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Development of Infrared Heating Technology for Corn Drying and Decontamination to Maintain Quality and Prevent Mycotoxins

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Development of Infrared Heating Technology for Corn Drying and Decontamination to Maintain Quality and Prevent Mycotoxins

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by

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Abstract

Infrared (IR) heating of corn followed by tempering treatments has potential to rapidly dry and simultaneously decontaminate corn without adverse effect on the overall quality. However, it is vital to determine the optimal processing parameters that maximize throughput and minimize drying energy without affecting overall corn quality. This study investigated the effects of IR heating and tempering treatments on moisture removal, mold load reduction, corn color change, and drying energy requirements. In addition, the study evaluated the feasibility of scaling up IR drying process using a newly built, pilot scale IR dryer. Freshly harvested corn with initial moisture content (IMC) of 20%, 24% and 28% wet basis (w.b.) were dried using a laboratory scale IR batch dryer in one- and two- drying passes. The dried sample were then tempered for 2, 4, and 6 h at 50°C, 70°C, and 90°C. The result showed that as tempering temperature and tempering duration increased, moisture removed increased and was higher for one-pass treatments compared to two-pass; similar trends were observed for mold load reductions. For the studied range of processing conditions, mold load reduction ranged from 1 to 3.8 log CFU/g for one-pass and 0.8 to 4.4 log CFU/g for two-pass treatments. Scaled up IR drying treatments of corn at IMC of 24% w.b. with IR intensity of 2.39, 3.78 and 5.55 kW/m^2 required only 650 s, 455 s, and 395 s to dry corn down to a safe moisture content (MC) of 13% (w.b.); the corresponding mold load reduction ranged from 2.4 to 2.8 log CFU/g, 2.9 to 3.1 log CFU/g, and 2.8 to 2.9 log CFU/g as intensity increased ($p>0.05$). This work showed that IR drying of corn holds promise as a rapid drying method with potential benefits of microbial decontamination of corn; this may help producers combat mold related problems such as mycotoxin contamination.

Keywords. Corn, Drying and tempering, Infrared heating, Moisture removal, mold load reduction, color.

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Table of Contents

Chapter 1
Statement of Research

I. Problem Identification

Development of effective drying and decontamination strategies to maintain corn quality and prevent mycotoxin development has become a priority for the corn industry. In the United States (U.S.) corn is typically harvested at moisture contents (MCs) ranging from 18% to 24% wet basis (w.b.) and must be dried as soon as possible to about 12% to 14% moisture content. Otherwise, the corn is susceptible to mold contamination which may lead to production of mycotoxins. Some mycotoxins are known carcinogens and pose health hazards to humans and animals who consume contaminated products.

Unfortunately, the natural air, in-bin drying of corn is weather dependent, and under some drying scenarios, may be characterized with untimely corn drying which poses risks of grain molding and mycotoxin formation, especially in the bin upper layers. Although the convective heated air drying method may speed up corn drying, the conventional process is deficient of energy fluxes to inactivate heat tolerant mold spores and requires multiple drying passes to mitigate corn quality reduction. This increases the risk of mycotoxin production on the corn during storage.

Infrared (IR) heating, compared to conventional convective air heating has merits of high heat delivery and rapid product surface heating characteristics. The energy flux associated with IR heating may simultaneously dry corn and inactivate harmful mold spores while maintaining the corn quality. The advent of special catalytic type of infrared (CIR) emitters for producing IR energy at peak wavelength that maximizes heating of water in food materials offers new avenues for industrializing the IR heating technology for drying and decontamination of corns. Thus, successful development and implementation of the IR drying technology for corn may lead to very positive gains in maintaining the quality of corn while preventing formation of mycotoxin.

This research sought to develop effective strategies which utilize IR energy to achieve simultaneous drying and decontamination of corn while maintaining product quality and preventing mycotoxin development.

II. Objectives

The objectives for this research are as follows:

1. Determine the effectiveness of IR heating to dry freshly-harvested corn of different initial moisture contents and at various product-to-emitter gap sizes (IR intensity).
2. Determine effectiveness of combining IR heating and tempering to achieve simultaneous drying of corn and microbial decontamination.
3. Scale up IR drying of corn and investigate the performance of a newly-built continuous-flow, IR heating system for corn drying and microbial decontamination.
4. Evaluate the implications of the new IR drying process on dried product quality.

Chapter 2
Literature Review

Corn is normally harvested at a moisture content (MC) higher than the required level of 12% to 14% wet basis (w.b.) for safe storage. In order to reduce the MC to the safe storage level, corn needs to be dried. There are several methods of drying corn. Natural-air in-bin drying takes place in a one- to two-foot thick drying zone that moves slowly up through the bin. Under some natural- air drying scenarios, the duration required for complete drying of corn may cause mold growth in the grain mass leading to development of mycotoxins (D'Mello and Macdonald, 1997). To circumvent the limitations of slow, low-temperature air drying systems, some processors use high-temperature convective dryers. However, the energy flux associated with the high-temperature dryers require exposing corn kernel to high temperatures for prolonged duration before complete drying can be accomplished. Although, hot air can almost completely dry the corn to safe storage MC, the heat flux associated with the process is not sufficient to inactivate some harmful, heat tolerant mold spores such *aspergillus flavus* and *fusarium verticillioides* (Bittman and Kowalenko, 2004). Also the high temperature causes kernel pores to shrink and almost close, leading to crust formation or "case hardening", which is usually undesirable. In practice, several passes may be necessary to reduce the amount of heat damage. However, the more the drying passes needed, the larger the energy input is required (Hellevang, 2011).

IR heating has recently received considerable attention for different applications in food processing (Pan and Atungulu, 2010). IR heating has been associated with advantages of high energy transfer rate, short drying duration, and less environmental footprints. In some cases, compared with convective heated air treatments, IR treatments have been touted to produce products with better or comparable quality (Ratti and Mujumdar, 1995; Afzal et al., 1999; Pan et al., 2008). The IR electromagnetic spectrum can be classified into three regions, namely, near infrared (NIR), mid-infrared (MIR), and far-infrared (FIR), corresponding to spectral ranges of 0.75 to 1.4, 1.4 to 3, and 3 to 1000 μm, respectively (Sakai and Hanzawa, 1994). Most food components, especially water, absorb radiative energy in the FIR region (Ginzburg, 1969; Sandu, 1986; Pan et al., 2011). IR radiation is transmitted through water at short wavelengths, whereas at longer wavelengths it is absorbed at the surface (Sakai and Hanzawa, 1994). Hence, drying of thin layers seems to be more efficient at the FIR region, while drying of thicker bodies should give better results at the NIR region. (Hashimoto et al. 1990, 1994) studied the penetration of FIR energy into sweet potato and found that FIR radiation absorbed by a vegetable model was damped to 1% of the initial values at a depth of 0.26 to 0.36 mm below the surface, whereas NIR showed a similar reduction at a depth of 0.38 to 2.54 mm.

The IR emitters used in this study to treat corn emitted FIR radiation of 3 to 7 μm wavelength corresponding to the peak wavelength for maximum absorption of IR energy by water. Studies have shown that FIR energy penetrates very little with almost all the energy being converted to heat at the surface of the food (Hashimoto et al., 1994; Sakai and Hanzawa, 1994). IR does not heat up dry air, but may heat the water molecules in the air slightly raising the temperature. Compared to convective heated air, IR heating may not be limited by wet bulb temperature of air. This means that for corn drying, kernel surface could be quickly heated to high temperatures thereby shortening drying duration.

Combining the IR heating process with tempering stages may lead to removal of significant amounts of moisture from a product while maintaining quality (Nishiyama et al., 2006). During tempering stage, IR energy is not transferred to the grain, but the grain is held at a certain temperature to rest. The tempering stage allows the transfer of moisture from the center to the surface of the grain before another cycle of heating (Li et al., 1999); this eliminates the moisture gradient inside the grain imposed during the previous drying stage. Intermittent heating and tempering stages, as in the case of multiple drying passes have been reported to positively influence drying rates and the quality of final products (Franca et al., 1994; Kowalski and Pawlowski, 2010). Combining tempering stage with a drying process leads to reduction of energy consumption by reducing the duration required for drying. Continuous drying alone would increase the corn temperature while removing less moisture compared to sequential drying and tempering process (Thakur and Gupta, 2006). In addition, it is also possible to use sensible heat from the corn to remove more moisture in a natural cooling process after tempering.

The energy flux associated with IR heating has been reported to result in microbial decontamination as well (Wang et al., 2014). The authors (Wang et al., 2014) reported the potential of inactivating *Aspergillus flavus* molds on rice by using IR heating. *A. flavus* is a common and opportunistic pathogen that may grow on corn and produce aflatoxins (Sandeep, 2011). Compared to rice, corn is less susceptibility to stress-crack formation and may endure larger doses of IR energy before the quality is compromised. Therefore, it may be possible to achieve greater reductions of *A. flavus* mold in corn than rice by using greater IR treatment intensities, longer IR exposure durations, and incorporating tempering steps during the drying process.

Large amounts of aflatoxins produced by *A. flavus* have been reported to occur in cereals, peanuts, and oilseeds, especially with insufficient drying and inappropriate storage facilities (Arim, 1995; Lubulwa and Davis, 1994). Consumption of aflatoxin contaminated food cause several diseases in humans (Reddy and Raghavender, 2007). According to the U.S. Food and Drug Administration (FDA), grain with 20 parts per billion or more cannot be used for human consumption (CAST, 2003). Corn exceeding 20 ppb can be fed to animals of a specific weight, and production stage (CAST, 2003). Both acute and chronic toxicity on human could occur as a result of aflatoxin accumulation in body causing acute liver damage, liver cirrhosis, induction of tumors and teratogenic effects (Stoloff, 1977).

Poor drying practices may negatively affect U.S. grain export market (Dohlman, 2003). Corn above the FDA action level of 20 ppb cannot be exported (Dohlman, 2003). The current U.S. corn export markets are Japan, Mexico, and South Korea (Ye, 2015). According to Ye (2015), the revenue generated from corn export amount to approximately 50 billion dollars. Such revenue could be lost due to a negative image of U.S. corn quality. It is therefore vital that corn be managed appropriately to attract premium prices in a global market. In the past, it was possible to divert corn contaminated with aflatoxin to the ethanol production stream. However, the ethanol production industry now seeks to generate additional revenue from the by-products of the ethanol production processes and has therefore, placed a large demand on premium aflatoxin-free raw materials.

Despite the advantages of IR heating technology, the applications of IR heating of food and agricultural products are still very limited due to lack of knowledge about the technology (Sundu, 1986; Paakkonen, 1998; Hebbar and Rastogi, 2001; Seyed-Yaoobi and Wirtz, 2001; Mongpraneet et al., 2002; Pan et al., 2005). No previous reports were found on the feasibility of IR heating to achieve simultaneous drying and decontamination of corn. However, literature suggest that IR heating could save energy up to 38% for drying apples, significantly shorten the processing duration, and improve product quality (Ginzburg, 1969; Pan and McHugh, 2004). Therefore, this study sought to extend the benefits associated with IR heating to realize scaled up drying operation for high MC corn.

