Rita Khathir

Controlling *Oryzaephilus surinamensis* in soft winter wheat by using microwave energy

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Controlling *Oryzaephilus surinamensis* in soft winter wheat by using microwave energy

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Rita Khathir

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I. Introduction

1.1. Background

Oryzaephilus surinamensis (L.) is a secondary stored-grain insect pest, which was found for the first time in Suriname, South America. The first incident of *O. surinamensis* in Germany was reported in 1953 (Reinhardt *et al*., 2003). In a survey done in grain stores of ecological farming in Baden-Württemberg-Germany, it was showed that *O. surinamensis* is one of the most important secondary pests because it has the infestation frequency at level 25 % (Niedermayer and Steidle, 2006). According to Beckel *et al*. (2007), over the past decades, the incident of this insect has significantly increased in the storages facilities. It was estimated due to the increase production of the broken grains as a consequence of the increase use of mechanical equipment in post harvest handling.

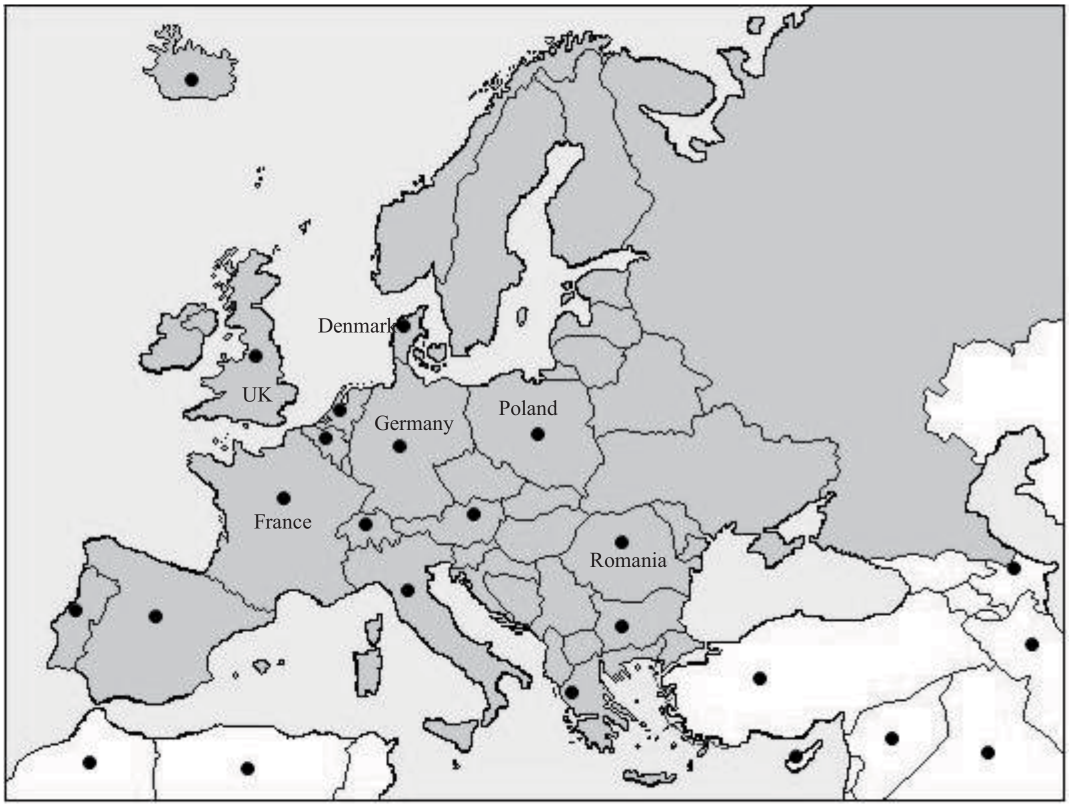


Figure 1: The European distribution of *Oryzaephilus surinamensis* (http://www.cabi.org/isc/DatasheetDetailsReports.aspx?&iSectionId=EU*0&iDatasheetID=37988&sSystem=Product&iPageID=481), 11.04.2011

The rapid spread of the insect is transpired through the exported and imported grain products among the countries worldwide, especially in the warm regions. However, since the insect is living in storage facilities, the incident of this insect is also found in the temperate regions such as Germany. The spread of this insect in European countries globally can be seen in Figure 1. Therefore, it seems that the insect could spread worldwide without limitation of geographical location.

Arthur (2001) stated that *O. surinamensis* becomes a cosmopolitan insect pest of stored grains because it has high speed reproduction rate. In agreement with this, Lessard *et al*. (2005) confirmed that the calculated progeny per pair of parental generation of this insect could reach more than 2000 individuals after 3 months at temperature 30 ^{0}C in grain at moisture 13.7 %. It is estimated that at such high population, the insects will consume large amount of grains and produce the dust and other contamination materials. About 1.89 % weight loss was indicated under a low population level of *O. surinamensis* (Hurlock, 1967), thus, the higher weight loss could be expected at the higher number of the initial population. Moreover, the insects have built serious infestation problems that reached the economic threshold, especially because of their high adaptation ability, high mobility, and ability to attack the packaged food (Beckel *et al*., 2007).

There are a number of methods, which were used for controlling this insect pest, for instance chemical and biological methods. The chemical method (i.e. by using the insecticides) is the common method to be used because of its low cost. However, it suffers from some serious drawbacks. One of these drawbacks is that *O. surinamensis* could build resistance against the insecticides. Conyers *et al*. (1998) investigated that *O. surinamensis,* strain 7012/1malRR Whitminster, was resistant to organophosphorus (malathion, fenitrothion, pirimiphos-methyl, chlorpyrifos, and methacrifos). Beckel *et al*. (2007) also reported that the ability to hide in many places in the storage facilities become another drawback for the insecticides application in controlling this insect.

