means of 2.50 Log (CFU/g-grain) and 0.50 Log (CFU/g-grain) and standard deviations of 0.71 Log (CFU/g-grain) and 0.71 Log (CFU/g-grain) respectively.

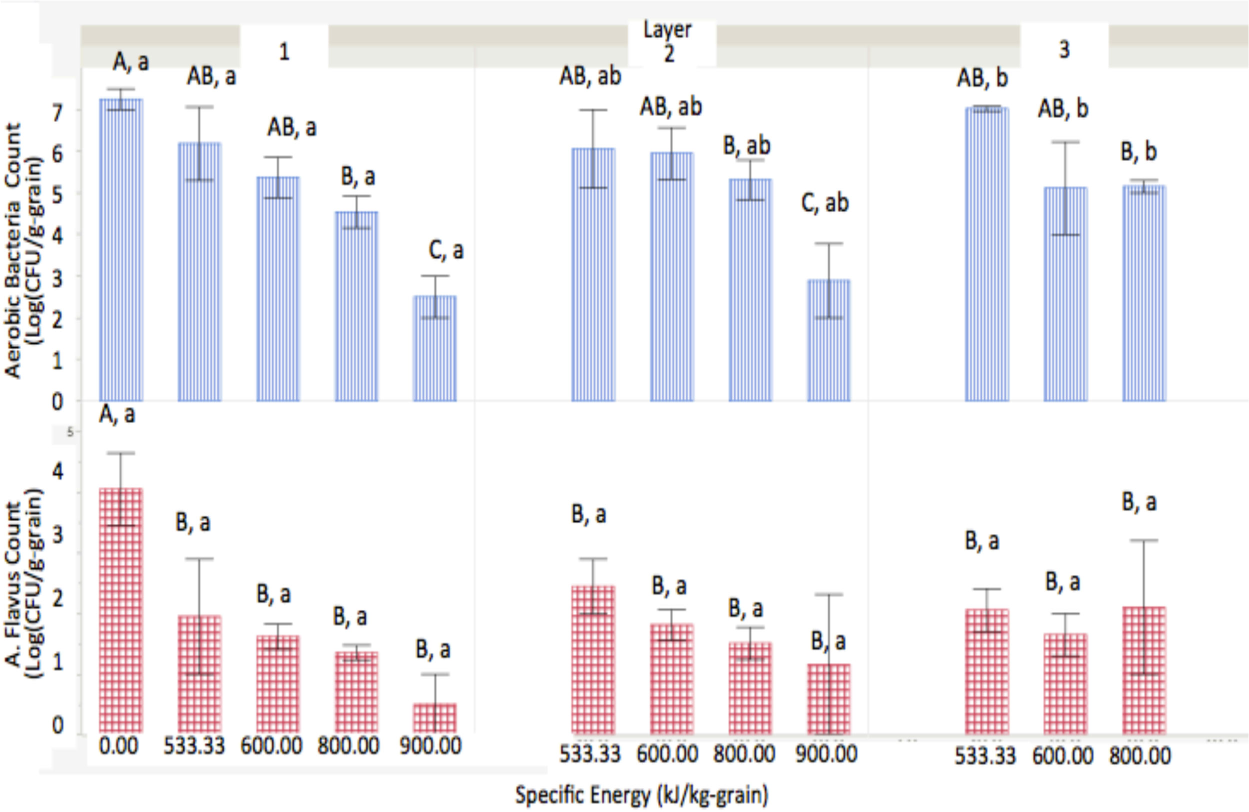


Figure 6.3: Effect of increasing microwave specific energy and rice bed layer thicknesses (1, 2 and 3 which correspond to 5.00 10.00 and 15.00 cm) on the aerobic bacterial and *Aspergillus flavus* populations on medium grain rice. Means with the same type of letters are not significantly different at $\alpha = 0.05$.

Optimization of Microbial Load Reduction

Specific energy is calculated using the variables of MW power (kW), the treatment duration (min), and mass (kg) of the treated sample and can be obtained by using many different combinations of these variables. For example, a specific energy of 600 kJ-kg-grain can be obtained using the following combinations of power, mass, and duration in Table 6.5:

Table 6.5: Possible power, loading mass and treatment durations necessary to achieve a microwave specific energy of 600 kJ/kg-grain

Power (kW)	Mass (kg)	Duration (min)
10.00	6.00	6.00
15.00	6.00	4.00
15.00	9.00	6.00

Due to the combinatorial nature of MW specific energy, the process must be optimized to determine the best combinations of power, mass and heating durations necessary to achieve the greatest responses in terms of physical characteristics of the end product. Typically in the analysis of industrial data, there are many response variables to be investigated. The problem arises when all of these responses are under investigation at the same time. The experimenter must decide which responses are most important, usually at the expense of other responses. In order to overcome this problem, optimization was carried out using RSM.

Table 6.6 shows the effect summary table for the aerobic bacteria count and *A. flavus* count response. The tables list the model effects, sorted by ascending *p*-values. Smaller p-values indicate higher significance to the model. The effect summary table for the microbial load response indicates high statistical significance ($p<0.05$) for the main effects of power and mass (or thickness). The effect of heating duration was found to be insignificant ($p = 0.06$). It was determined that there were no significant quadratic effects in the model. This means that if the relationship between responses and heating duration were represented by a graph, the optimal responses would be at the extremes of the experimental region.

Table 6.6: Effect summary table showing the effects of microwave power, loading mass and heating duration on the aerobic bacteria and *Aspergillus flavus* mold count response (Log (CFU/g-grain).

Source	Log Worth	P Value
Power (kW)	2.533	0.00293
Mass (kg)	1.898	0.01265
Duration (min)	1.199	0.06324
Power (kW)*Mass (kg)	1.157	0.06962
Power (kW)*Duration (min)	0.998	0.10053
Mass (kg)*Mass (kg)	0.869	0.13522
Power (kW)*Power (kW)	0.679	0.20924
Mass (kg)*Duration (min)	0.287	0.51616
Duration (min)*Duration (min)	0.240	0.57607

According to the prediction profiles it was determined that minimum levels of microbial load could be obtained at factor settings shown in Table 6.7; the corresponding prediction profiles are shown in Figure 6.4 and Figure 6.5.