Chapter 3
Procedures

I. Corn Sampling

Freshly-harvested corn (Pioneer hybrid PI 1319 YHR/PI 2088) grown in a commercial producer's field in Northeastern Arkansas were procured for use in batch IR drying experiments. The samples were cleaned by sorting and removing any material other grain and immediately stored in a laboratory cold room set at 4°C. Before conducting any experiments, the samples were retrieved and allowed to equilibrate with ambient conditions. The initial moisture contents (IMCs) of the samples were determined by using an AM 5200 Grain Moisture Tester (PERTEN Instruments, Hägersten, Sweden). All reported IMCs are on wet basis. The IMCs of the samples used were 20.0 ± 0.1%, 24.0 ± 0.1%, and 28.0 ± 0.3%. Another set of corn samples were procured from Des Arc, Arkansas for continuous-flow non-batch IR drying experiments which used a pilot scale IR drying equipment. The non-batch, continuous-flow IR treatment used yellow dent corn with IMC of 24 ± 0.6%.

II. Infrared Heating Devices

Batch Infrared Drying

A catalytic IR dryer (Catalytic Drying Technologies LLC, Independence, KS) was used to dry corn (Figure 1a-c). The lab-assembled IR dryer was equipped with catalytic infrared (CIR) emitters which generated IR radiant energy through a catalytic reaction. In principle, air across a platinum sheet embedded in the emitter assembly combined with propane gas and reacted by oxidation reduction to yield IR energy, as well as small amounts of carbon dioxide and water vapor (Khir et al., 2011; Khir et al., 2012 ; Pan et al., 2011; Pan et al., 2008). The equipment had an effective heating area of 0.32 m^2 (two emitters enjoined with dimensions of 0.58 m length and 0.28 m width).

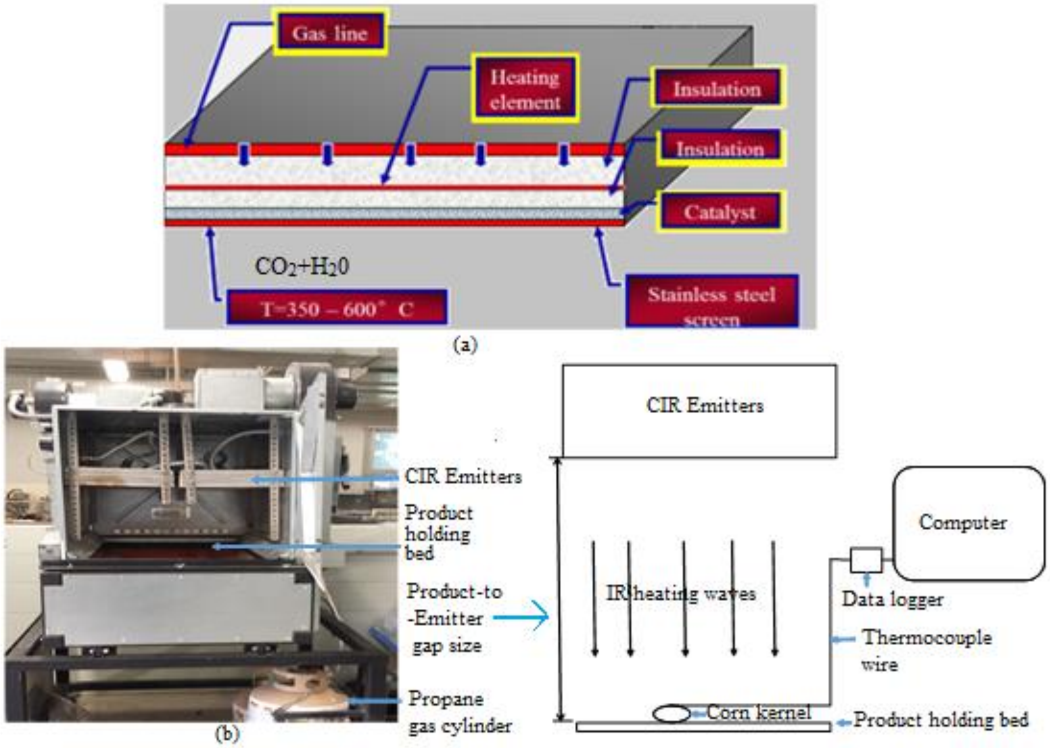

Figure 1. (a) Construction of catalytic infrared emitter showing the heating element, catalyst, insulation; (b) a laboratory assembled infrared dryer equipped with catalytic infrared emitters with effective heating area of 0.32 m^2; (c) schematic diagram of the infrared heating set-up for measurement of surface temperature profile of corn sample (loading rate of 3.77 kg m^{-2}).

Infrared Drying of Corn using a Continuous-flow Pilot Scale Equipment

Tests were conducted using a pilot scale IR heating system (Catalytic Drying Technologies LLC, Independence, KS) (Figure 2). The recently designed and built system was used to simulate continuous-flow IR treatments to dry corn from harvest moisture content (MC) to safe storage MC. The single zone system utilizes CIR emitters powered by either natural or propane gas and has a modular design to allow adjustment of process parameters such as belt speed, IR intensity, belt vibration intensity, air circulation level within the drying zone, and product-to-emitter-gap (PEG) size. Similar to the emitter construction used in the batch experiments, air across a platinum sheet embedded in the emitter assembly combined with the propane gas and reacted by oxidation reduction to yield IR energy, and small amounts of carbon dioxide and water vapor (Khir et al., 2011; Khir et al., 2012 ; Pan et al., 2011; Pan et al., 2008). In the continuous-flow process using a pilot scale IR equipment, corn samples were heated with IR then allowed to cool to reach room temperature (26°C) and then heated again. The process was repeated until the corn samples reached the safe storage MC of 13%. The intermittent IR treatment was used to avoid burning and discoloration of corn at elevated surface temperatures. Since IR heating is superficial, rapid cooling of corn to room temperature was achievable within 5 minutes. The different levels of process parameters used to perform the experiments are shown in Table 1.

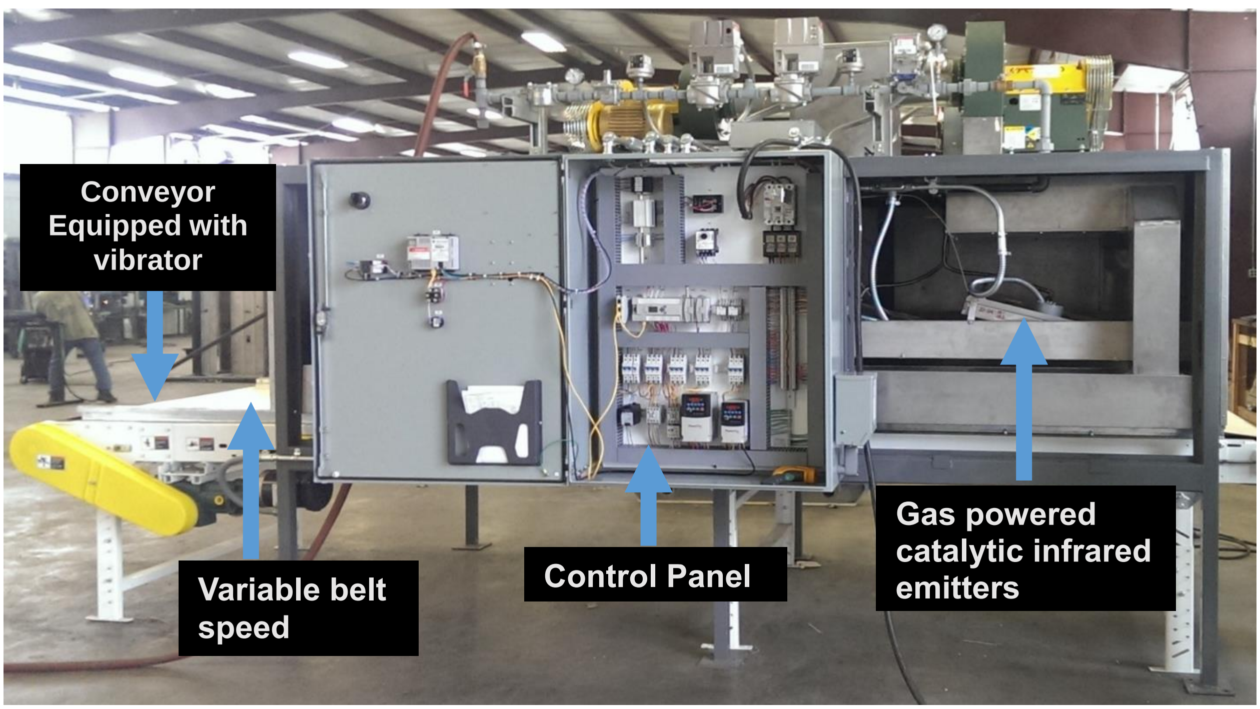

Figure 2. Pilot scale equipment for continuous-flow IR drying of corn and mold inactivation.

Table 1. Experimental design for testing pilot-scale infrared (IR) heating equipment for drying and decontamination of corn at product-to-emitter gap size of 450 mm.

Intermittent IR Drying Duration (s)	Conveyor Belt Speed (m/s)	IR Intensity (setting) (kW/m^2)
30	0.115	2.39 (Low)
50	0.069	3.78 (Medium)
180	0.019	5.55 (High)

III. Measurement of Radiant Energy Transfer

A radiometer (Ophir-Spiricon, LLC, North Logan, UT) was used to determine energy transfer (IR intensity) from IR energy source to the product. The radiometer measured power emitted in kW; the IR intensity was then calculated by dividing the supplied power by area of heated black body (equation 1).

$$\text{Energy transfer (IR heating intensity)} = \frac{Measured\ power\ (kW)}{Heated\ black\ body\ area\ (m^2)} \qquad (1)$$

IV. Determination of Corn Kernel Temperature Profile

A single layer of corn kernels at a loading rate of 3.77 kg m^{-2} and IMCs of 20%, 24% or 28% was placed on an aluminum tray and set at PEG sizes of 110, 240, or 430 mm. The corn kernels were allowed to have contact with one another to simulate what would be realistic in a typical processing line. A type K, insulated beaded wire thermocouple (Omega, Engineering Inc., Stamford, CO) was inserted in individual corn kernels to allow surface temperature profile measurement during IR heat treatment. Data representing corn kernel temperature rise during IR heating was recorded on a data logger (HH147, Omega, Engineering Inc., Stamford, CO). The results were compared with the profiles of corn kernels during convective heating with hot air at temperature of 110°C and relative humidity of 10%. The hot air temperature of 110°C and relative humidity of 10% was chosen to simulate the current industrial drying conditions.

V. Infrared Drying and Tempering

A single layer of corn samples at a loading rate of 3.77 kg m^{-2} was placed under the IR emitters with an effective heating area of 0.32 m^2. The samples were heated using IR at three PEG sizes of 110, 240, and 430 mm until corn surface temperatures of 50°C, 70°C, and 90°C were achieved. The weight loss during IR heating was determined; the corn MC after heating and percentage points of moisture removed were calculated. In order to determine the effect of combining IR heating with tempering, samples of corn at IMC of 20%, 24%, and 28% were heated by IR to surface temperatures of 50°C, 70°C, and 90°C, tempered at 50°C, 70°C, and 90°C for 0, 2, 4 and 6 h, and then allowed to cool to room temperature. The percentage points of moisture removed after IR heating and tempering of the corn were determined.