Searle *et al*. (1984) studied the biological method in controlling adult *O. surinamensis*. The application of fungus *Beauveria bassiana* (Bals.) Vuill. was found effective at dosage of 10^3 spores per *ml*, temperature 25 °C and 100 % humidity. However, they could not confirm the safety of using this fungus for human health. Haas-Costa *et al*. (2010) confirmed that the infestation of *B. bassiana* in commercial chicken food has positive effect on improving weight of *Gallus domesticus L*. (male chicken) However, there is no information about the concentration of spores used that would be a very important factor to cause the malfunction on the bird health. In addition, so far, the application of this method is not commonly used.

Besides the two methods discussed above, the use of thermal effect is considered as an effective method in controlling the pests with some advantages such as no chemical contamination and no risk of pest resistance. The thermal effect can be generated by using hot water, hot air, and steam. Lurie (1998) suggested that the use of such methods is possible to disinfest fruits, vegetables, and flowers.

At the present, the use of those thermal methods to control *O. surinamensis* in the grain products is not implemented yet. Therefore, the possibility of using microwave (MW) energy to generate heat on grain products is expected to have the advantages of using the thermal method in controlling *O. surinamensis*. It is revealed that the MW energy could be an alternative of thermal method since it increases rapidly the temperature in the wet product, thus reduces the application time.

This idea is not new since there are several attempts that have been made to investigate the potential use of MW energy in controlling the insect pests at secure temperature for the products (Hamid *et al*., 1968; Zhao *et al*., 2007; Vadivambal, 2009; and Singh *et al*., 2011). However, at the moment, the MW technology in controlling insect pests is not commercially implemented yet. The primary consideration is the high cost, which is needed to transmit this technology into practice. Therefore, further researches on MW technology are needed to reach the reasonable usage of MW in the area of food protection by improving the MW performance. Especially, since the MW energy produces the irregular temperature distribution, the study on temperature distribution should be conducted to improve the heating uniformity in the product and later it is expected to enhance the product quality. The improvement of MW performance is still a challenge for the grain disinfestations in the industrial application at a reasonable cost.

1. 2. Objectives

This study was aimed to address the following objectives that are integrated in the field of agricultural engineering, entomology science, and food protection, those are:

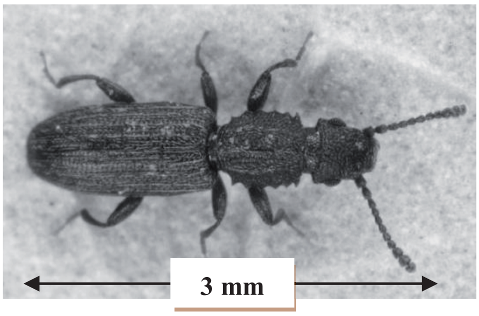
1. To study the heating uniformity on wheat grains after MW heating based on its surface temperature
2. To determine the potential of MW heating for controlling *O. surinamensis*.
3. To investigate the germination rate of grain after the MW heating.
4. To analyze the quality of flour produced from the grain treated by using the MW heating.

II. Literature review

2.1. Introduction to *Oryzaephilus surinamensis*

2.1.1. The biology and ecology

According to the scientific classification, *O. surinamensis* is belonged to family silvanidae and the common name for this insect is the Sawtoothed grain beetle. Silvanidae family is the flat grain beetles that are regarded as common and important domestic pests (Hill, 1994). Reinhardt *et al*. (2003) discussed that *O. surinamensis* not only act as the grain storage pest, but it also found as household pests.



Scientific classification:

Kingdom : Animalia
Phylum : Arthropoda
Class : Insecta
Order : Coleoptera
Family : Silvanidae
Genus : Oryzaephilus
Species : ***O. surinamensis***

Source of picture: www.kerbtier.de

Figure 2: The photo and scientific classification of *Oryzaephilus surinamensis*

The insect has the body up to 3 mm long, narrow, and dark color as tobacco-brown and it has 6 sharp teeth running down the both sides of the prothorax (Figure 2). The egg has white color sizing 0.8 x 0.3 mm. The growth of larva is up to a 5 mm long whereas the pupa with cream-colored grows up to a 3 mm long. A female could lay about 150 to 375 eggs during her reproductive age (Reichmuth, 1997). It was noticed at temperature above 17.5 °C that the female of insect deposits her eggs near by the damaged parts or in the groove in the case of wheat (Lessard, 1988).

The development of egg to larva needs about 5 days. The larva will molt in 2 weeks for about 3 to 5 times. After 8 days in pupa stage, the adults emerge and their life span could reach about 3 year olds (Reichmuth, 1997). It was found that the largest number of larva was yielded from the 10th to the 20th day, and the largest number of pupa was produced from the 30th to the 35th day (Beckel *et al*., 2007).

Benzing (2000) stated that under favorable environment, the life cycle of *O. surinamensis* takes around 21 days. Beckett and Evans (1994) determined this favorable environment at temperature 35 °C and 70 % r.h. (Table 1). Furthermore, according to Beckel *et al*. (2007), under 25±0.5 ^{0}C and 65±5 % r.h., the mean total development time of egg to adult was about 35 days, but most adults (63.4 %) emerged at the 46th day after the infestation.