Table 6.7: Optimized parameter settings for aerobic bacteria and *Aspergillus flavus* mold count reduction (Log (CFU/g-grain))

Response	Factors			Microbial Count
	Power (kW)	**Mass (kg)**	**Duration (min)**	**(Log (CFU/g-grain))**
Aerobic Bacteria	12.26	7.14	6.67	4.77
Aspergillus flavus	12.38	7.13	6.65	1.41

Of the possible power (5, 10 and 15 kW), mass (3, 6 and 9 kg which corresponds to equivalent thicknesses of 5, 10 and 15 cm) and duration (4, 6 and 8 mins) combinations, it was determined that a power of 12.26 kW, a mass of 7.14 kg and a heating duration of 6.67 min are preferred for optimum inactivation of aerobic bacteria. It should be noted that a mass of 7.14 kg corresponds to an equivalent thickness of 11.90 cm. The optimized factor settings correspond to a specific energy of 687.18 kJ/kg-grain. At these settings, optimized responses of aerobic bacteria count should be 4.77 Log (CFU/g-grain). For the *A. flavus* count response, optimization analyses suggest that a power of 12.38 kW, a mass of 7.13 kg and a heating duration of 6.65 min are preferred for optimum inactivation of *A. flavus*. It should be noted that a mass of 7.13 kg corresponds to an equivalent thickness of 11.88 cm. The optimized factor settings correspond to a specific energy of 692.79 kJ/kg-grain. At these settings, optimized responses of *A. flavus* mold count should be 1.41 Log (CFU/g-grain).

In addition to the determination of the optimal factor levels, the prediction profiler also gives insight to the significance of impact a factor has on the performance parameter in question. A steep slope indicates that an operational parameter has a significant impact on the given performance parameter, whereas a shallow slope indicates little or no effect on a performance parameter. For the aerobic bacteria count response, the operational parameter of mass (or thickness) was determined to be the most significant and for the *A. flavus* count response, the operational parameter of power was determined to be the most significant. This indicates that the effects of increasing mass or rice bed layer thickness and power contributed the most change to the aerobic bacteria and *A. flavus* count response respectively.

The Desirability Profile

The last row of plots shows the desirability trace for each factor (Fig. 4 and Fig. 5). The numerical value beside the word ‘Desirability’ on the vertical axis is the geometric mean of the desirability measures. This row of plots shows both the current desirability and the trace of desirability that result from changing one factor at a time. A desirability of 0.4650 indicates that approximately 46.50 % of the goals to minimize rice aerobic bacteria count were achieved.

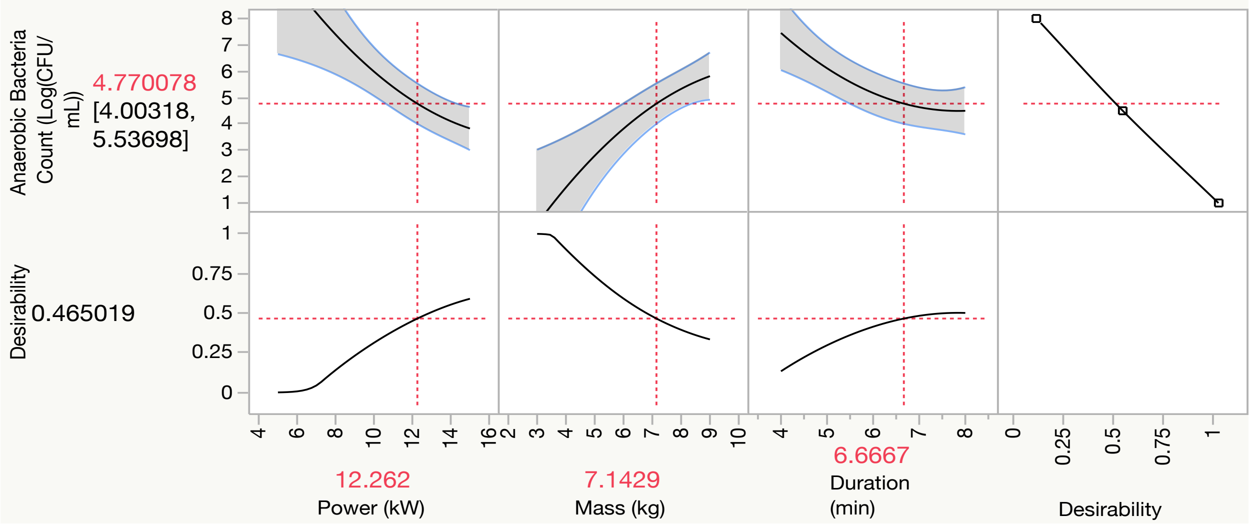


Figure 6.4: Prediction profile for aerobic bacteria count (Log (CFU/g-grain)) responses with parameter settings power (kW), loading mass (kg) and duration (min)

A desirability of 0.5200 indicates that approximately 52.00 % of the goals to minimize rice *A. flavus* mold count was achieved.

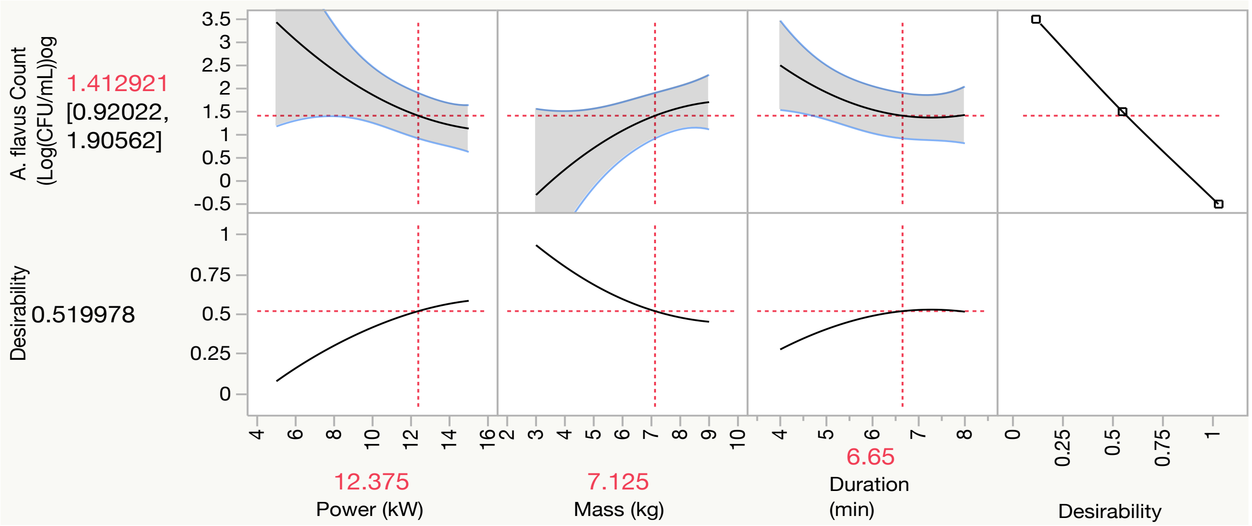


Figure 6.5: Prediction profile for *Aspergillus flavus* count (Log (CFU/g-grain)) responses with parameter settings power (kW), loading mass (kg) and duration (min)

Validation

Using optimization analyses, it was determined that a power of 12.26 kW, a mass of 7.14 kg and a heating duration of 6.67 min provide the optimal response in terms of aerobic bacteria load reduction. These factor levels translate into a thickness of 11.90 cm and an optimized specific energy of 687.18 kJ/kg-grain. At these settings, optimized responses of aerobic bacteria count should be 4.77 Log (CFU/g-grain). For the *A. flavus* count response, optimization analyses suggest that a power of 12.38 kW, a mass of 7.13 kg and a heating duration of 6.65 min are preferred for optimum rice *A. flavus* count. It should be noted that a mass of 7.13 kg corresponds to an equivalent thickness of 11.88 cm. The optimized factor settings correspond to a specific energy of 692.79 kJ/kg-grain. At these settings, optimized responses of *A. flavus* mold count should be 1.41 Log (CFU/g-grain). Predicted data for aerobic bacterial load and *A. flavus* mold count was compared to experimental data. At 600.00 kJ/kg-grain, specific energy experimental bacterial load and *A. flavus* mold count were 5.86 Log (CFU/g-grain) and 1.97 Log (CFU/g-grain) respectively; these levels were well within the range of the predicted data.