In case of tempering treatments, samples were transferred into glass jars immediately after IR heating, and the jars were sealed air-tight and incubated at the desired tempering temperature of 50°C, 70°C, or 90°C. The jars were allowed to stay in the tempering environment for the entire tempering duration. After tempering, the samples were removed from the jars and spread on a flat wire mesh, and allowed to cool naturally until surface temperatures dropped to ambient condition (26°C). The weight of the cooled sample was determined. The percentage points of moisture removed after IR heating, tempering and natural cooling was calculated as the difference between the original and final MCs after natural cooling. The effect of one-pass and two-pass IR heating and tempering on moisture removal were determined. One-pass treatment constituted IR heating followed by tempering and natural cooling, sequentially. Two-pass treatment constituted IR heating followed by tempering, natural cooling, another IR heating, tempering and then natural cooling. Test for one-pass and two-pass treatments were performed using a select PEG size that gave the greatest moisture removal by comparing all the IR treatments.

In the experiments, the total moisture removal was comprised of water removed during IR heating and tempering steps. Calculations were performed to evaluate energy supplied by the IR emitter versus the total water removal during combined IR heating and tempering process, in one- and two-pass processes. Total energy supplied by the emitter to remove moisture from corn at various IMCs, when heated with IR to surface temperatures of 50°C, 70°C, and 90°C, followed by tempering at 2, 4 and 6 h, for one- and two-pass processes, was evaluated as indicated in the following example:

- The loading rate of corn and supplied IR intensity are considered to be *L* kg m^{-2} and *I* kW m^{-2}, respectively.
- A unit mass of corn receives $I/L = E$ (2)

  where

  I is the supplied IR intensity (kW m^{-2})

  L is the loading rate of corn (kg m^{-2})

  E is the energy per unit mass of corn (kW kg^{-1})
- The supplied energy is considered to contribute to moisture removal for a one-pass process of IR heating and tempering that liberates *R* and *T* kg of moisture per kg of corn, respectively.
- The effectiveness of the process to remove a unit mass of water was calculated as $E/(R+T)$ kW kg^{-1} water removed.

VI. Analysis of Mold Load Reduction

Standard procedures for microbial isolation, plating and counting were used (AOAC method 997.02) to determine the corn total mold counts. Phosphate-buffered dilution water (0.5 M, pH = 7.2) was used and sterilized by autoclaving at 121°C (AOAC method 997.02).

To determine total mold counts on corn, the samples were masticated using a lab masticator (Silver Panoramic, iUL, S.A., Barcelona, Spain) to dislodge the microorganisms. A 10 g sample of corn was mixed with 90 mL phosphate-buffered dilution water in a sterile stomacher bag and masticated. The masticator was set at 240 s and 0.7 stroke/s. This process resulted in corn samples that were pulverized into powder for total microbial load analysis. Preliminary tests indicated that the masticating method produced comparable results as blending method with the merit of keeping the sample temperature low so that the microbes are not affected, and also avoided potential cross contamination resulting from the typical grinding process. Serial ten-fold dilutions of the samples were prepared in phosphate-buffered. Preliminary tests were used to determine the total number of dilutions used. The 3M Petrifilm Mold Count Plates (3M Microbiology Product, Minneapolis, MN) were used to enumerate mold counts per manufacturer recommendations. The inoculated plates were stacked to a maximum of 20 units and incubated.

Mold Count Plates were incubated at 25°C for 120 h before counting. After incubation, the colony forming units (CFU) on each plate were counted. Mold colony colors were blue, black, yellow, or green. The appropriate dilution factor, volume, and sample weight were taken into account to obtain the total CFU/g of each sample:

$$T_{cfu} = \frac{P_{cfu}}{D_r} \tag{3}$$

where, T_{cfu} is total colony forming units per gram of corn (cfu/g), P_{cfu} is colony forming units counted on plate per gram of corn (cfu/g) and D_r is dilution rate (10^{-1} to 10^{-5} times).

VII. Determination of Corn Color

The International Commission on Illumination (CIE) color parameters (L*/a*/b*) were measured using a colorimeter (Hunter Associates Laboratory, Reston, VA). The parameters L* measures the brightness from 100 (lightness) to 0 (darkness), a* describes red-green color with positive a* values indicating redness and negative a* values indicating greenness, and b* describes yellow-blue color with positive b* values indicating yellowness and negative b* values indicating blueness (Good 2002; Lamberts et al. 2007). Delta E (ΔE) indicates the overall change in color. The ΔE is a combination of all the CIE parameters and was calculated using equation 4.

$$\Delta E = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \qquad (4)$$

where the subscripts 1 and 2 on the variables L*, a*, and b* represents freshly harvested corn (control) and infrared dried corn, respectively.

VIII. Statistical Analyses

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

Chapter 4
Results and Discussion

I. Batch Drying of Freshly-Harvested Corn using Infrared Heating

Infrared Intensity and Surface Temperature Profile

The measured intensity of IR energy reaching the corn surface at product-to-emitter-gap (PEG) sizes of 110, 240, and 430 mm was 10.84, 2.83 and 2.15 kWm^{-2}, respectively. The temperature profiles of shelled corn kernels at initial moisture contents (IMCs) of 20%, 24%, and 28% during heating with IR are shown in Figure 3a-c. The rate of surface temperature rise of the shelled corn kernels depended on the IMC and was greatest for kernels at the lowest IMC of 20%. Generally, shelled corn with high moisture content (MC) are expected to have higher specific heat capacity than low MC corn. Hence, relatively longer duration was required for the surface temperature of corn kernels at IMC of 28% to reach 50°C, 70°C, and 90°C compared to corn at IMC of 20%. Durations of up to 110, 120, and 140 s were required to achieve kernel surface temperature of 90°C at the largest PEG size of 430 mm and IMC of 20%, 24%, and 28%, respectively. Durations of up to 35, 44, and 45 s were required to achieve kernel surface temperature of 90°C at the smallest PEG size of 110 mm and IMC of 20%, 24%, and 28%, respectively.

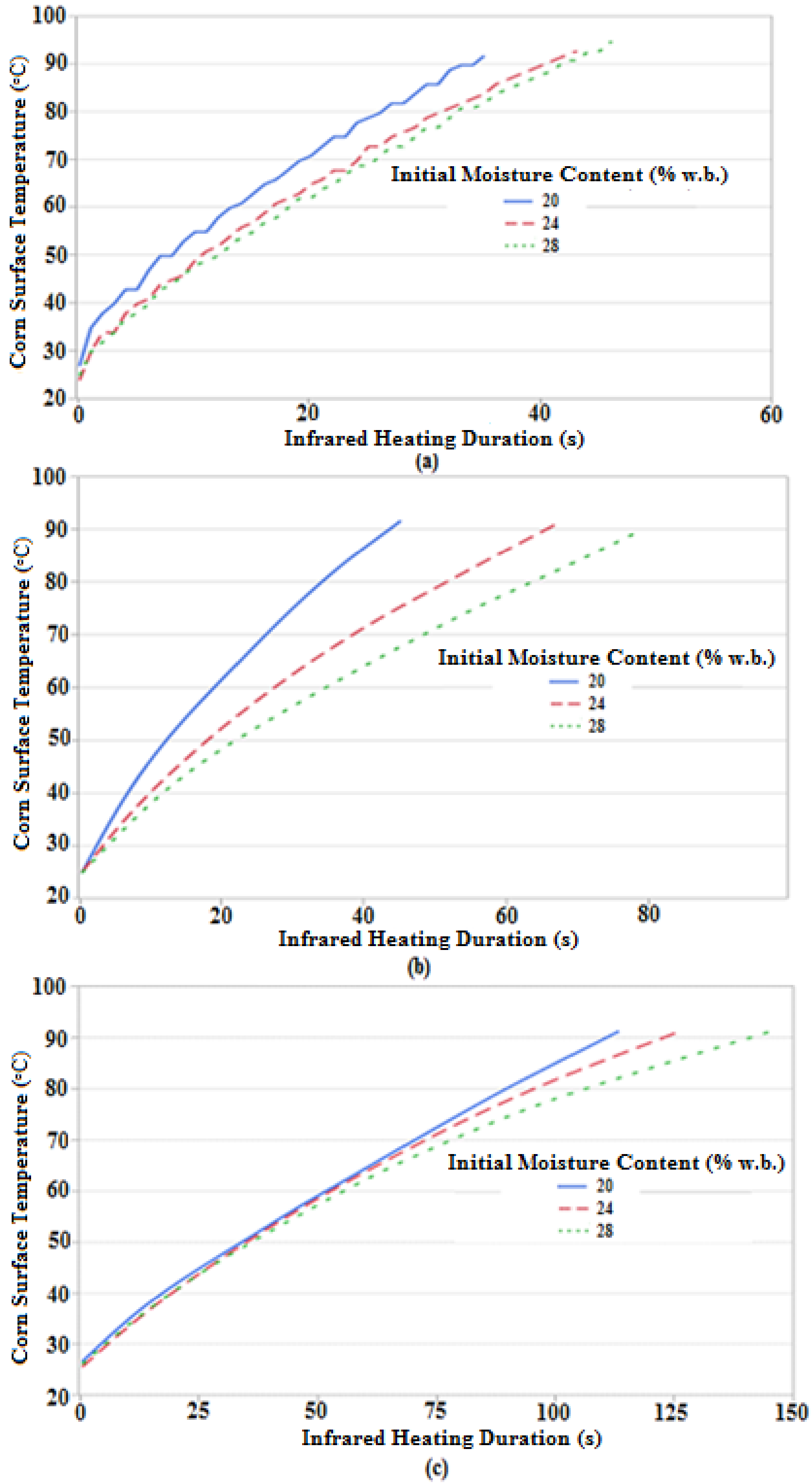

Figure 3. Surface temperature profiles of corn kernels during infrared heating to temperature of 90°C and at product-to-emitter-gap sizes of (a) 110 mm, (b) 240 mm, and (c) 430 mm corresponding to infrared intensities of 10.84, 2.83, and 2.15 kW m^{-2}, respectively.

The temperature profiles resulting from IR heating were compared with those of convective heated air. For corn drying, the typically recommended air temperatures range from 98°C to 110°C. Compared to IR heating, the convective heated air requires longer durations to raise the corn kernel surface temperature to 90°C (Figure 4). The rate of surface temperature rise of the shelled corn kernels depended on the IMC and was greatest for kernels at the lowest IMC of 20%. By convective heated air at 110°C and relative humidity of 10%, heating durations of 420, 480, and 550 s were required to raise the surface temperature of corn kernels at IMC of 20%, 24% and 28%, respectively, to 90°C. The corresponding durations with IR heating at PEG size of 430 mm were 110, 120, and 140 s, respectively.

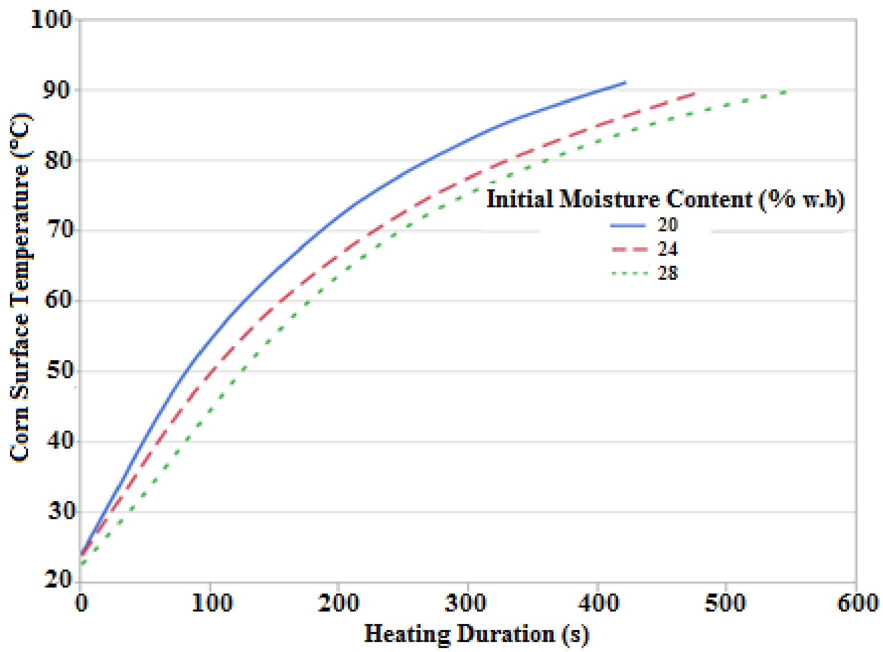

Figure 4. Surface temperature profiles of corn kernels during convective heating with an air temperature of 110°C.