The population growth of the insect can be calculated as the weekly finite rate of population increase (λ_p). Beckett and Evans (1994) had investigated that the highest weekly finite rate was 2.2278, which was detected at temperature 30 °C and 70% r.h. as it is shown in Table 1. This condition was found as the optimal living environment for *O. surinamensis* development, which was signed by the lowest mortality rate. Based on their finding, they recommended that the most sensitive stage was egg, while the most resistant stage was pupa.

Table 1: The weekly finite rate of population increase (λ_p) and the immature development period in day (D) of *Oryzaephilus surinamensis*

Temperature (°C)	**Relative humidity (%)**					
	30		**50**		**70**	
	λ_p	**D**	λ_p	**D**	λ_p	**D**
25	1.4270	39.1	1.5114	35.4	1.5797	34.2
30	1.6944	27.0	1.8671	23.9	2.2278	22.4
35	0.9293	28.1	1.3143	23.0	1.7935	20.8

(Beckett and Evans, 1994)

2.1.2. The maintaining methods of *Oryzaephilus surinamensis*

A considerable amount of literatures has been published on rearing methods, which is applied to prepare *O. surinamensis*. Beckel *et al.* (2007) reared *O. surinamensis* on wheat meal at 25±0.5 °C and 65±5 % r.h. The meal was produced by grinding the grains after disinfesting at temperature 60 °C for 1 h and cooling down for 3 h. Each glass jar was filled by 80 g of disinfested wheat meal and then 100 insects were put inside. The glass was covered by using filter paper. After 10 days from infestation, the insects were removed to another glass jar, and the number of eggs, larvae, and pupae were accounted at five-day intervals until all adults from the second generation emerged.

In another study conducted by Stubb *et al.* (1985), *O. surinamensis* was maintained in darkroom at 25 °C and 70 % r.h. on wheat meal, rolled oats and powdered yeast in ratito 5:5:1 based on the weight. Conyers *et al.* (1996) used heat-sterilized rolled oats as medium and kept 150 insects on 150 g food at 25 °C and 70 % r.h. Lord (2006) reared them on rolled oats with brewer’s yeast at 30±1 °C and

55±10 % r.h. Mikolajczak *et al*. (1984) and Pierce *et al*. (1990) used the same medium of rolled oats and brewer's yeast in ratio 95:5 by weight with considerable differences in their two studies. Mikolajczak *et al*. (1984) considered the cycle of photoperiod at 16 h under the light and 8 h in the darkness, and used the climate at 27 °C and 60 % r.h, while Pierce *et al*. (1991) applied the darkness for the whole time rearing and maintained at 28 °C and 60-70 % r.h.

There is a problem to handle the eggs since their sizes are very small and they have a thin hull. Beckett and Evans (1994) reared *O. surinamensis* on thin kibbled wheat medium maintained at approximately 30 °C and 65 % r.h. Eggs less than 24 h old were collected in stacked layers of black filter paper. The same method was used by Beckel *et al*. (2007). A stack of at least three layers of filter papers was buried just under the surface of the culture and after 5 days assessment the eggs were removed by brushing the stack gently.

2.1.3. The economic loss due to the infestation of *Oryzaephilus surinamensis*

Wheat shares about 53 % of grain production in Germany (FAOSTAT, 2011). Since wheat production dominates the grain production, it is reasonable to predict the estimation loss due to the infestation of *O. surinamensis* based on the wheat production.

Table 2: The estimation loss in wheat due to the infestation of *Oryzaephilus surinamensis* in Germany

		Year	
		2008	**2009**
a	Total wheat production[1], tones	25,988,565	25,190,336
b	Estimated loss due to storage pests[2], 1 % x a, tones	259,886	251,903
c	Estimated loss due to *O. surinamensis*[2], 1 % x b, tones	2,599	2,519
d	Producer price[1,3], € per tones	172	172
e	Total loss, c x d, €	447,003	433,274

[1] FAO, 2011
[2] Reichmuth cited by Reinhardt *et al*. (2003)
[3] Since the price in 2009 was not available, the price in 2008 was used

According to Hurlock (1967), it was nearly 1.89 % weight losses of wheat caused by 25 insects after 16 weeks infestation at temperatures ranging from 25 to 31.1 °C and 70% r.h. The average number of the insects had increased to 160 individuals and the population growth rate was 1.6 determined as the monthly finite reproduction rate. Irrespective to Table 1, a higher weight loss can be expected because the weekly finite reproduction rate calculated by Beckett and Evans (1994) was higher than the monthly finite rate reproduction reported by Hurlock (1967).

Reichmuth, the president of Biologische Bundesanstalt (the former of Julius Kühn Institut, Berlin) from 1999 to 2007, estimated that the amount of losses caused by *O. surinamensis* is about 1 % of the total losses due to the storage pests. In addition, frequently *O. surinamensis* is a forerunner for *Rhyzopertha dominica* (the lesser grain borer), which is responsible to the loss of 10 %. Thus, both insects could contribute to the loss about 11 % (Reinhardt *et al*., 2003). Based on this assumption, the loss in wheat due to *O. surinamensis* was estimated approximately € 444,003, and € 433,274, in 2008 and 2009, respectively (Table 2).

2.2. The potential of thermal method for insect control

The thermal effect can be generated by using the heat treatments such as the hot water, the vapor heat, as well as the hot air. Hot water was originally used for fungal control, but it has been extended to control the insects. Vapor heat has been specifically developed for insect control, and the hot air has been used for both. The products that were suggested to be disinfested by thermal method are fruits, vegetables, and flowers (Lurie, 1998).