CONCLUSION

The results indicate that MW heating may be used to achieve bacterial and mold inactivation on rough rice kernels. The effects of increasing specific energy on the rice microbial populations were determined. Aerobic bacteria and *A. flavus* mold counts of the control samples were significantly higher than samples treated with MW. It was noted that increasing the specific energy supplied to the rice resulted in decreasing microbial loads for both the aerobic bacteria and the *A. flavus* mold.

The effects of increasing rice bed layer thickness (1, 2 and 3 which correspond to 5.00

10.00 and 15.00 cm) were determined for the aerobic bacteria, and *A. flavus* mold counts. The factor of rice bed thicknesses was only significant for the aerobic bacteria load populations ($p = 0.02$). Increasing the rice bed layer thickness resulted in a disparity in decontamination of aerobic bacteria between the top and bottom layers. This level of significance was not seen for the *A. flavus* decontamination ($p = 0.28$). There was no disparity in decontamination of *A. flavus* between any of the layers.

Optimization analyses suggest that a power of 12.32 kW, a mass of 7.14 kg and a heating duration of 6.66 min provide the optimal response in terms of rice microbial bacteria load reduction. These factor levels translate to a thickness of 11.10 cm and an optimized specific energy of 689.99 kJ/kg-grain.

The significant reduction of the harmful mold is expected to help prevent rice losses related to aflatoxin contamination. Moreover, reduction of aerobic bacteria counts will aid in suppressing respiration of rice, therefore, improving overall rice quality.

FUTURE WORK

There is growing research suggesting that rice aerobic bacterial and *A. flavus* mold counts vary based on the presence of the hull and bran layers. Ueda and Kuwabara (1988), showed a reduction in microbial counts related to the milling processes. For example, reductions were seen after rice hull removal to create brown rice, and an additional reduction after the removal of bran to create white rice. Additionally, the mean aerobic bacterial counts for hulls were statistically greater ($p<0.05$) than that of the bran, which was statistically greater ($p<0.05$) than that of the broken kernels; the mean aerobic bacterial counts for the broken kernels were higher ($p<0.05$) than that of the head rice. Consequently, future studies could involve further investigation on the implications of varying MW specific energy and rice bed thicknesses on the microbial populations of different rice partitions.

Additionally, the responses of certain microbes may vary based on the level of MW specific energy and frequency. Investigations into the implications of different MW specific energies and frequencies on the responses of specific microbes could open possibilities of maximizing inactivation of especially harmful microbes including specific heat tolerant mold spores without compromising rice quality metrics.

ACKNOWLEDGEMENTS

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Optimization of Microwave Drying of Rice: Overall Quality and Energy Use Consideration

ABSTRACT

Microwave processing has found various applications for industrial purposes, especially in the grain drying industry. The use of an industrial microwave to dry grain has added benefits of high thermal efficiency and shorter drying durations compared to conventional hot air drying methods. Additionally, unlike microwaves, conventional hot air drying methods are not metered to inactivate heat tolerant molds such as Aspergillus flavus whose proliferation can lead to aflatoxin contamination. Despite the various advantages cited in the literature, it is necessary to optimize microwave drying to provide an energy and cost efficient process that produces high-quality final product. To that end, the objective of this paper is to present a logical and systematic analysis of the economic and energy utilization factors involved in the implementation of a 915 MHz industrial microwave to dry freshly harvested rice. Optimization analyses using response surface methodology were based on experimental data gathered from the microwave drying of medium-grain rough rice (cv. CL721) at initial moisture content (MC) of 24% (w.b.). The MW was set to transmit energy at power levels 5, 10, and 15 kW for 4, 6, and 8 minutes and 15 cm rice bed thicknesses. Optimum parameter settings for power (kW) and heating durations (min) are determined for optimum milled rice yield (MRY), head rice yield (HRY) and final moisture content (FMC). Corresponding microbial load reduction at these parameter settings are also taken into account. Related costs and energy consumption of microwave drying at optimum parameter settings was analyzed and compared to conventional drying methods.

Optimization analyses suggest that a power of 10.00 kW and a heating duration of 6.00 min are preferred for optimum rice aerobic bacteria and A. flavus mold count, MRY, HRY and FMC of *rice beds of equivalent bed thickness of 15 cm. These factor levels equate to a specific energy of 400.00 kJ/kg-grain. At these parameter settings, a ton of freshly harvested rice the energy required to dry a ton of freshly harvested rough rice was 111.11 kWh. Drying at this MW specific energy for batch processes will cost $9.88 per ton and a heating duration of 667.85 min (11.13 hours). Scaling up the MW drying operation for industrial use by implementing a continuous drying process with a larger MW system and increased loading rate will result in a dramatic decrease in drying time.*

Keywords: Energy utilization, rice quality, milling, microwave drying, volumetric heating, physiochemical properties, microbial load reduction

INTRODUCTION

Drying is one of the oldest methods of food preservation. The role of drying is to reduce the moisture content (MC) of foods to inhibit the growth of microorganisms and to inhibit enzymatic reactions hence preserving the food quality and making it safe for storage. Unfortunately, conventional natural and convective heated- air drying methods tend to introduce temperature and MC gradients within the rice kernel thus inducing tensile stress at the surface and compressive stress in the interior of the kernel (Fan et al., 2000). These stresses cause degradation of the rice kernel’s mechanical properties, which then leads to fissuring. Fissuring is responsible for the rice kernels' inability to withstand the milling processes without breaking and negatively impacting the rice milling yield. The rice milling yield, to a significant part, is quantified by the head rice yield (HRY) (USDA-GIPSA 2010). HRY comprises milled rice kernels that are at least three-fourths of the original kernel length; HRY represents the mass percentage of a rough rice lot that remains as head rice after milling. Preventing HRY reduction during drying is very critical and bears significant economic importance to the rice milling industry (Cnossen and Siebenmorgen, 2000). Head rice is the high-value portion of processed rice. Under ideal conditions, a perfect HRY recovery would be about 70% of the total rough rice produced after the rice hulls and bran are removed. However, with current conventional rice drying methods, HRY recovery averages only about 58%, and can be even lower depending on other pre-harvest and post-harvest factors (USDA, 2014; Atungulu et al., 2015). To avoid lowering the rice milling quality, conventional drying methods necessitate rice grains be exposed to relatively low air temperatures (about 43^{o}C) (Kunze and Calderwood. 1985). However, these drying temperatures are below the temperature needed to be able to meet the National Advisory Committee on Microbiological Criteria for Foods (NACMCF) disinfection requirements for a 5-log reduction in the level of pathogens. Often, to meet these requirements, some chemical application is employed. However, the prolonged chemical residual resistance on rice and the compounds discharged to water and air are potentially hazardous to the environment, animals, and humans.