The temperature profiles indicated (Figures 3 & 4) do not take into account the typical airflow rates encountered in industrial corn drying scenarios. In practice, increasing airflow rate would result in increased mass transfer at the surface of the corn kernel. The evaporative cooling that occurs at the kernel surface may affect the rate of change in the temperature profiles. The reported surface temperatures of corn kernels may be higher than what might be observed in practice since this study only accounted for natural convection and not forced-air convection. Comparing results of the Figures 3 and 4 revealed that IR heating accorded more rapid heating of the corn kernel surface compared to convective heating. Afzal and Abe (1997) reported that when drying rice using IR heating there was higher moisture reduction and shorter drying duration than when using convective heating. My results for the application of IR for drying corn are in agreement with the results of Afzal and Abe (1997).

Effect of Product-To -Emitter Gap Size on Moisture Removal

From IR drying stand-point, it is important to select the PEG size such that a significant amount of moisture is removed within a short duration while not burning the corn. From preliminary experiments the surface color characteristics of the kernels were not compromised when the surface temperatures reached 90°C. However, kernel surface burning was observed when surface temperature of 110°C was attained. Therefore, to ensure good quality of processed corn, the study limited corn surface temperature to 90°C. The percentage point of moisture removed from IR dried corn depended on the PEG size, IMC of the corn, and the final surface temperature of the kernels after IR heating (Figure 5). The product heated with IR while at the larger PEG size of 430 mm resulted in the greatest moisture removal. In general, at a PEG size of 430 mm, durations required for the corn surface temperatures to reach 50°C, 70°C, and 90°C were longer than at 110 mm. Longer IR heating durations resulted in larger amounts of moisture evaporated from the corn.

When shelled corn kernels at IMC of 20%, 24% and 28% were heated by IR to the greatest surface temperature of 90°C, the disparity of percentage points of moisture removed for the lowest PEG size of 110 mm and largest PEG size of 430 mm were 0.9, 1.2, and 1.4 percentage points, respectively (Figure 5). When corn kernels at IMC of 20%, 24% and 28% were heated by IR to surface temperature of 70°C, the disparity of percentage points of moisture removed for the lowest PEG size of 110 mm and largest PEG size of 430 mm were 0.3, 0.6, and 0.8 percentage points, respectively. When corn at IMC of 20%, 24% and 28% were heated by IR to corn surface temperature of 50°C, the disparity of percentage points of moisture removed for the lowest PEG size of 110 mm and largest PEG size of 430 mm were 0.1, 0.3, and 0.3 percentage points, respectively.

A one-way fixed effects ANOVA was conducted to determine if there was any difference in percentage point moisture removed based on the PEG, corn surface temperatures, and IMCs. There was a statistically significant interaction between the IMCs and surface temperatures ($p < .0001$). Tukey's HSD analysis was then conducted to determine where the differences occurred and the results are presented in Table 2. There was a significant difference between the PEG and corn surface temperatures ($p = 0.0013$). It was apparent that the corn moisture removal increased with the increased corn surface temperature under specific IR intensity levels and IMCs. The forgoing phenomenon was expected due to additional energy absorption leading to increased evaporation. The results also clearly showed that more moisture was removed from corn with high IMCs. From a practical standpoint, it might be justifiable to use the largest PEG of 430 mm instead of 110 mm to achieve large moisture removal without impacting the product quality. At the lowest PEG size of 110 mm, corn kernels surface discolored within a shorter heating duration than at 430 mm, which also restricted how much moisture could be removed before the surface quality of corn deteriorated. Similar results were reported for rice (Khir et. al. 2012). The rice moisture removal increased with increased IMC and was attributed to energy absorption and therefore greater evaporation (Khir et. al. 2012).

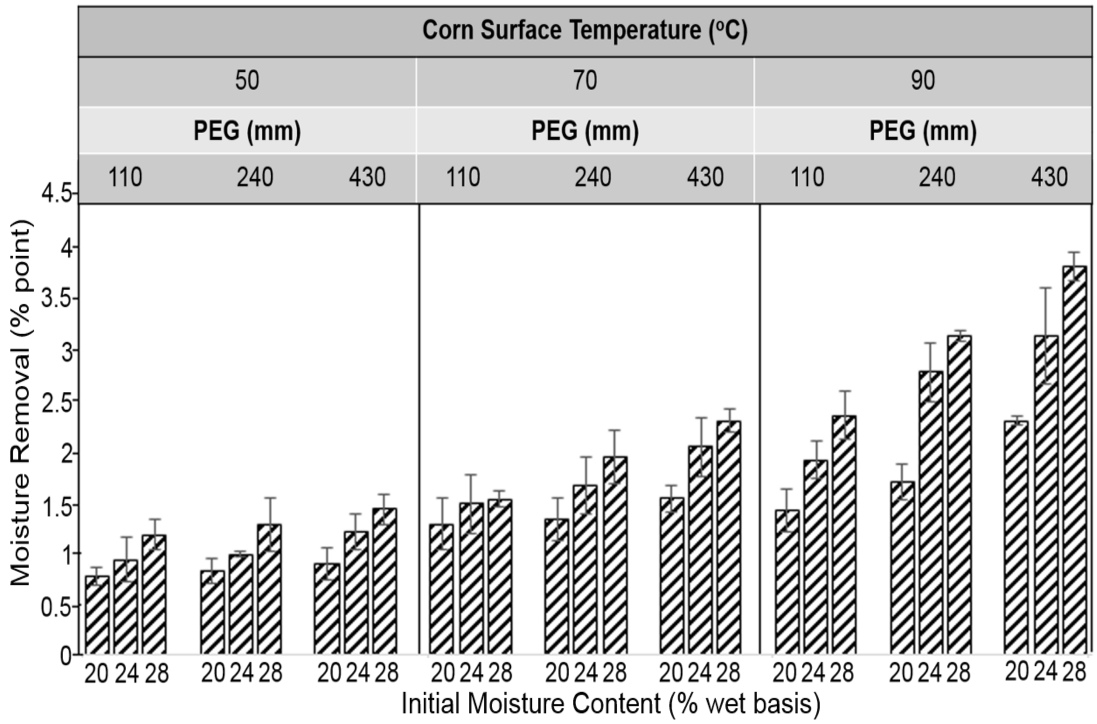

Figure 5. The effect of initial moisture content and product-to-emitter-gap size on percentage points of moisture removal when corn kernels were heated to surface temperatures of 50°C, 70°C and 90°C.

Table 2. Tukey's HSD test for interaction between corn initial moisture content and final surface temperatures after infrared (IR) heating, and product-to-emitter-gap size and corn final surface temperatures after IR heating on the least square means of percentage point moisture removed.

Initial moisture content (% w.b.)	Corn surface temperatures (°C)	LS Mean	SD	Product-to-emitter-gap size (mm)	Corn surface temperatures (°C)	LS Mean	SD
20	50	0.95^{F}	0.15	110	50	1.07^{F}	0.23
	70	1.84^{D}	0.41		70	1.99^{E}	0.50
	90	2.37^{C}	0.46		90	2.76^{C}	0.79
24	50	1.19^{EF}	0.19	240	50	1.18^{F}	0.22
	70	2.42^{C}	0.53		70	2.35^{D}	0.62
	90	3.30^{B}	0.58		90	3.19^{B}	0.74
28	50	1.42^{E}	0.24	430	50	1.33^{F}	0.31
	70	2.62^{C}	0.55		70	2.55^{CD}	0.53
	90	3.84^{A}	0.70		90	3.57^{A}	0.82

A - F data set lacking a common letter differs ($p < 0.05$); LS and SD symbolize least square and standard deviation respectively.

Effect of Infrared Heating and Tempering on Moisture Removal

The PEG size of 430 mm was used in the treatments to study the effect of IR heating followed by tempering. Tempering resulted in further moisture removal from IR heated corn kernels. Figure 6 shows the effect of one-pass IR heating to kernel surface temperature of 90°C, followed by tempering treatments at 50°C, 70°C, and 90°C for 0, 2, 4 and 6 h on moisture removal. The longer the tempering duration, the more the moisture was removed for all the treatments. When corn at IMC of 28% was heated by IR to surface temperature of 90°C and tempered at 50°C, 70°C, and 90°C for 6 h, a total of 4.0, 4.5, and 5 percentage point of moisture removal were achieved, respectively. Statistical analyses were performed to determine if there were significant differences in percent point moisture removed based on the tempering temperature, tempering duration, and IMCs. In general, the tempering duration at various tempering temperature had a significant impact percentage point moisture removal for one-pass IR treatment ($p < 0.05$) as shown in table 3.

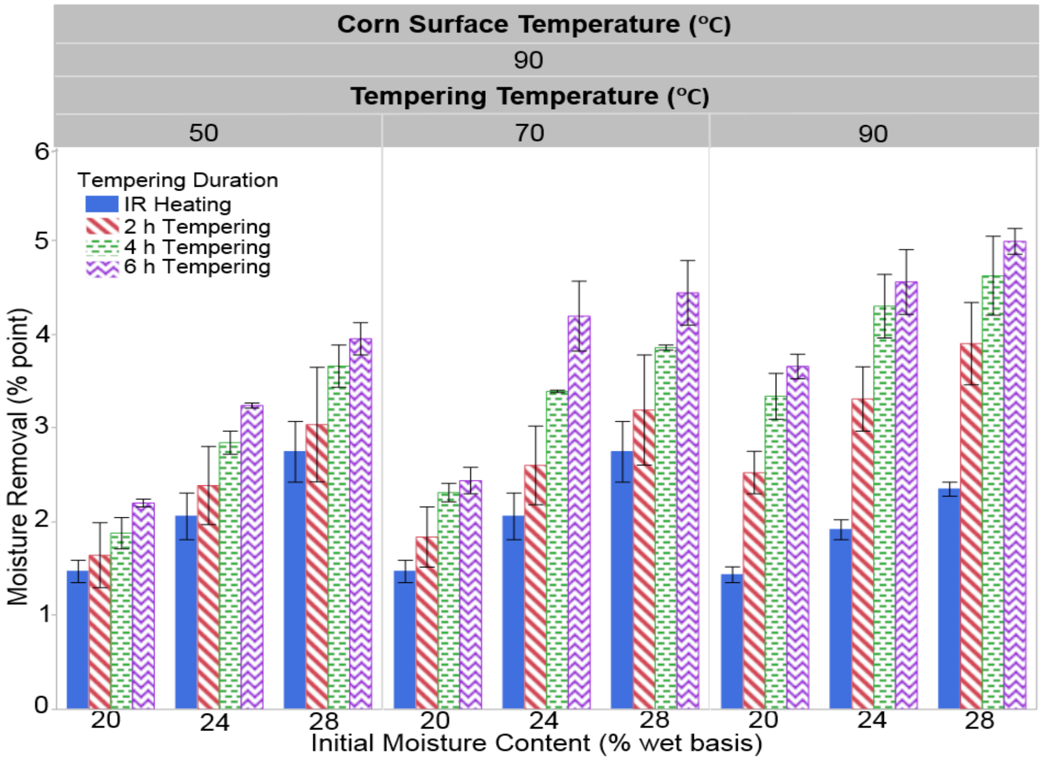

Figure 6. The effect of one-pass infrared heating of corn kernels to surface temperatures of 90°C followed by tempering treatments at 50°C, 70°C, and 90°C, for 0 to 6 h on moisture removal.