A complex reaction is integrated in the insect body due to the heat treatments such as metabolism, respiration, the heat shock protein, nervous, and endocrine system. The real cause of insect mortality following a heat treatment is not completely explained yet (Neven, 2000). Nevertheless, the heat treatment is promising to be used in controlling the insect as a non damaging physical treatment for chemical prevention (Lurie, 1998). Moreover, the use of thermal effect to disinfest storage structures is enjoying a resurgence of interest because it represents a possible replacement for whole structure fumigation with methyl bromide (Wright *et al*., 2002).

About 100 % of diapausing larvae of *Ephestia elurella* (Hb.) exposed at temperature 40, 43 and 45 °C died after 96, 24, and 16 h, respectively (Bell, 1983). Heat treatment under a convection oven at temperature from 50 to 90 °C was found applicable to control *Mayetiola destructor* (the Hessian fly) and *Sitodiplosis* *mosellana* (wheat midge). Pupae were killed at temperature 55 °C for 3 min, whereas larvae were controlled at temperature 52.5 °C for 7 min. When the temperature was decreased to 47.5 °C, about 37 min was needed to kill all larvae (Sokhansanj *et al*., 1992).

The use of hot water at 44 °C for 35 min followed by cold storage at 0.5 °C was effective to control leafroller species in *Malus domestica Borkh* (the Royal Gala apples) (Smith and Lay-Yee, 2000). All stages of *Tribolium castaneum* (the red flour beetle) and *Cryptolestes ferrugineus* (the rusty grain beetle) were sufficient to be lethal at 45 °C for 40 h. The temperature of 50 °C was lethal to *T. castaneum* and *Cryptolestes pusillus* (the flat grain beetle) for 35 and 65 min, respectively. By increasing the temperature to 55 °C, approximately 10 min was sufficient to produce a lethal effect on those species (Anonymous, 2003).

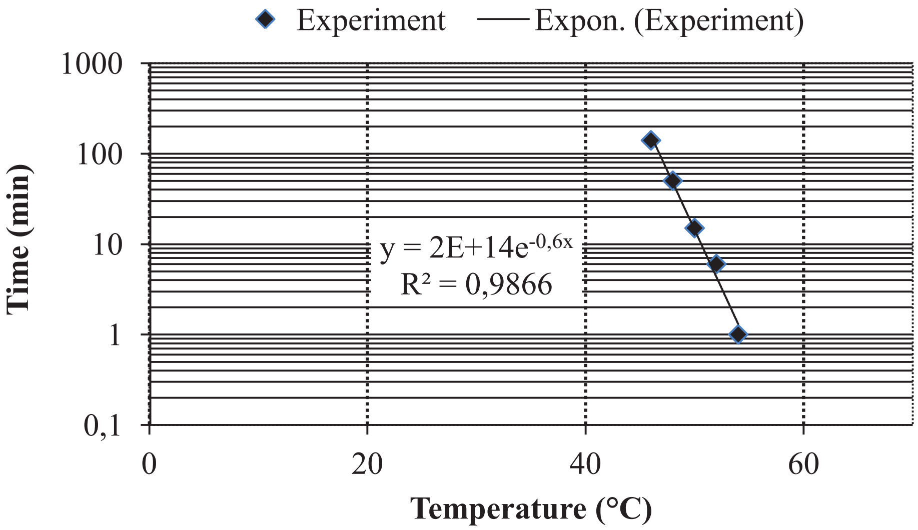


Figure 3: The temperature-time to reach 100 % mortality of the fifth-instar larva of *Amyelois transitella* by using a heating block system (Wang *et al*., 2002)

A study of the effect of thermal to control the fifth-instar larva of *Amyelois transitella* (the Navel Orangeworm) was done by using a heating block system, which was developed at Washington State University. The time required to achieve 100 % mortality of those larvae (n = 600) decreased with increasing temperature in a logarithmic manner as it is shown in Figure 3 (Wang *et al*., 2002). Moreover, Tang *et al*. (2000) had controlled the codling moth larvae in in-shell walnuts, which were based on the kinetic information of insect mortality and product quality. According to their finding, there is the possibility to develop high-temperature-short-time thermal heating under the safe limit for the product quality. As can be seen in Figure 4 (p. 9), there is a region for quarantine control, which determines the region that is safe to protect the product quality and lethal to the insect pests.

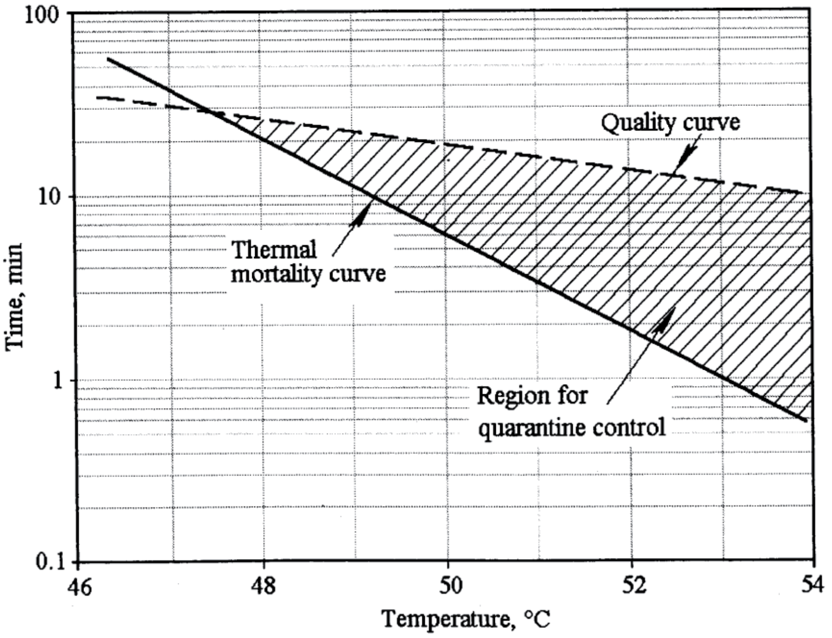


Figure 4: The region for quarantine control of codling moth in in-shell walnuts (Tang *et al*., 2000)