Microwave energy has been used in food processing applications due to its merits of time and energy savings, considerably reduced processing duration, fine microstructures and hence improved mechanical properties, and it is also environmentally friendly with very high heat energy transfer rates (heat fluxes) (>400°C/min) (Mullin, 1995; Thuery, 1992). These benefits are finding applications in the grain industry, making the use of industrial microwave drying of rice a possible avenue to mitigate food safety concerns related to bacteria and mold contamination.

This manuscript provides a systematic study of an industrial microwave for use as a method to simultaneously decontaminate and dry freshly harvested rice. Data from a series of experiments conducted on freshly harvested medium grain rice of cultivars CL 271 and Jupiter from the 2015 and 2016 Arkansas rice seasons was used to determine the implications of increasing MW specific energy and varying rice bed layer thicknesses on rice aerobic bacteria and *A. flavus* mold count, MRY, HRY and FMC. Optimization was carried out using response surface methodology (RSM).

RSM is a collection of mathematical and statistical techniques based on the fit of a polynomial equation to the experimental data, which describe the behaviors of a data set with the objective of making statistical inferences. It can be well applied when a response or a set of responses of interest are influenced by several variables. By evaluating the responses, the set of operating conditions for making the product with the overall best response can bed determined. This set of operating conditions is called the optimum condition for the process (Multiple Response Optimization Using JMP - SAS.)

Past Research

An industrial MW system with a frequency of 915 MHz was used to dry freshly harvested medium-grain rough rice samples (cv. Jupiter) at initial MC of 23% to 24% wet basis (w.b). Preliminary results indicated that drying rice to a MC of 14% to 16% was feasible with application of MW specific energy at 600 kJ/kg-grain followed by 4 hours of tempering at 60°C.

Resulting head rice yield (HRY) was not significantly different from that of control samples dried gently using natural air (25°C and 65% relative humidity). Additional experimentation focused on the implications of thickness variation to determine maximum rice throughput without negatively affecting rice milling yield, and microbial load reduction. MW specific energy had significant effects ($p < 0.0001$) on all responses studied. Increasing MW specific energy resulted in decreases in rice microbial loads. At the highest specific energy of 900 kJ/kg-grain, the reduction of the aflatoxigenic fungal and aerobic bacterial loads was 2.75 log and 3.00 log CFU/g-grain, respectively. Varying rice bed thickness had significant effects ($p < 0.05$) on rice final surface temperature (FST), HRY, MRY and aerobic bacteria count indicating a disparity in responses as a result of increasing rice bed thickness. Highest MRY and HRY were observed at the top and middle layer with bottom layer having the smallest. Similar trends were observed for the aerobic bacteria response.

OBJECTIVES

Research on the efficiency and related energy costs of the microwave drying of rough rice kernels is very limited. To successfully implement microwave technology for rice drying, there is need to optimize the process such that rice milling quality is improved and the rice nutritional and functional quality indices are maintained. The objective of this research was to determine optimal settings for power, mass, and heating durations to achieve one-pass rice drying with the use of a 915 MHz industrial-type microwave with minimum implications on the rice quality. The specific objectives of this study were to optimize the microwave drying process to:

1) Maximize rice-milling yields.
2) Maximize reduction of aerobic bacteria and the aflatoxigenic mold species.

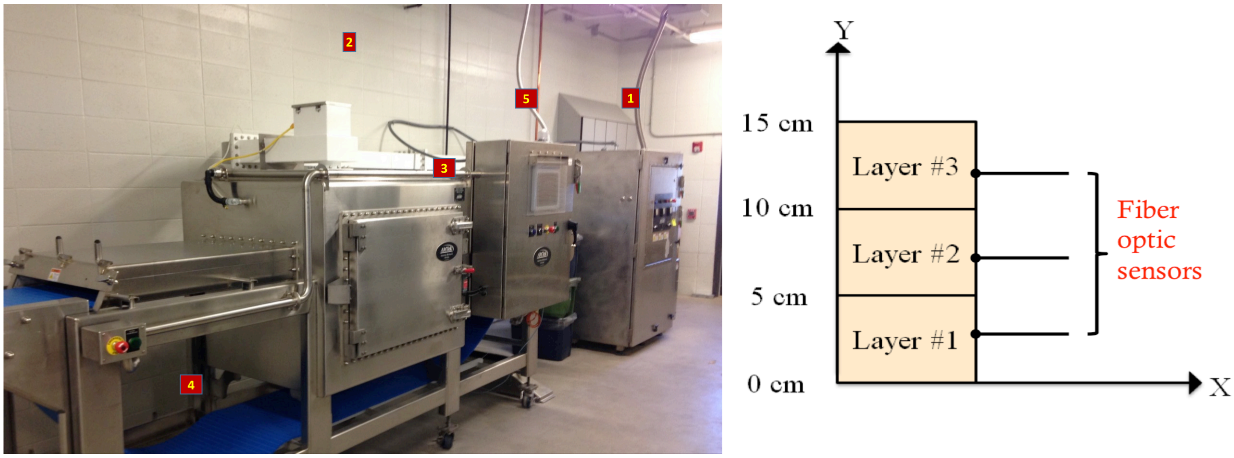
MATERIALS AND METHODS

Rice samples

Freshly-harvested, medium-grain rice samples (cv. Jupiter) at initial MC of 23.5% (wet basis) were used in this study. The samples were cleaned using a dockage equipment (MCi Kicker Dockage Tester, Mid-Continent Industries Inc., Newton, KS). The equipment used a series of small sized sieves to provide a fast, accurate and consistent way of separating shrunken, broken, scalped material, broken kernels, splits and dust from rice. The cleaned rice was stored in a laboratory cold room set at 4°C. At the beginning of the experiments, the samples were retrieved from the cold room and allowed to equilibrate with room conditions (25^o C) overnight before conducting any experiments. The MCs of the samples reported in this study were determined using an AM 5200 Grain Moisture Tester (PERTEN Instruments, Hägersten, Sweden) which was calibrated using the ASABE standard (Jindal and Siebenmorgen, 1987). The MC of each sample was measured by placing 15 g duplicate samples into a 130°C conduction oven (Shellblue, Sheldon Mfg., Inc., Cornelius, OR) for 24 h, followed by cooling in a desiccator for at least half an hour (Jindal and Siebenmorgen, 1987). All reported MCs are on wet basis.