Table 3. Statistical analysis showing the effect of parameters on percentage point moisture removed of corn dried using IR heating at different tempering temperature and tempering duration for one-pass.

		Moisture Removal (% point)
Parameters	DF	Pr. > F
Tempering Temperature (°C)	2	<.0001
Tempering Duration	3	<.0001
Initial Moisture Content (% wet basis)	2	0.0002
Tempering temperature (°C)*Tempering Duration	6	0.0011
Tempering temperature (°C)*Initial Moisture content (% wet basis)	4	0.6616
Tempering Duration*Initial Moisture content (% wet basis)	6	0.5189
Tempering temperature (°C)*Tempering Duration*Initial Moisture content (% wet basis)	12	0.9981

Figure 7 shows the effect of two-pass IR heating of corn kernels to surface temperatures of 50°C, 70°C, and 90°C, followed by tempering treatments at 50°C, 70°C, and 90°C for 0, 2, 4 and 6 h. Compared to one-pass treatment (Figure 6), more moisture was removed for two-pass (Figure 7) IR heating and tempering treatments. Two-pass IR heating and tempering treatments nearly doubled the percentage point of moisture removed compared to one-pass. Two-pass IR heating and tempering was most effective for drying corn kernels at the greatest IMC of 28% than at 20%. Although it may be more effective to reduce the tempering temperature to avoid cake formation.

Statistical analyses were performed to determine if there were significant differences for a two-pass treatment on percent point moisture removed due to the tempering temperature, tempering duration and IMCs. The effects of IMC (p <0.0001), tempering temperature (p = 0.005) and tempering duration (p <0.0001) were significant (Table 4).

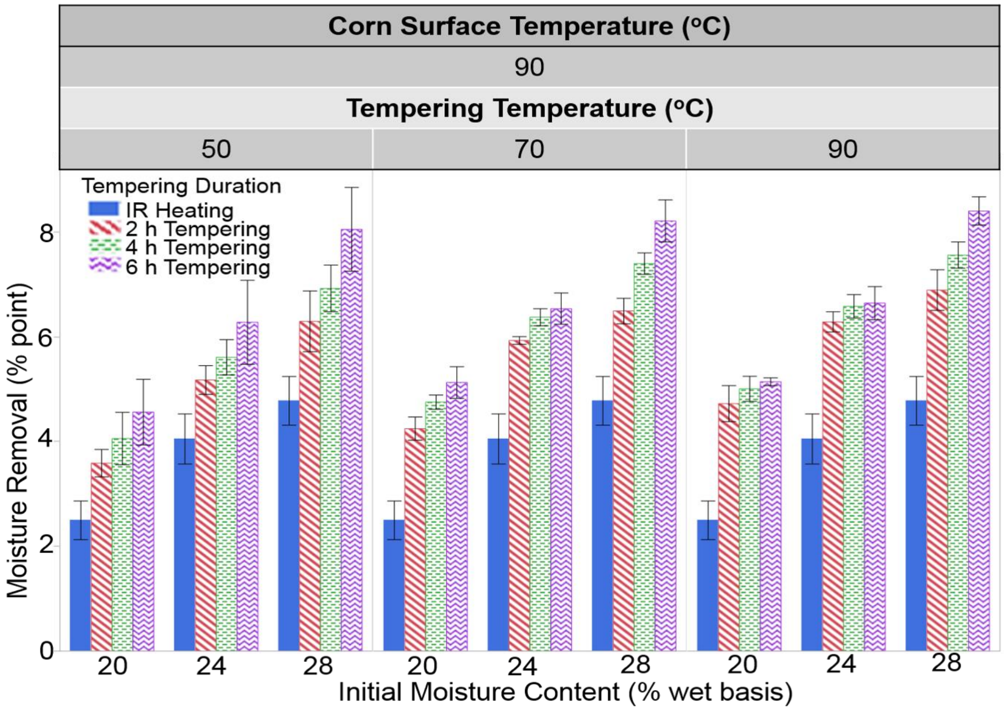

Figure 7. The effect of two-pass IR heating of corn kernels to surface temperatures of 90°C followed by tempering treatments at 50°C , 70°C , and 90°C , for 0 to 6 h.

Table 4. Statistical analysis showing the effect of parameters on percentage point moisture removed of corn dried using IR heating at different tempering temperature and tempering duration for two-pass.

		Moisture Removal (% point)
Parameters	DF	Pr. > F
Tempering Temperature (°C)	2	0.005
Tempering Duration	3	<.0001
Initial Moisture Content (% wet basis)	2	<.0001
Tempering temperature (°C)*Tempering Duration	6	0.469
Tempering temperature (°C)*Initial Moisture content (% wet basis)	4	0.947
Tempering Duration*Initial Moisture content (% wet basis)	6	0.264
Tempering temperature (°C)*Tempering Duration*Initial Moisture content (% wet basis)	12	1.000

The IR energy supplied to facilitate removal of a unit mass of water from corn in a combined IR heating and tempering process, for one-pass and two-pass treatments is shown in Figures 8 and 9. Statistical analyses were performed to determine if there were significant differences in IR energy supplied to facilitate removal of a unit mass of water from corn in a combined IR heating and tempering process, for one-pass and two-pass treatments based on the tempering temperature and tempering duration. There was a statistically significant interaction between IMC and tempering duration ($p = 0.0057$) for one-pass treatment (Figure 8). Tukey's HSD test was done to explain the differences in more details (Figure 8). There was also a significant interaction between IMC and tempering duration ($p < 0.0001$) for two-pass treatments (Figures 9). Tukey's HSD test was done to explain the differences in more details (Figures 9).

The IMC, tempering duration, tempering temperature, and number of passes dictated the overall energy utilized. Better energy utilization was noted when corn was treated with two-passes compared to one-pass. It should be noted that the energy values in Figures 8 and 9 are lower than those reported for convective heated air drying (Strumillo and Lopez-Cacicedo, 1987). The reason for the difference is because the values reported for this research include moisture liberated during tempering stage as well. Therefore, the energy values are expected to reduce as tempering duration increased because moisture continued to be liberated in the tempering stages without energy addition from IR heating. The processing conditions that corresponded to the lowest amount of energy to remove a unit mass of moisture in corn at IMC range of 20% to 28% MC is heating the corn kernels to surface temperature of 90°C followed by tempering in a one-pass IR and tempering treatment.

Overall, effective moisture removal was noted when corn was at high IMC. Therefore, IR heating could be appropriate for initial drying of high MC corn. In case of corn destined for high value products such as the protein zein (Shukla and Cheryan, 2001), IR pre-drying combined with convective heated air drying could be ideal to avoid product shrinkage due to steep moisture content gradients as well as other physicochemical changes in quality. Convective heated air drying in the falling-rate drying period, when the rate of removal of moisture from the interior of the product is a mass-transfer limiting process, could be used to improve dried product quality rather using IR drying throughout.

Industrial implementation of IR heating for drying shelled corn could be used to divert the wetter, high MC lot of corn at harvest to a high temperature continuous-flow IR dryer to be used for initial drying. Under these conditions, the corn would finish drying in an existing bin dryer at conventional drying air temperature. Another option would be to direct the wetter corn to separate bins in the dryer. The bins with the high MC corn kernels would be fitted with auxiliary IR emitters to heat the corn prior to entry into the bins. The IR emitter intensities could be ramped down based on the average corn MC determined by the rate of moisture removal versus residence duration under a given IR heating intensity. A third implementation would be to dry the high MC corn to safe storage MC by exclusively using optimized IR heating, tempering and natural cooling protocols.

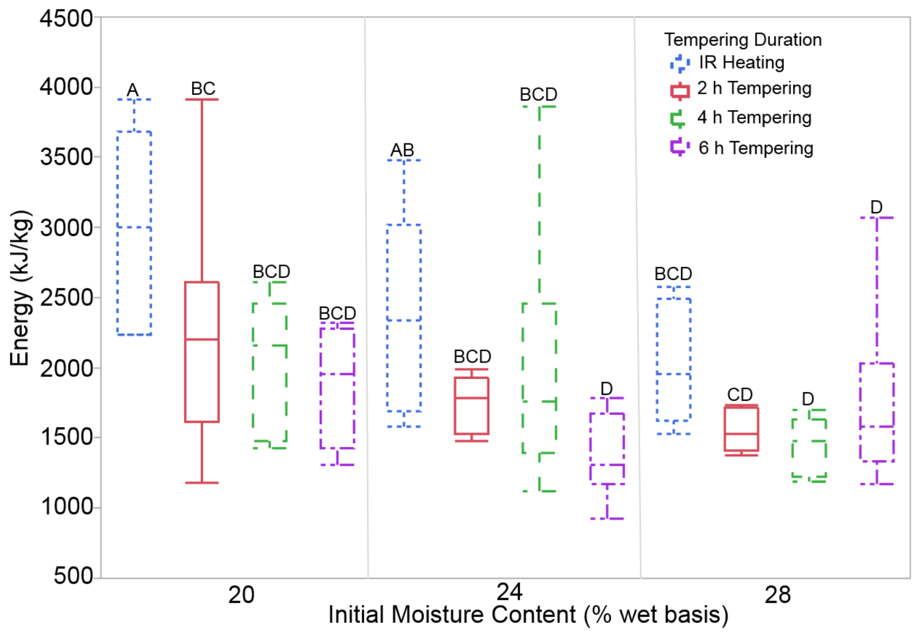

Figure 8. Infrared energy supplied to facilitate a unit mass of water removal from a combined infrared heating and tempering process, in a one-pass treatment. Means with the same type of letters are not significantly different at α = 0.05.

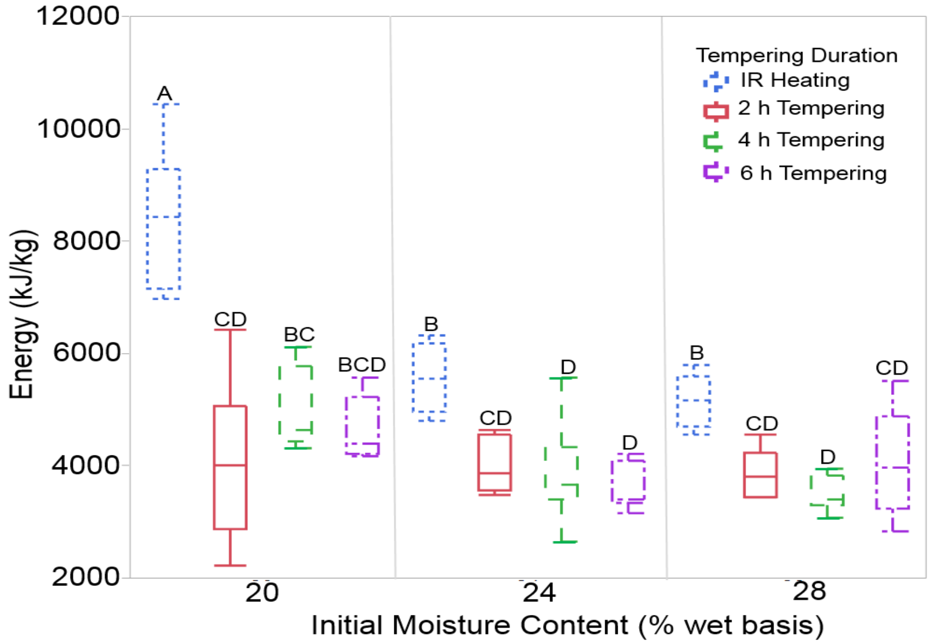

Figure 9. Infrared energy supplied to facilitate a unit mass of water removal from a combined infrared heating and tempering (effect of tempering duration) in a two-pass treatment. Means with the same type of letters are not significantly different at α = 0.05.