Although the conventional heating is widely used for the insect control, there is a limited condition that the uses of hot air or hot water often leave high cumulative thermal effect on the product and later cause the deterioration on the quality. Therefore, the use of radio frequency (RF) and MW heating has been suggested by Tang *et al.* (2000) to reduce the adverse thermal impacts on the products.

2.3. Theoretical aspects of high frequency

The thermal barriers of dried surface are transparent to the MW or RF energies (Metaxas and Meredith, 1993), where the MW and RF energies can directly couple with the water or fat contents inside the material. The power loss, the magnitude of heat generation by MW and RF energies, is influenced by the free space permittivity, the complex permittivity, the square of electric field, the energy loss in the material, and the operating frequency (Eq. 1). Since the energy loss in the material is a ratio between the dielectric loss factors to the dielectric constant (Eq. 2), the power loss can be written in a simple way as it is shown in Eq. 3. Receiving the MW or RF energies, the temperature of the material will be raised. However, as the water is evaporated in the heating process, the temperature will be arisen in the material, but then it will be reduced accordingly (Nelson, 1996). The evidence can be formulated as it is written in Eq. 4.

$$P_{loss} = 2 \times \pi \times f \times E^2 \times \varepsilon_0 \times \varepsilon_r^{\ *} \times \tan\delta \tag{1}$$

$$\tan\delta = \frac{\varepsilon_r^{**}}{\varepsilon_r^{*}} \tag{2}$$

$$P_{loss} = 55.6 \times 10^{-12} \times f \times E^2 \times \varepsilon_r^{\ **} \tag{3}$$

$$\frac{dT}{dt} = \frac{P_{loss}}{c \times \rho} \tag{4}$$

where:

P_{loss} = the power loss [W/m^3]

f = the operating frequency [Hz]

π = a mathematical constant representing a circumference of a circle with diameter 1 (3.14159)

E = the electric field [volt/m]

ε_0 = the free space permittivity (8.854 x 10^{-12}) [F/m]

$\varepsilon_r^{\ *}$ = the dielectric constant

$\varepsilon_r^{\ **}$ = the dielectric loss factor

tan δ = the energy loss in material

dT = the temperature increase [°C]

dt = the time [h]

c = the specific heat of the material in [kJ/(kg·°C)]

ρ = the material density [kg/m^3]

The amount of power that will be absorbed by the materials depends on the reflection coefficient (Eq. 5). Stratton (1941) cited in Nelson (1996) expressed the reflection coefficient as the function of the dielectric constant of the materials (Eq. 6). As the wave travels through a material that has high dielectric loss factor, the energy will be attenuated. If the attenuation is high in the material, the dielectric heating will taper off quickly as the wave penetrates the material. Thus, the power density diminishes as an exponential function of the attenuation and traveled distance of the wave through the materials (Eq. 7).

$$P_t = P_0 \times (1 - |\Gamma|^2) \tag{5}$$

$$\Gamma = \frac{1-\sqrt{\varepsilon^*}}{1+\sqrt{\varepsilon^*}} \tag{6}$$

$$P_d = P_t \times e^{-2\times\varphi\times z} \tag{7}$$

where:

P_t = the power absorbed [W]

P_0 = the power given [W]

Γ = the reflection coefficient

P_d = power density [W]

φ = the attenuation

z = the traveled distance of the wave [m]

The penetration depth, d_p, is defined as a distance at which the power drops to an exponential function (e^{-1}) at the surface of the material. Consequently, in the MW heating, it is found that the lower values of frequency and moisture content are responsible to the lower attenuation and the deeper penetration depth (Nelson, 1996).

$$d_p = \frac{\lambda_w}{4\pi\sqrt{\frac{1}{2}\varepsilon^*\left[\sqrt{1+\left\{\frac{\varepsilon_r^{**}}{\varepsilon_r^*}\right\}^2}-1\right]}} \tag{8}$$

where :

λ_w = wave length [m]

There is a possibility of advantageous selective heating in the mixtures of the different materials (Hamid *et al.*, 1968), which is based on the dielectric properties. For example, Taylor approach (1965) cited in Hamid *et al.* (1968) can be used to calculate the dielectric constant of a mixture of wheat and insects by using the following equation.

$$\varepsilon_r^{\ *} \approx \frac{\left[V_w \times (\varepsilon_r^{\ **})_w\right] + \left[n \times V_i \times (\varepsilon_r^{\ **})_i\right]}{\left[V_w + (n \times V_i)\right]} \tag{9}$$

where :

V_w = the volume of wheat [m^3]