Microwave equipment

An industrial microwave system (AMTek, Applied Microwaves Technology Inc., Cedar Rapids, IW) was used in this study. The system (Fig. 7.1a) consists of a transmitter, a wave guide, and the microwave heating zone (oven) and operates at a frequency of 915 MHz. The transmitter is a high-powered vacuum tube that works as a self-excited microwave oscillator. It is used to convert high-voltage electric energy to microwave radiation. The waveguide consists of a rectangular or cylindrical metal tube or pipe through which the electromagnetic field propagates lengthwise. It is used to couple microwave power from the magnetron into the lab oven. The lab oven is the internal cavity of the microwave that provides uniform temperatures throughout while in use.



(a) (b)

Figure 7.1a: Diagram of microwave system showing the transmitter (1), heating zone (2), wave guide (3), conveyor belt (4), and control panel (5), **Figure 7.1b:** Diagram of 9 kg of rice in 3 stackable microwave blind trays fitted with fiber optic cables in each layer

Experimental Design

The experimental conditions were determined based on a feasibility study. It was determined that MW treatments over 800 kJ/kg-grain result in the rice burning and popping. Consequently, for this research specific energies above 800 kJ/kg-grain were omitted. MW treatments were done in batch with power levels of levels of 5, 10 and 15 kW and heating durations of 4, 6 and 8 minutes for rice beds of thicknesses 5, 10 and 15 cm which translates to loading masses of 3, 6 and 9 kg. The experimental design is shown in Table 7.1.

Table 7.1: Rice bed thicknesses, microwave power levels heating durations and resultant microwave specific energies used in the rice drying experiments

Bed Thickness (cm)	Microwave Power (kW)	Heating Duration (min)	Specific Energy (kJ/kg)
5	5	8	800.00
5	10	4	800.00
10	10	6	600.00
10	10	8	800.00
15	10	8	533.33
10	15	4	600.00
10	15	6	900.00
15	15	6	600.00
15	15	8	800.00

ǂ Microwave treatment power (kW), heating duration (min) and bed thicknesses (cm) combinations were chosen based on its ability to reduce rough rice MC from 24% to 12% w.b. in one pass and the resultant HRY as determined by the feasibility study. A full factorial design was not feasible because under some power levels and heating durations the rice would pop.

Microwave Treatments

The implications of MW intensity and heating duration on treatments of rice beds of different thicknesses (5, 10 and 15 cm) were studied. For each layer a sample of 3000 g rice was massed out and placed into MW safe trays (Fig. 7.1 b) for the treatment. Each tray was stackable allowing for a total of up to 9000 g of rice to be treated at once. The outsides of the trays were made of polypropylene with a Teflon coated fiberglass mesh at the bottom to hold the samples. The trays with rice sample were set in the oven on the belt and treated at various power levels and durations (Table 7.1). The temperature of rice during MW heating was measured using fiber optic temperature sensors (OMEGA Engineering, INC., Stamford, CT 06907). After MW treatments, the samples were separated by layer then transferred immediately after to glass jars and sealed air tight. A HOBO sensor (Onset Computer Corporation, Bourne, MA) was placed in the jars to determine the changes in temperature and relative humidity inside the jars. The jars were placed in an environmental chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 60°C and relative humidity of 65%. The rice was tempered for 4 h. After the tempering, the rice was spread uniformly on individual trays, transferred to an EMC chamber (Platinous chamber, ESPEC North America, Inc. Hudsonville, MI) set at a temperature of 25°C and relative humidity of 65%.

Rice Milling

Triplicate, 150 g sub samples of rough rice, obtained from each sample dried to 12.50% MC, were dehulled using a laboratory huller (Satake Rice Machine, Satake Engineering Co., Ltd., Tokyo, Japan), milled for 30 s using a laboratory mill (McGill #2 Rice Mill, RAPSCO, Brookshire, TX) and aspirated for 30 s using a seed blower (South Dakota Seed Blower, Seedboro, Chicago, IL). MRY was calculated as the mass proportion of rough rice that remains including head rice and broken, after milling. Head rice was then separated from broken kernels using a double tray sizing machine (Grainman Machinery Manufacturing Corp., Miami, FL). Head rice are considered as kernels that remain at least three-fourths of the original kernel length after complete milling (USDA-GIPSA 2010). HRY was calculated as the mass proportion of rough rice that remains as head rice after complete milling.

Statistical Analysis

Statistical analyses were performed with statistical software (JMP version 11.0.0, SAS Institute). A one-way fixed effects analysis of variance (ANOVA) and Tukey's honest significant difference (HSD) test were performed to determine significant differences within and among samples. All tests were considered to be significant when $p < 0.05$.

Optimization Factors

Based on a feasibility study it was determined that changes in MW specific energy have statistically significant ($p < 0.05$) effects on the rice in terms of surface temperature, final MC, milled rice and physiochemical properties and that optimum responses occurred at or around 600 kJ/kg-grain. Accordingly, future experimentation involved exploration of microwave specific of 533.33, 600 and 800 kJ/kg.

MW specific energy (kJ/kg) is defined as the microwave energy transferred per unit mass of product being treated and is calculated as follows;

$$SE = \frac{P \times T}{M} \quad (1)$$

Where:

SE is the microwave specific energy (kJ/kg)

P is the microwave power (kW)

T is the microwave heating duration (s)

M is the mass of product being treated (kg)

Minute changes in MW power, heating durations or product loading mass exact changes in the magnitude of MW specific energy. For example, an increase in product mass will cause a decrease in MW specific energy and vice versa. Therefore the factors of importance for this study are the factors that lead to changes in MW specific energy.

Response Variables

Variables of interest in an experiment (those that are measured or observed) are called response or dependent variables. The response variables that will be optimized in this experiment are MRY, HRY, aerobic bacteria and *A. flavus* mold counts. These response variables and their response goals were determined as most important based on a literature review and are presented in Table 2.

Head Rice Yield And Milled Rice Yield

Preventing HRY reduction during drying is very critical and bears significant economic importance to the rice industry. Hence, HRY and MRY were given the highest importance (3) because they hold the most economic importance for the rice milling industry. The response goal was set to maximize responses.

Final Moisture Content

High MC rice is susceptible to spoilage especially from the proliferation of fungal spores inherent in the rice production and harvesting systems. Drying rough rice below harvest MCs to that necessary for safe storage conditions (12.50% w.b) is the most effective and widely used method to preserve the microbial quality of rice. The introduction of a one-pass drying system that can dry rough rice lots from harvest conditions to a MC of 12.50 -13.00% w.b in one pass with HRY comparable or better than conventional drying methods will translate into a large cost savings for the rice milling industry. To that end, rice FMC was also given an importance of 1. The response goal was set to minimize responses (Table 7.2).