II. Effectiveness of Combining IR Heating and Tempering to Achieve Microbial Decontamination for Corn

Effectiveness of Combining IR Heating and tempering on Mold Load Reduction

Figure 10 shows that the mold count decreased significantly with tempering for one-pass treatments. The maximum mold load reduction was observed after IR heating corn of IMC 20%, 24% and 28% followed by tempering at 50°C for 4 h. The corresponding mold load reductions were 3.8, 3.8 and 4.5 log CFU/g for one-pass, respectively. A one-way fixed effects analysis of variance was conducted to determine if there were statistically significant differences in mold counts based on the effects of tempering temperature, tempering duration, and IMCs for one-pass. The effect of tempering duration was statistically significant ($p < 0.0001$). Tukey's HSD test was then conducted to determine where the differences occurred and the results are presented in Table 5.

Figure 11 shows that the mold count decreased significantly with tempering for two-pass treatments. The maximum mold load reduction was observed after IR heating corn of IMC 20%, 24% and 28% followed by tempering at 70°C for 2 h. The corresponding mold load reductions were 3.9, 4.2 and 4.7 log CFU/g, respectively for two-pass. The tempering duration (p <0.0001) and tempering temperature (p = 0.0016) were statistically significant. Tukey's HSD test was conducted to determine where the differences occurred and the results are presented in table 6. Based on the results, a 2 h tempering duration might be recommended when two-pass treatments are used. The 2 h tempering duration came close to achieving approximately 5 log reductions which is recommended by the National Advisory Committee on Microbiological Criteria for Foods (NACMCF, 1999) and for food in general.

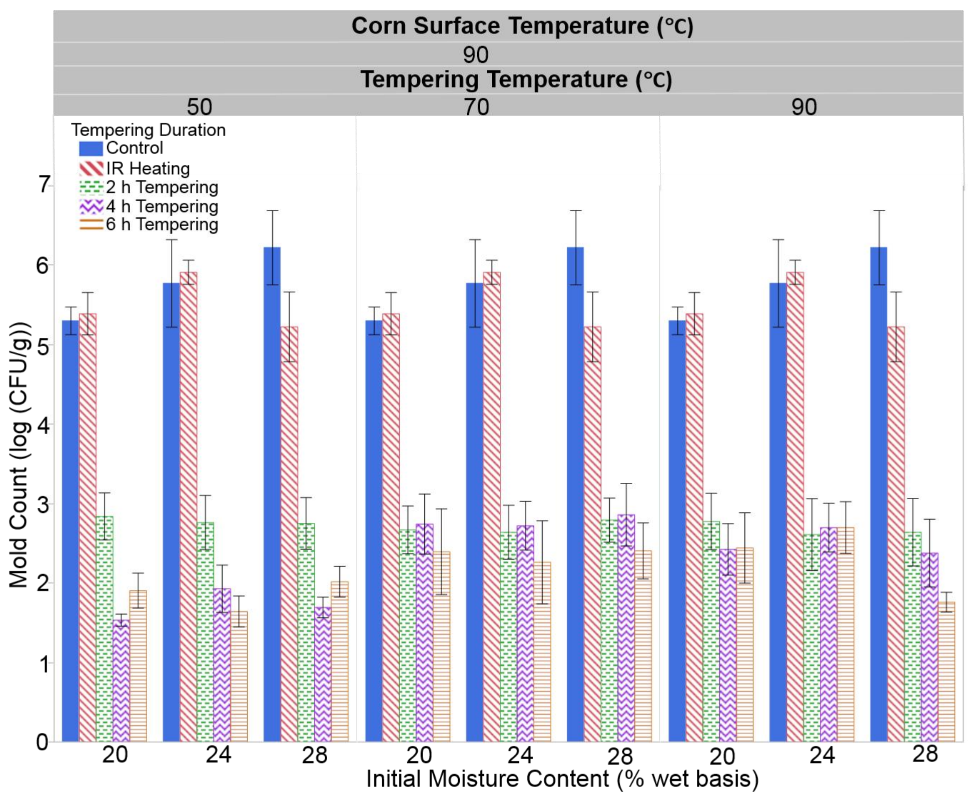

Figure 10. The effect of one-pass infrared heating of corn kernels to surface temperatures of 90°C followed by tempering treatments at 50°C, 70°C, and 90°C, for 0 to 6 h on the mold count (in terms of log colony forming units (CFU) per gram of corn sample).

Table 5. Tukey's HSD test for the effect of tempering duration after one-pass infrared (IR) heating on the least square means of mold count expressed in log colony forming (CFU) per gram of corn sample.

Tempering Duration	LS Mean Mold Count (log(CFU/g))	SD
Control	5.76^{A}	0.73
IR Heating	5.51^{A}	0.76
2 h	2.72^{B}	0.79
4 h	2.33^{BC}	0.84
6 h	2.17^{C}	0.88

A - C data set lacking a common letter differs ($p < 0.05$); LS and SD symbolize least square and standard deviation respectively.

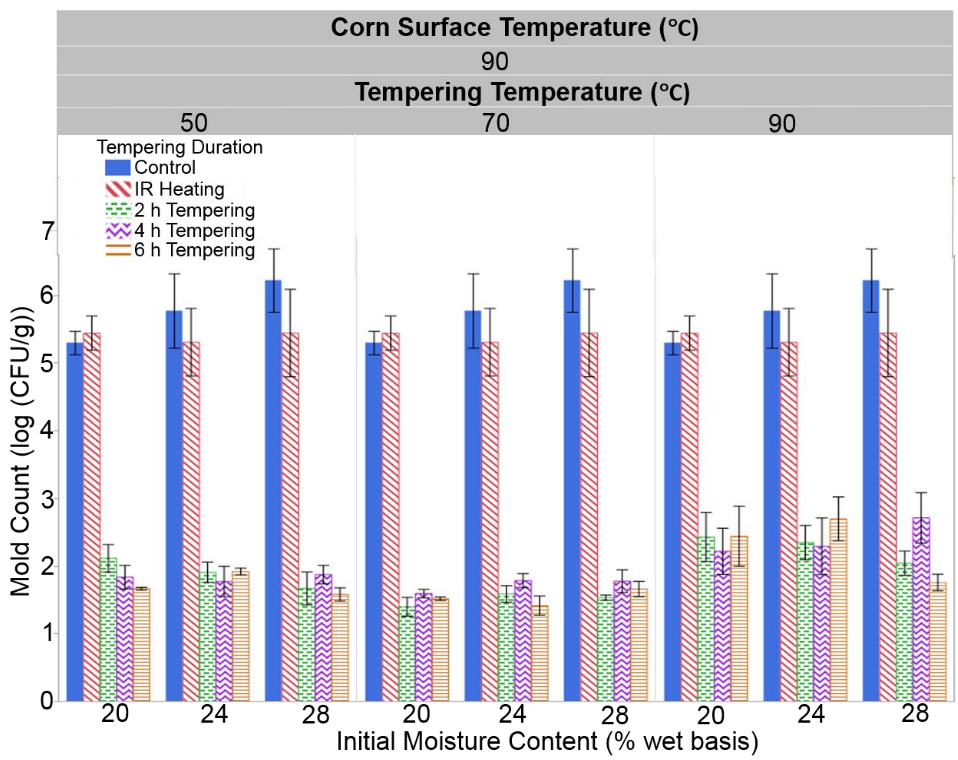

Figure 11. The effect of two-pass infrared heating of corn kernels to surface temperatures of 90°C followed by tempering treatments at 50°C, 70°C, and 90°C, for 0 to 6 h on the mold count (in terms of log colony forming units (CFU) per gram of corn sample.

Table 6. Tukey's HSD test for the effect of tempering temperature and tempering duration after two-pass infrared (IR) heating on the least square means of mold count expressed in log colony forming (CFU) per gram of corn sample).

Tempering Duration	LS Mean Mold Count (log(CFU/g))	SD	Tempering Temperature (°C)	LS Mean Mold Count (log(CFU/g))	SD
Control	5.76^{A}	0.73	90	3.63^{A}	1.80
IR Heating	5.40^{A}	0.76	50	3.32^{B}	1.90
2	2.00^{B}	0.79	70	3.18^{B}	1.70
4	1.90^{B}	0.84			
6	1.90^{B}	0.88			

A - B data set lacking a common letter differs ($p < 0.05$); LS and SD symbolize least square and standard deviation respectively.

Effect of Infrared Heating and Tempering on Color

The deviation of color (ΔE) of the IR dried corn samples from the color of non-treated freshly-harvested corn, control sample was determined. There were statistically significant interactions between IMC and tempering duration (p= 0.0058) and tempering duration and tempering temperature (p = 0.0007) for one-pass treatments. Tukey's HSD analyses were conducted to determine where the differences occurred and the results are presented in Figures 12 and 13, respectively. There were statistically significant interactions between IMC and tempering duration (p = 0.004) and tempering duration and tempering temperature (p = 0.0007), for two-pass treatments. Tukey's HSD analyses were then conducted to determine where the differences occurred and the results are presented in Figures 14 and 15. Although color change was seen in comparison to the control samples, for ΔE below 13 the visual response with reference to color change is expected to be negligible (Lite et al. 2001; Atungulu et al. 2004).

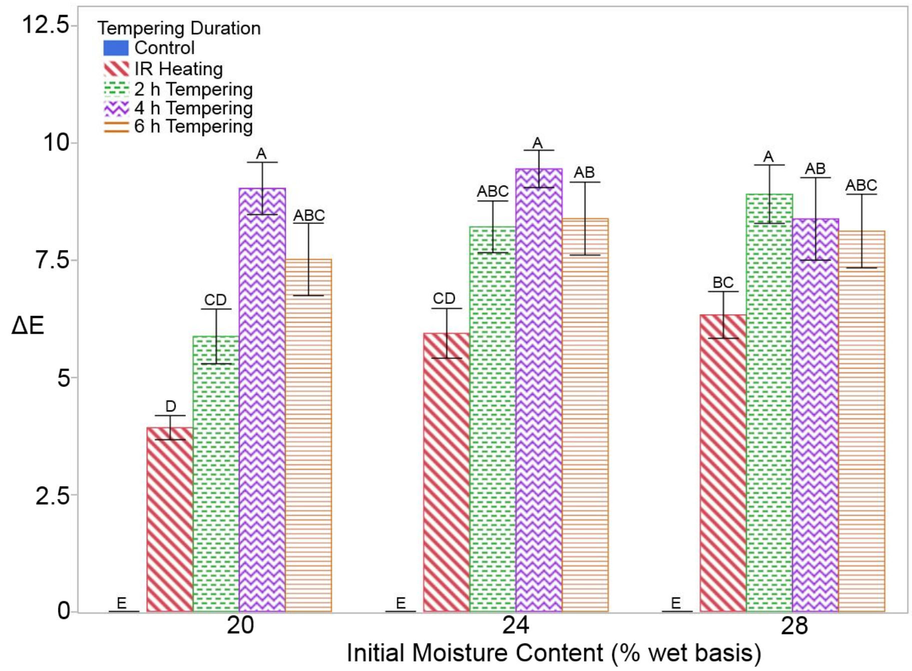

Figure 12. Tukey's HSD test for interaction between corn initial moisture content and tempering duration after one-pass infrared heating on corn color. Means with the same type of letters are not significantly different at α = 0.05.