V_i = the volume of insect [m^3]

n = the number of insects

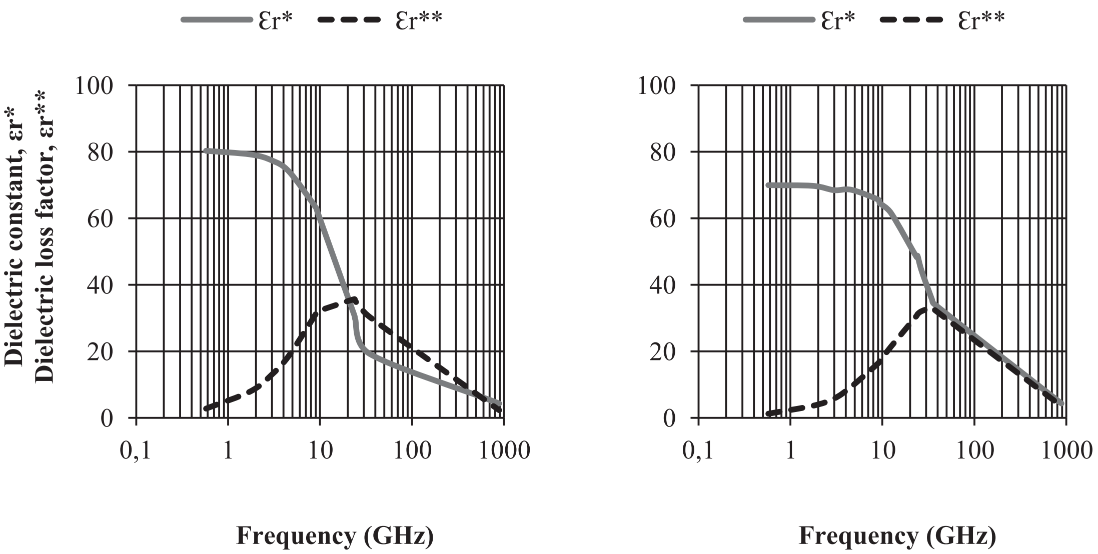
2.4. Factors influencing the dielectric properties of materials

Regarding the theory of high frequency, the dielectric properties of the material are very important because they will influence the amount of the MW energy absorption. Furthermore, the dielectric properties are influenced by other factors such as frequency, temperature, moisture content (MC), and density.

2.4.1. Frequency

The dielectric constants of bulk samples of wheat and adult rice weevils decreased continuously with the increasing frequency from 250 Hz to 12.2 GHz. The dielectric constants for rice weevils were considerably higher than those for wheat in the region between 100 kHz and 1 GHz. On the other hand, the values for the dielectric loss factors of wheat and rice weevils decreased with increasing frequency from 250 Hz to 50 kHz, then increased to a peak in the region between 5 and 100 MHz, and then declined again to a minimum values at frequency above 1 GHz (Nelson and Charity, 1972).

It can be seen from Figure 5 that the dielectric constant of water at temperature 20 and 50 °C decreased with slight manner as the frequency increased up to 3 and 12.5 GHz, respectively, and it continued decreasing dramatically at higher frequency. Contrary, the dielectric loss factor of water increased as the frequency increased to 36.3 GHz, and then it is followed with decreasing values at higher frequency.



(a) (b)

Figure 5: The dielectric properties of liquid water with different frequencies at temperature 20 °C (a) and 50 °C (b) [Hasted (1973) in Nelson (1994)]

Nelson (1994) confirmed that the dielectric loss factor might be increase or decrease depending on the ratio between the operating and the relaxation frequency. It is apparent in Figure 6 (p. 15) that the dielectric loss factor of chickpea flour decreased as the frequency increased at temperature above 70 °C (Guo *et al*., 2008). Irrespective to Figure 9 (p.17), it can be seen that the dielectric properties of hard red winter wheat decreased as the frequency increased (Sokhansanj and Nelson, 1988). This agrees completely with the findings of Sharma *et al*. (2010) who investigated that the increase of frequency from 4.6 to 14.2 GHz led to the decrease of wheat flour dielectric properties.

2.4.2. Temperature

Guo *et al*. (2008) confirmed that the dielectric properties of chickpea flour increased as the temperature increased from 20 to 90 °C. It can be seen in Figure 6 (p. 15) that the dielectric loss factors at temperature below 50 °C increased in slight manner, while at temperature above 70 °C, the values increased dramatically.