Microbial Load Reduction

Conventional convective heated air rice drying methods are not metered to decontaminate the harmful and heat tolerant microbes common to food products left in storage. Additionally, the specific conditions of temperature and relative humidities of storage vessels can contribute to the rapid deterioration of stored rice by promoting microbial growth (Christensen and Saucer 1992). Microbial contaminations of rice can lead to kernel discoloration, changes in chemical and nutritional characteristics, reduced germination and most importantly, lead to mycotoxin contamination (Paster et al. 1993). Although research has shown no correlation between aerobic bacterial counts with levels of pathogens they can be used as indicator organisms to assess the performance of antimicrobial interventions such as that of MW. The response goal was set to minimize responses and was given an importance of 2. The response goal was set to minimize responses

Table 7.2: Experimental responses, response goals, and importance

Response Name	Lower Limit	Upper Limit	Response Goal	Importance
Aerobic Bacteria (Log (CFU/g-grain)			Minimize	2
Aspergillus flavus (Log (CFU/g-grain)			Minimize	2
Milled Rice Yield (%)			Maximize	1
Head Rice Yield (%)			Maximize	1
Final Moisture Content (%)			Minimize	1

RESULTS AND DISCUSSION

Experimental Model

The effect of increasing MW power and heating durations was determined for the aerobic bacteria and *A. flavus* mold count, MRY, HRY and FMC of rice (Table 7.3). It was determined that for all the responses in question there was a statistically significant main effect ($p< 0.05$).

Additionally, there was a significant interaction effect between power and duration ($p = 0.00126$). This means that the effect of the independent variable of power depends on the level of the other independent variable, duration.

Table 7.3: Effect summary table showing the effects of microwave power, loading mass and heating duration on the aerobic bacteria and *Aspergillus flavus* mold count, milled rice yield, head rice yield and final moisture content responses

Source	Log Worth	P Value
Power (kW)	6.002	0.00000
Duration (min)	3.391	0.00041
Power (kW)*Duration (min)	2.900	0.00126

Summary of fit tables for rice microbial load, and milled rice quality parameters can be found in Tables 7.4 and 7.5. Root mean square error is an estimate of standard deviation of the model. The R-square error for the microbial load responses ranged from 0.360697 for the *A. flavus* mold count to 0.613907 for the aerobic bacteria response. This means that the fitted model respectively explains 36.07 to 61.39% of the variation in the *A. flavus* and aerobic bacteria responses. However, the microbial responses had significant predictors (power and/or duration), therefore meaningful conclusions about how changes in the predictor values are associated with changes in the response value can be determined and were therefore left in the model. A low R-squared is most problematic when reasonably precise predictions are needed. Adj R-Sq is an alternative to R-Square, adjusted for the number of parameters in the model. Although a high R-square value is usually preferred as it provides an estimate of the strength of the relationship between the model and the response variable, it does not give a formal hypothesis test for this relationship. The F-test of overall significance determines whether this relationship is statistically significant.

Table 7.4: Summary of fit table for aerobic bacteria and *Aspergillus flavus* mold count responses

Aerobic Bacteria	R-Square	0.613907
	R-Square Adj	0.564089
	Root Mean Square Error	1.279532
	Mean of Response	6.053817
***Aspergillus flavus* mold**	R-Square	0.360697
	R-Square Adj	0.278206
	Root Mean Square Error	0.510033
	Mean of Response	1.870449

The root mean square error for the milled rice quality responses was 0.387063 for the HRY, 0.582026 for the MRY and 0.673298 for the FMC. This means that 38.71% to 67.33% of the variation in the HRY, MRY and FMC responses respectively response is explained by the fitted model.

Table 7.5: Summary of fit table for milled rice yield, head rice yield and final moisture content responses

Milled Rice Yield (%)	R-Square	0.582026
	R-Square Adj	0.528094
	Root Mean Square Error	1.760393
	Mean of Response	70.52938
Head Rice Yield (%)	R-Square	0.387063
	R-Square Adj	0.307974
	Root Mean Square Error	8.14391
	Mean of Response	50.7613
Final Moisture Content (%)	RSquare	0.673298
	R-Square Adj	0.631143
	Root Mean Square Error	1.384913
	Mean of Response	14.18565

The Analysis of Variance (ANOVA) table partitions the total variation of a sample into two components, the mean square for the model and the mean square error. The Model mean square estimates the variance of the error, but only under the hypothesis that the group means are equal. The Error mean square estimates the variance of the error term independently of the model mean square and is unconditioned by any model hypothesis. The ratio of the two mean squares forms the F ratio. If the probability associated with the F ratio is small ($p < 0.05$), then the model is a better fit statistically than the overall response mean.

For the microbial load responses (Table 7.6) the affiliated F ratios were all under the stated alpha of p = 0.05. This indicates that there was a statistically significant relationship between the model and the experimental data.

Table 7.6: Analysis of variance table for aerobic bacteria and *Aspergillus flavus* mold count responses

Response	Source	DF	Sum of Squares	Mean Square	F Ratio
Aerobic Bacteria (Log(CFU/g)	Model	4	80.70039	20.1751	12.3229
	Error	31	50.75328	1.6372	Prob > F
	C. Total	35	131.45367		<.0001*
Aspergillus flavus (Log(CFU/g)	Model	4	4.549813	1.13745	4.3726
	Error	31	8.064139	0.26013	Prob > F
	C. Total	35	12.613952		0.0064*

For the milled rice quality responses (Table 7.7) the affiliated F ratios were all under the stated alpha of p = 0.05. This indicates that there was a statistically significant relationship between the model and the experimental data.

Table 7.7: Analysis of variance table for milled rice yield, head rice yield and final moisture content responses

Response	Source	DF	Sum of Squares	Mean Square	F Ratio
Milled Rice Yield (%)	Model	4	133.77470	33.4437	10.7918
	Error	31	96.06853	3.0990	Prob > F
	C. Total	35	229.84323		<.0001*
Head Rice Yield (%)	Model	4	1298.3527	324.588	4.8940
	Error	31	2056.0216	66.323	Prob > F
	C. Total	35	3354.3743		0.0035*
Final Moisture content (%)	Model	4	122.53550	30.6339	15.9719
	Error	31	59.45755	1.9180	Prob > F
	C. Total	35	181.99305		<.0001*

Optimization

JMP's Prediction Profiler was used to set desirability goals for the rice physiochemical properties, microbial load, and milled rice quality responses to find optimal settings for the power and duration factors and its output is shown in Figure 7.2.

Of the possible power (5, 10 and 15 kW) and heating durations (4, 6 and 8 mins) combinations it was determined that a power of 10 kW and a heating duration of 6 minutes are preferred for optimum protein content, total color difference, peak and final viscosities, aerobic bacteria and *A. flavus* mold count, MRY, HRY and FMC of rice beds of mass 9 kg and equivalent bed thickness of 15 cm. These factor levels equate to a specific energy of 400 kJ/kg-grain. Resultant optimum responses are located in Table 7.8 It should be noted that MRY and

HRY of 72.79 and61.54 % are not significantly different ($p < 0.05$) from control samples that were not treated with microwave but gently dried to an MC of 12.5% w.b.