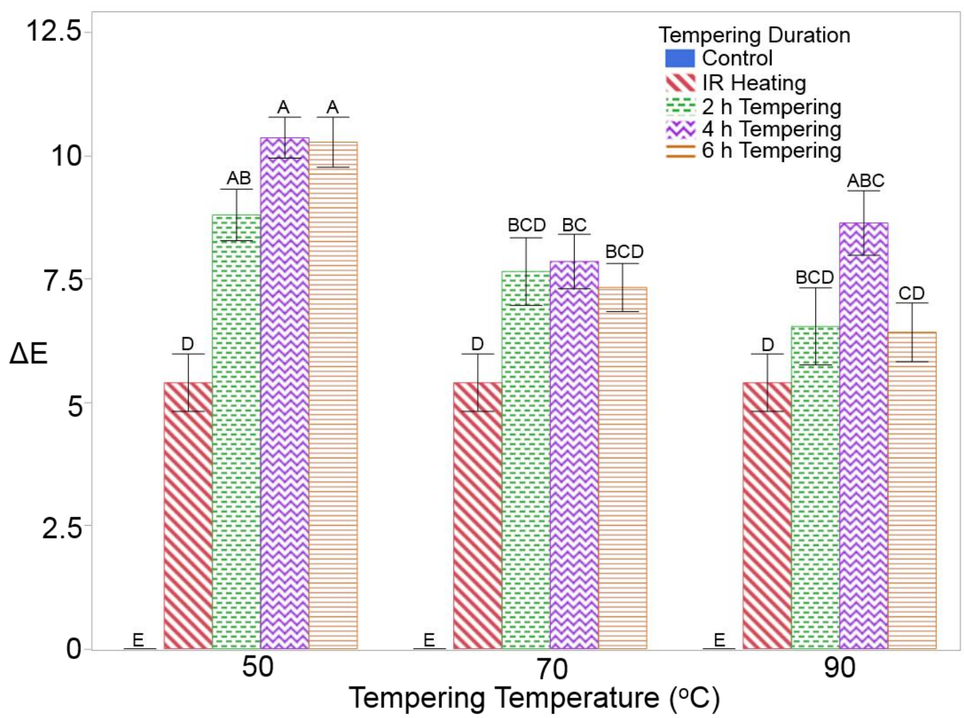

Figure 13. Tukey's HSD test for interaction between tempering temperature and tempering duration after one-pass infrared heating on corn color. Means with the same type of letters are not significantly different at α = 0.05.

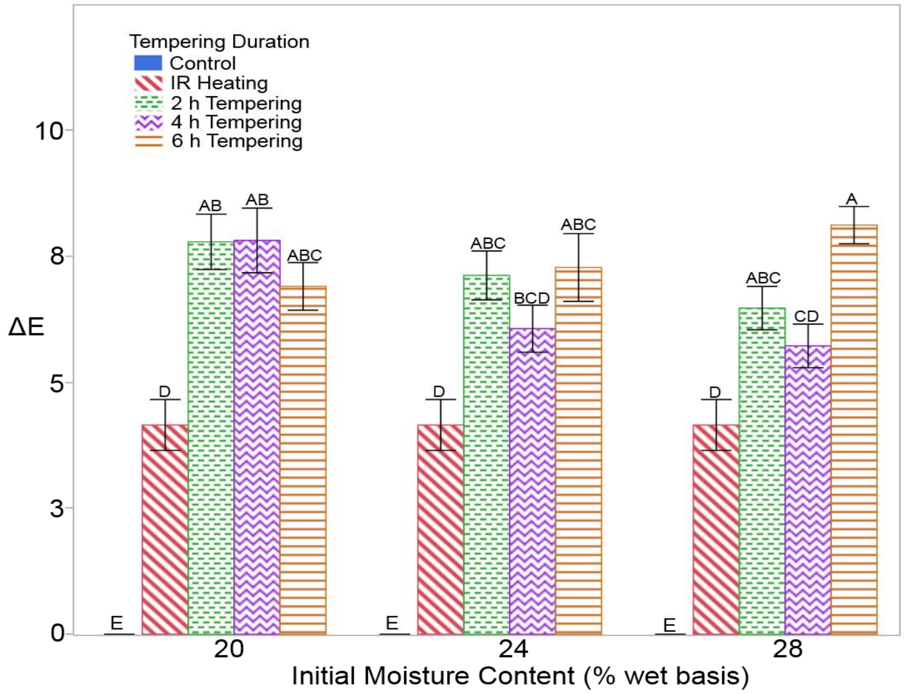

Figure 14. Tukey's HSD test for interaction between corn initial moisture content and tempering duration after two-pass infrared heating on corn color. Means with the same type of letters are not significantly different at α = 0.05.

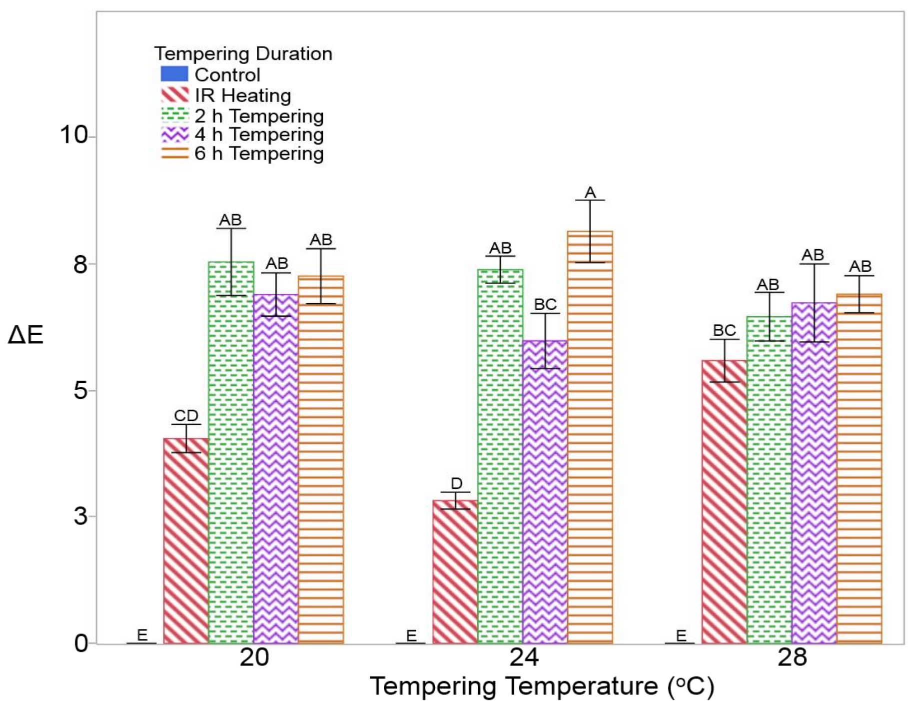

Figure 15. Tukey's HSD test for interaction between tempering temperature and tempering duration after two-pass infrared heating on corn color. Means with the same type of letters are not significantly different at α = 0.05.

III. Continuous-flow infrared drying of corn using a pilot scale equipment

Effect of Infrared Heating on Drying Duration

Multiple passes of IR heating of corn were done to dry corn with IMCs of 24 % to a final MC of 13%. The total duration required to dry the corn at different levels of IR intensities and intermittent IR heating durations is shown in Figure 16. A completely randomized full factorial analysis was done to determine if there were any significant interactions among the process variables. In cases where there were interactions, analyses were done to understand which effect significantly contributed to variations in the drying duration.

There was an interaction between IR intensity and the intermittent IR heating duration ($p < 0.0001$). Tukey's HSD test was done to identify where the differences were. Treatments with high IR intensity took the shortest total drying duration to dry corn (Figure 16). All treatments carried out with an intermittent IR heating duration of 30 s took a shorter total drying duration while intermittent IR heating duration of 180 s resulted in the longest total drying duration (Figure 16). The highest IR heating intensity and the shortest intermittent IR heating duration gave the lowest total drying duration.

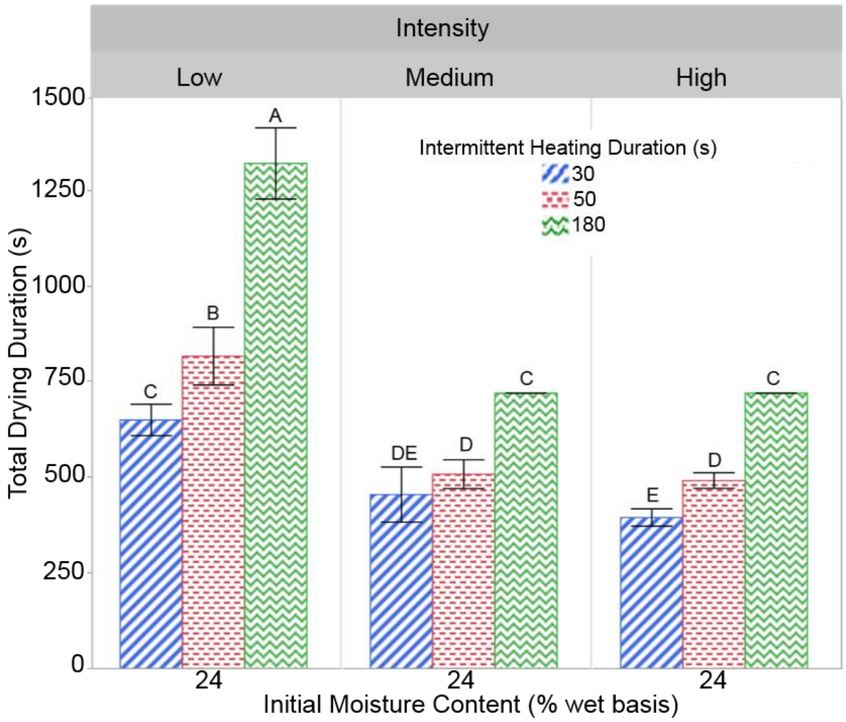

Figure 16. The effect of intermittent infrared heating of corn kernels (30, 50, and 180 s) and infrared intensity (low, medium and high intensities which correspond to 2.9, 3. and 5.55 kW/m^2) on total drying durations of corn from initial moisture content of 24% to final storage moisture of 13% (wet basis). Means with the same type of letters are not significantly different at α = 0.05.