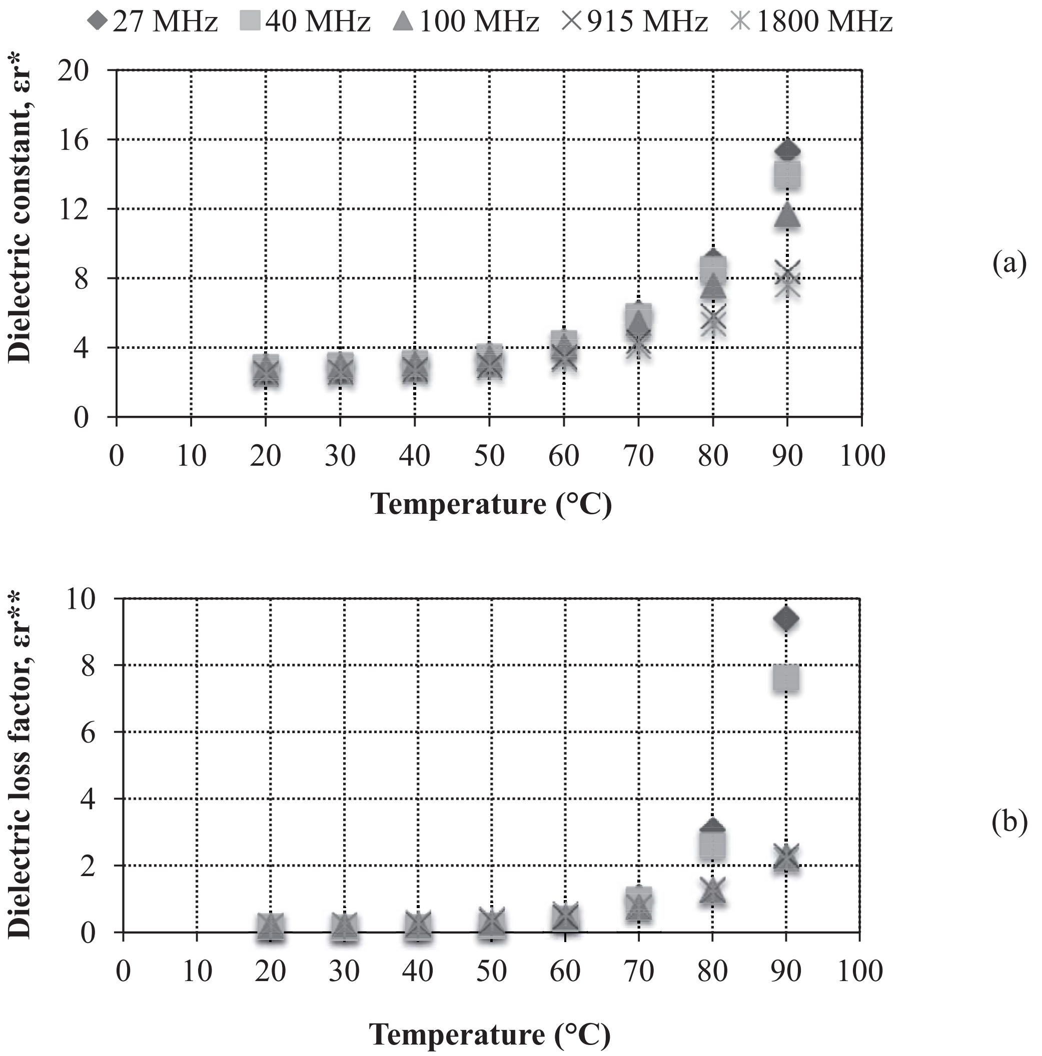


Figure 6: The dielectric constant (a) and loss factor (b) of chickpea flour at moisture 11.4 % (Guo *et al*., 2008)

As can be noted from Figure 7 (p. 16), at frequency 10 MHz, it can be seen that the dielectric constant of water decreased as the temperature increased from 20 to 100 °C in slight manner (Atkins *et al*., 2011). Ndife *et al*. (1998) studied that the increase in temperatures from 35 to 70 °C decreased the dielectric loss factor of starch solution, but the increase of temperature from 70 to 95 °C led to the increase of the dielectric loss factor of starch solution. In contrast, the dielectric loss factor of starch granular slightly increased in the temperature region of 30 to 95 °C (Figure 8, p. 16).

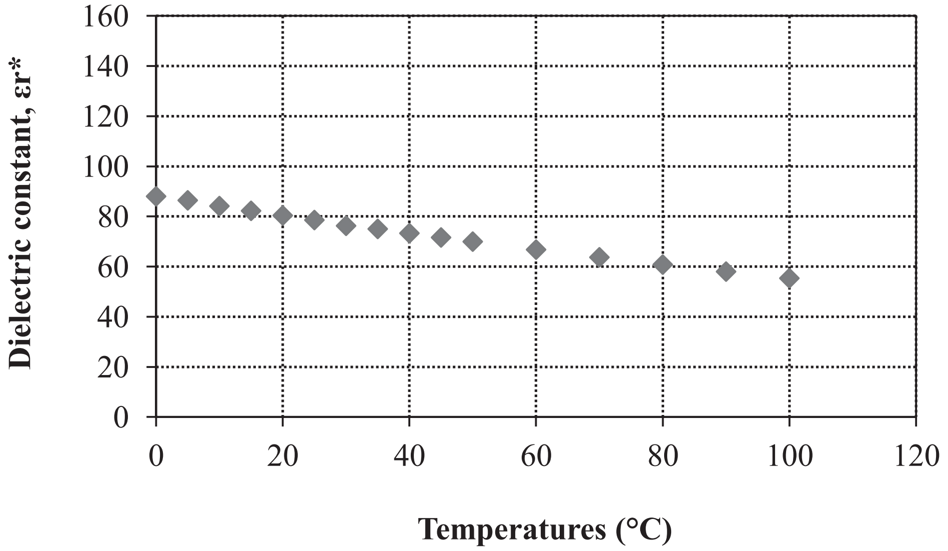


Figure 7: The dielectric constant of water with temperature at frequency 10 MHz (Atkins *et al.*, 2011)

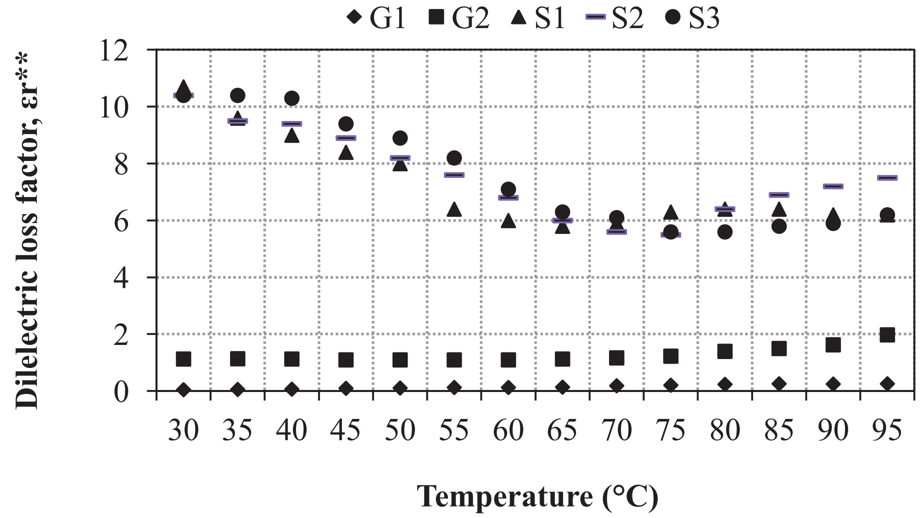


Figure 8: The dielectric loss factor of wheat starch; G1, granular starch at 1 % MC; G2, granular starch at 13 % MC; S1, starch solution with 50 % water; S2, starch solution with 60 % water; S3, starch solution with 66 % water (Ndife *et al.*, 1998).