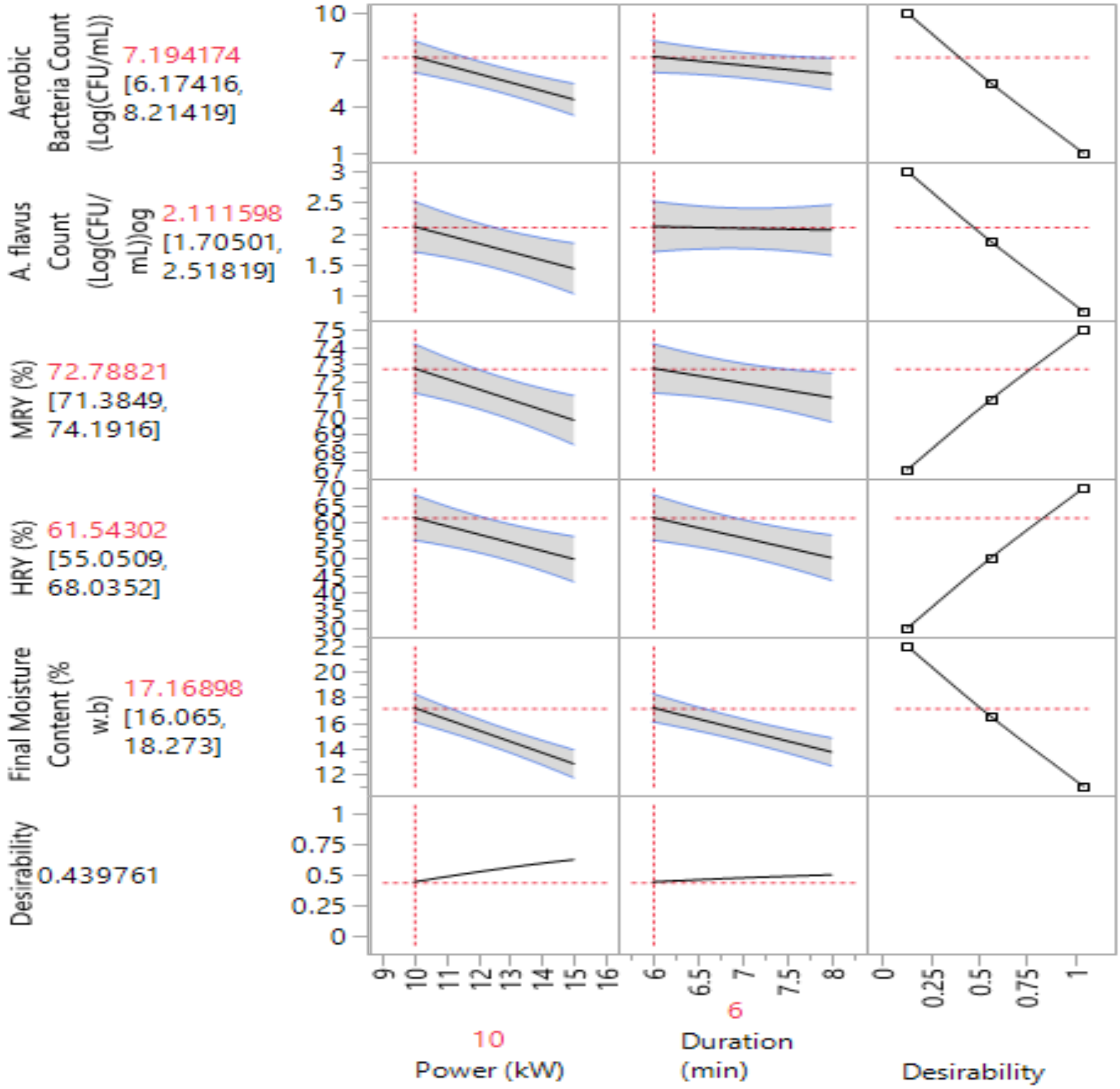


Figure 7.2: Prediction profiler output showing optimum power and duration levels for a 15 cm rice bed thickness and resultant responses for aerobic bacteria count, *Aspergillus flavus* count, milled rice yield (MRY), head rice yield (HRY) and final moisture content (FMC)

Table 7.8: Optimized parameter settings for aerobic bacteria and *Aspergillus flavus* mold count, milled rice yield, head rice yield and final moisture content responses

Parameter	Optimized parameter setting
Microwave Power (kW)	10
Heating Duration (min)	6

Table 7.9: Optimized parameter responses for aerobic bacteria and *Aspergillus flavus* mold count, milled rice yield, head rice yield and final moisture content responses

Response	Optimized Response Level
Aerobic Bacteria (Log (CFU/g-grain))	7.19
***Aspergillus flavus* (Log (CFU/g-grain))**	2.11
Milled Rice Yield (%)	72.79
Head Rice Yield (%)	61.54
Final Moisture Content (%)	17.17

Validation

Predicted data was compared to experimental data at 533.33 kJ/kg-grain, and it was determined that experimental data was very close to optimized responses (Table 7.10). However, some discrepancy is expected as optimized responses were obtained at MW specific energy of 400 kJ/kg-grain.

Table 7.10: Experimental responses for aerobic bacteria and *Aspergillus flavus* mold count, milled rice yield, head rice yield and final moisture content at 533.33 kJ/kg-grain microwave specific energy

Response	Experimental response at 533.33 kJ/kg-grain
Aerobic Bacteria (Log(CFU/g))	6.50
***Aspergillus flavus* (Log(CFU/g))**	2.16
Milled Rice Yield (%)	71.33
Head Rice Yield (%)	49.13
Final Moisture Content (%)	14.32

Microbial Loads

The least square mean of the population of aerobic bacteria and *A. flavus* of control samples were 7.25 and 4.05 Log (CFU/g-grain). An optimized response of 6.50 and 2.11 Log (CFU/g-grain) for aerobic bacteria and *A. flavus* load was a decrease of 10.34% and 47.90% respectively.

Final Moisture Content

Freshly harvest rice must be dried down to safe storage conditions to preserve milling quality and to reduce microbial loads. Conventional rice drying methods require multiple drying passes to obtain this MC without damaging the rice kernel. An optimized response of 17.17% (Table 7.10) indicates that in order to obtain optimum rice milling properties concessions must be made in terms of rice FMC. An additional natural air drying step after MW treatments is suggested.

Milled Rice Yield and Head Rice Yields

The least square means of the control MRY and HRY were 70.35% and 63.13% standard deviations were 3.02% and 4.38% respectively. An optimized response of 72.79% for the MRY is an increase of 3.47%, and an optimized response of 61.54% for the HRY is a decrease of 2.52% from the control samples. However, it should be noted that these yields were not statistically different from the MRY and HRY of control samples gently dried with natural air.