Effect of Infrared Heating on Energy

The IR energy supplied to facilitate removal of a unit mass of water from corn dried using continuous-flow, intermittent IR heating process is shown in Figure 17. A completely randomized full factorial analysis was done to determine if there were any significant interactions. There was a significant interaction between IR heating intensity and the intermittent IR heating duration ($p < 0.0001$). Tukey's HSD test was done to identify where the differences were. The intermittent IR heating duration of 30 s at low intensity required the lowest energy to remove a unit mass of water from the corn kernel (Figure17). The energy utilized at the high IR intensity for intermittent IR heating durations of 30, 50 and 180 s was significantly higher than at low and medium intensities (Figure 17).

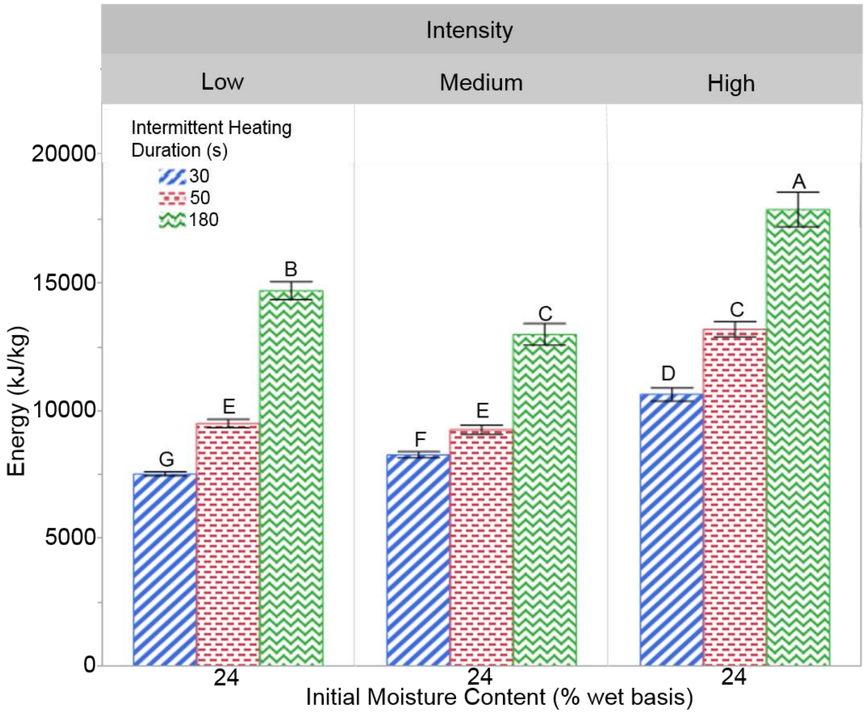

Figure 17. Effect of initial moisture content and infrared heating intensity (Low, Medium and High corresponding to 2.9, 3.78 and 5.55 kW/m^2, respectively) on energy required to remove a unit mass of water from the corn kernel. Means with the same type of letters are not significantly different at α = 0.05.

Effect of Infrared Heating on Mold Load Reduction

A completely randomized factorial design with fixed effects was conducted to determine if there were significant interactions between the IR heating intensity and intermittent IR heating duration. The effect of intermittent IR heating duration was statistically significant ($p < 0.0001$). Figure 18 indicated that the mean (M) mold counts on the control samples in terms of log CFU/g (M = 4.79, SD = 0.15) were significantly higher than those on samples treated at intermittent IR heating durations of 30 s (M = 1.95, SD = 0.9), 50 s (M = 1.98, SD = 0.7) and 180 s (M = 2.03, SD = 1.2).The results indicates that IR heating may be used effectively for mold inactivation.

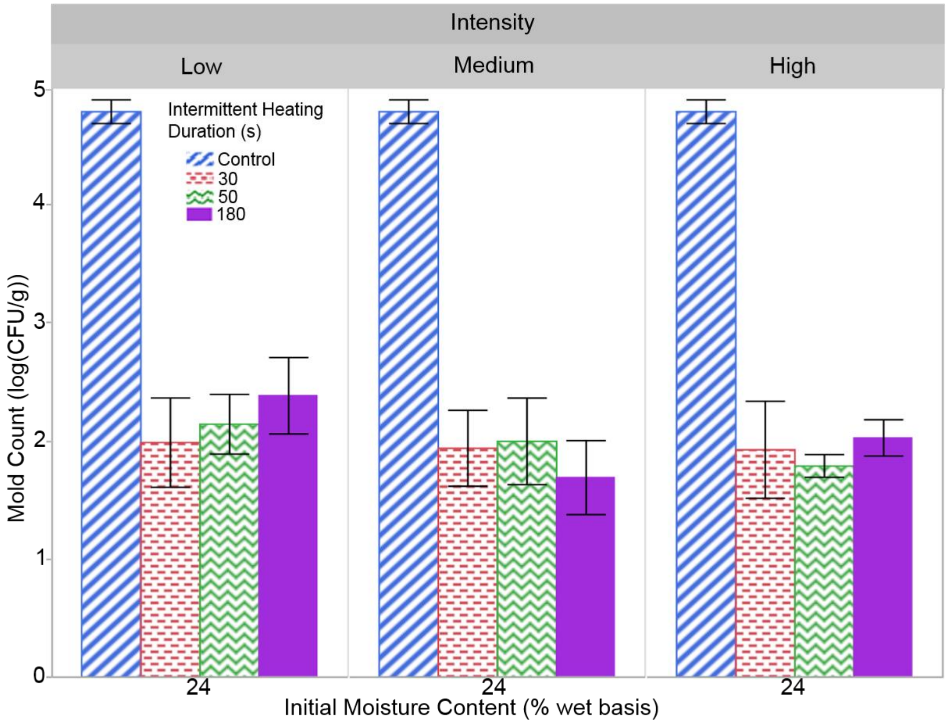

Figure 18. Effect of initial moisture content and infrared heating intensity (Low, Medium and High corresponding to 2.9, 3.78 and 5.55 kW/m^2, respectively) on mold counts (log colony forming units (CFU) per gram of corn sample).

Effect of Infrared Heating on Color

The results show that corn could be dried at the high IR intensity (5.55 kW/m^2) for long durations (720 s) without significant impact on color characteristics (Figure 19). A completely randomized factorial design with fixed effects was conducted to determine if there was significant difference in the values of L*, a* and b*, among treatments with different IR heating intensities and intermittent IR heating durations. There was no significant difference in L*(p = 0.14), a* (p = 0.07), and b* (p = 0.65).

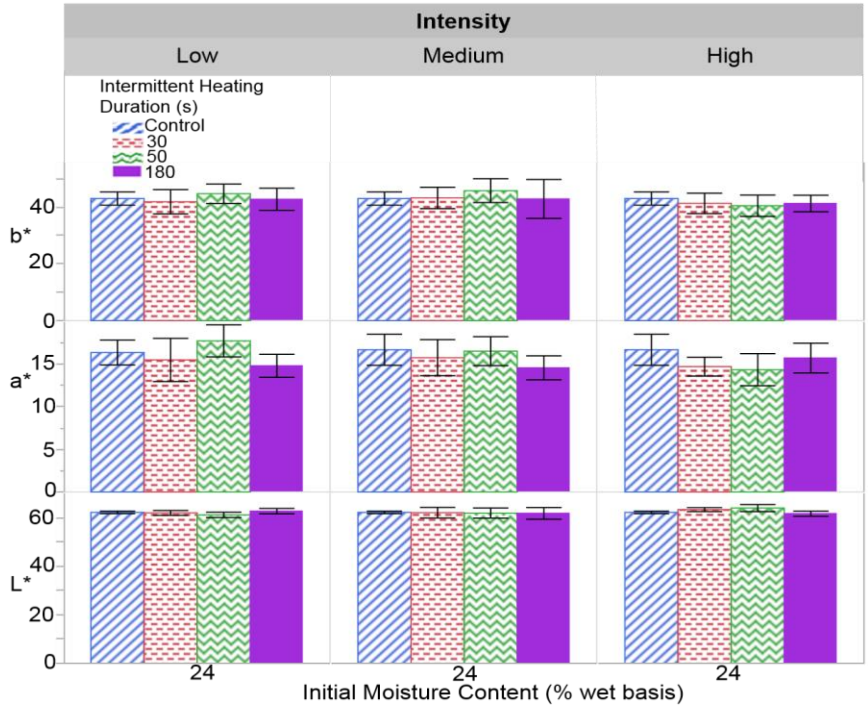

Figure 19. Effect of infrared heating intensity (Low, Medium and High corresponding to 2.9, 3.78 and 5.55 kW/m^2, respectively) and intermittent infrared heating duration on treated corn color characteristics.

Chapter 5
Conclusions

Batch Infrared Drying of Corn using Infrared heating

The percentage points reduction of moisture content achieved by combined infrared (IR) heating of corn kernels to surface temperature of 90°C, and tempering for 2, 4, and 6 h at 50°C, 70°C, and 90°C were determined. The following observations were made:

- The processing conditions that corresponded to the lowest amount of energy utilized to remove a unit mass of moisture from corn of initial moisture content (IMC) range 20% to 28% wet basis (w.b.) was heating the corn kernels to surface temperature of 90°C at a product-to-emitter gap size of 430 mm followed by tempering for 2, 4 and 6 h in a one-pass IR heating and tempering treatment.
- For corn at IMC of 20%, the energy required to remove a unit mass of moisture was statistically different and greater than that for corn at IMCs of 24% and 28%.
- Tempering was found to be very crucial for corn at IMCs of 20% and 24% compared to 28%. Overall, effective moisture removal was noted when corn was at 28%bIMC.
- There was a significant mold reduction on treated corn after IR and tempering treatments; with reference to the freshly-harvested sample the treatments resulted in a significant change in dried corn color, but may not be detected visually.

In summary, at high IMCs, longer IR exposure duration may be necessary to achieve high corn surface temperatures compared to low IMCs. For such cases, it may be more effective to reduce the tempering temperature to avoid cake formation.

Infrared Drying of Corn using a Continuous-flow Pilot Scale Equipment

Infrared (IR) treatments for corn drying and microbial decontamination were scaled up using a recently built pilot scale IR drying equipment. Freshly harvested corn were intermittently heated for 30, 50, and 180 s using IR energy at low, medium and high IR intensities (corresponding to 2.9, 3.78 and 5.55 kW/m^2, respectively) to accomplish drying of corn from initial moisture content (IMC) of 24% to final safe storage moisture content (MC) of 13% (w.b.). The following conclusions were drawn:

- IR heating could be scaled up and holds potential to simultaneously dry and decontaminate corn.
- The total drying durations were significantly dependent on the IR intensity and intermittent IR heating duration.
- The total drying duration decreased with an increase in IR intensity and a decrease in intermittent IR heating duration.
- Drying energy requirement increased as the IR intensity and intermittent IR heating duration increased.
- There was a significant mold load reduction on the treated corn after the IR treatments at the lowest intensity of 2.9 kW/m^2, however the mold load reduction was not significantly different compared to that with treatments done at the medium and high intensities.
- For the studied range of process parameters and product characteristics, treating the corn with IR only to dry the kernels to a final safe storage MC of 13% (w.b.) did not have a significant impact on the corn kernel color characteristics.

In summary, IR heating technology for corn drying may hold promise not only to achieve rapid removal of moisture from freshly harvested, high MC corn, but also to simultaneously inactivate microbes on the corn kernels, thereby reducing the risk of mycotoxin development. When fully optimized, intermittent IR heating of corn without additional convective heated air, or long tempering durations may hold potential to dry, freshly harvested high MC corn kernels to final safe storage MC. The new IR drying technology could be implemented at the front end of the current corn drying systems without complex retrofitting requirements.

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