The Desirability Profile

The last row of plots shows the desirability trace for each factor. The numerical value beside the word ‘Desirability’ on the vertical axis is the geometric mean of the desirability measures. This row of plots shows both the current desirability and the trace of desirability that result from changing one factor at a time. A desirability of 0.439761 indicates that approximately 43.98 % of the goals to optimize aerobic bacteria and *A. flavus* mold count, MRY, HRY and FMC responses were achieved.

Energy Consumption and Cost

Based on a 8.9 cent/kWh cost of electricity in Arkansas it was determined that the optimized parameter settings of 10 kW and a 6 min heating duration is necessary to effectively dry freshly harvested medium grain rough rice to safe storage conditions without negatively effecting milled rice quality, physiochemical and properties and maximized microbial load reduction. The energy required to dry a ton of freshly harvested rough rice at these parameter settings was 111.11 kWh. Drying at this energy will cost $9.88 per ton of rice, with MRY of 72.79% and HRY of 61.54% respectively and a heating duration of 667.85 min (11.13 hours). Scaling up the MW drying operation for industrial use by implementing a continuous drying process with a larger MW system and increased loading rate will result in a dramatic decrease in drying time.

Table 7.11: Energy consumption and cost to dry a ton of rice from 24.5% to 13.5% moisture content using a 915 MHz industrial microwave set at optimized parameter settings

Specific energy (kJ/kg-grain)	Power (kW)	Heating Duration (min)	Energy Consumption (kWh)	$/ton-dried rice
400.00	10.00	6.00	111.11	9.88

Conventional air-drying methods used to dry rice typically have an average HRY of 58%. According to Lawrence et al., (2015) the cost for drying rice using conventional methods ranged from $8.90 to $12.70 to dry a ton of rice. These averages vary based on the drying strategy used and the initial and final MCs of the rice harvest. It should be noted that this cost does not include the price of tempering or for transporting rice to dryers.

CONCLUSION

This research showed the feasibility of using a 915 MHz industrial MW to simultaneously dry and decontaminate rough rice without negatively impacting milled rice and functional quality. It was determined that the energy consumption necessary to dry a ton of rice with optimized milling and functional qualities is 111.11 kWh. In the state of Arkansas, this energy consumption translates to a cost of $9.88 per ton and a heating duration of 667.85 min (11.13 hours). Scaling up the MW drying operation for industrial use by implementing a continuous drying process with a larger MW system and increased loading rate will result in a dramatic decrease in drying time. Compared to conventional drying costs ranging from $8.90 to $12.70 to dry a ton of rice and associated energy consumption 7534 to 7699 kWh it was determined that MW drying is more beneficial to the rice milling industry by introducing reduced energy consumption, improved rice milling and physiochemical properties and shorter drying durations. The volumetric heating phenomenon afforded by the use of microwave heating offers the accelerated increase in temperature at the interior of the product, therefore, the rate of heating is not limited, and the uniformity of heat distribution is greatly improved resulting in improved efficiencies and major cost savings. Additionally, as a result of the high heat fluxes afforded by the use of an industrial MW, the process could decontaminate freshly harvested rice. These added benefits translate to large cost savings.

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PROJECT CONCLUSIONS

The performance of an industrial type microwave system for rice drying was tested. The MW system was operated at a frequency of 915 MHz to dry freshly harvested medium-grain rough rice samples (cv. Jupiter) at initial MC of 23% to 24% wet basis (w.b). The rice beds were contained in a modified tray that accommodated up to 9 kg of rice separated by thin fiberglass mesh in 3 kg increments. Each layer of rice was fitted with fiber optic sensors connected to a real time data logger during MW treatments. The implications of MW specific energy and varying rice bed thicknesses on the rice surface temperature, percentage points of moisture removed and rice quality indicators such as milling yields and physiochemical properties were evaluated.

It was determined that specific energy caused statistically significant increases ($p < 0.0001$) on the rice surface temperature. Rice beds of 5 cm thicknesses treated with MW specific energy of 133.33 kJ/kg-grain had a surface temperature of 57.29°C. By contrast, at specific energy of 800.00 kJ/kg-grain the surface temperature increased to 113.03 °C. There was disparity in the final surface temperatures within rice beds as a result of increasing thicknesses. Rice bed middle layers had surface temperatures greater than the top and bottom layers as a consequence of the limited airflow at the middle. Additionally, the top rice bed layer had a much lower surface temperature than the middle and bottom layers as a result of evaporative cooling.

Drying rice to a MC of 14% to 16% was feasible with application of MW specific energy at 600 kJ/kg-grain followed by 4 hours of tempering at 60°C. Resulting head rice yield (HRY) was not significantly different from that of control samples dried gently using natural air (25°C and 65% relative humidity).

The effect of increasing MW specific energies on milled rice was investigated. Increasing specific energies was determined to have the following effects:

- Increased SLC, rice protein content, final and peak viscosities. Responses increased to a high at 600 kJ/kg-grain then decreased at specific energies over 800 kJ/kg-grain. The opposite profile was true for total color difference (TCD).
- Decreased TCD with increasing energy then increased at specific energies more than 600 kJ/kg-grain.
- Decreased microbial loads. At the highest specific energy of 900 kJ/kg-grain, the reduction of the aerobic bacterial and aflatoxigenic fungal loads was 4.56 and 2.93 log CFU/g-grain, respectively.

Additional experimentation focused on the implications of thickness variation to maximize rice throughput without negatively affecting rice drying and quality. The effect of varying rice bed thickness had significant effects ($p < 0.05$) on rice final surface temperature, HRY, MRY and aerobic bacteria count. Highest MRY and HRY were observed at the top and middle layer with bottom layer having the smallest. Similar trends were observed for the aerobic bacteria response.

Optimization analyses suggest that a power of 10.00 kW and a heating duration of 6.00 min are preferred for optimum aerobic bacteria and *A. flavus* mold count, MRY, HRY and FMC of rice beds of equivalent bed thickness of 15 cm. These factor levels equate to a specific energy of 400.00 kJ/kg-grain. At these parameter settings, a ton of freshly harvested rice the energy required to dry a ton of freshly harvested rough rice was 111.11 kWh. Drying at this MW specific energy for batch processes will cost $9.88 per ton of rice, with MRY of 72.79% and HRY of 61.54% respectively and a heating duration of 667.85 min (11.13 hours). Scaling up the

MW drying operation for industrial use by implementing a continuous drying process with a larger MW system and increased loading rate will result in a dramatic decrease in drying time.

These findings suggest that MW drying of rice followed by tempering could be optimized to remove significant amounts of moisture from rice in one pass. However, in order to obtain optimal quality indices including MRY and HRY it is suggested that MW specific energies less than 400 kJ/kg-grain be used to dry rice to a MC around 17.17% and then completed with a gentler drying method such as that of natural air cooling.