2.4.3. Moisture content

The dielectric properties of hard red winter wheat increased with the increase of moisture contents from 2.7 to 23.8 % (Nelson and Stettson, 1976). It was in agreement with the finding from Sokhansanj and Nelson (1988) as it is shown in Figure 9 (p. 17). Guo *et al.* (2008) had also investigated the same trend for the chickpea flour (Figure 10, p. 18). Ajibola (1985) also confirmed a highly dependence of moisture content to the dielectric constant of *Manihot utilisima* (cassava) at frequency 1 kHz, where the dielectric constant increased as the moisture content increased.

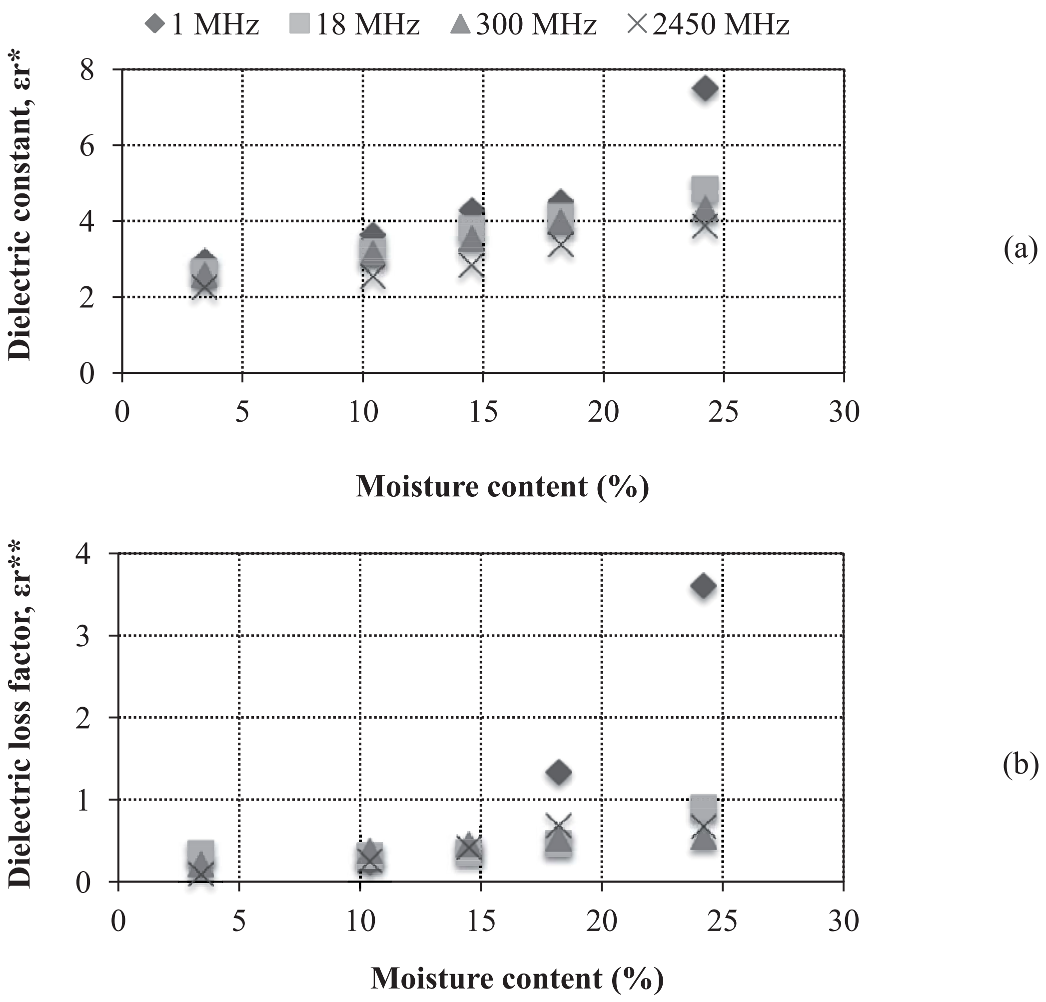


Figure 9: The dielectric constant (a) and loss factor (b) of hard red winter wheat at low density with moisture content from 3.4 to 24.2 % (Sokhansanj and Nelson., 1988)

These finding agree with the work of Ndife *et al.* (1998), which is shown in Figure 8 (p.16). The dielectric properties of starch were affected by the changes in moisture content. At temperature lower than 70 °C, the dielectric loss factor of starch solution increased as the moisture increased from 50 to 66 %, while at temperature above 70 °C, the highest dielectric loss factor of starch solution was at the moisture 60 %. In contrast, at temperature ranging from 35 to 95 °C, the increase of moisture in starch granular from 1 to 13 % increased the dielectric loss factor with slightly manner.

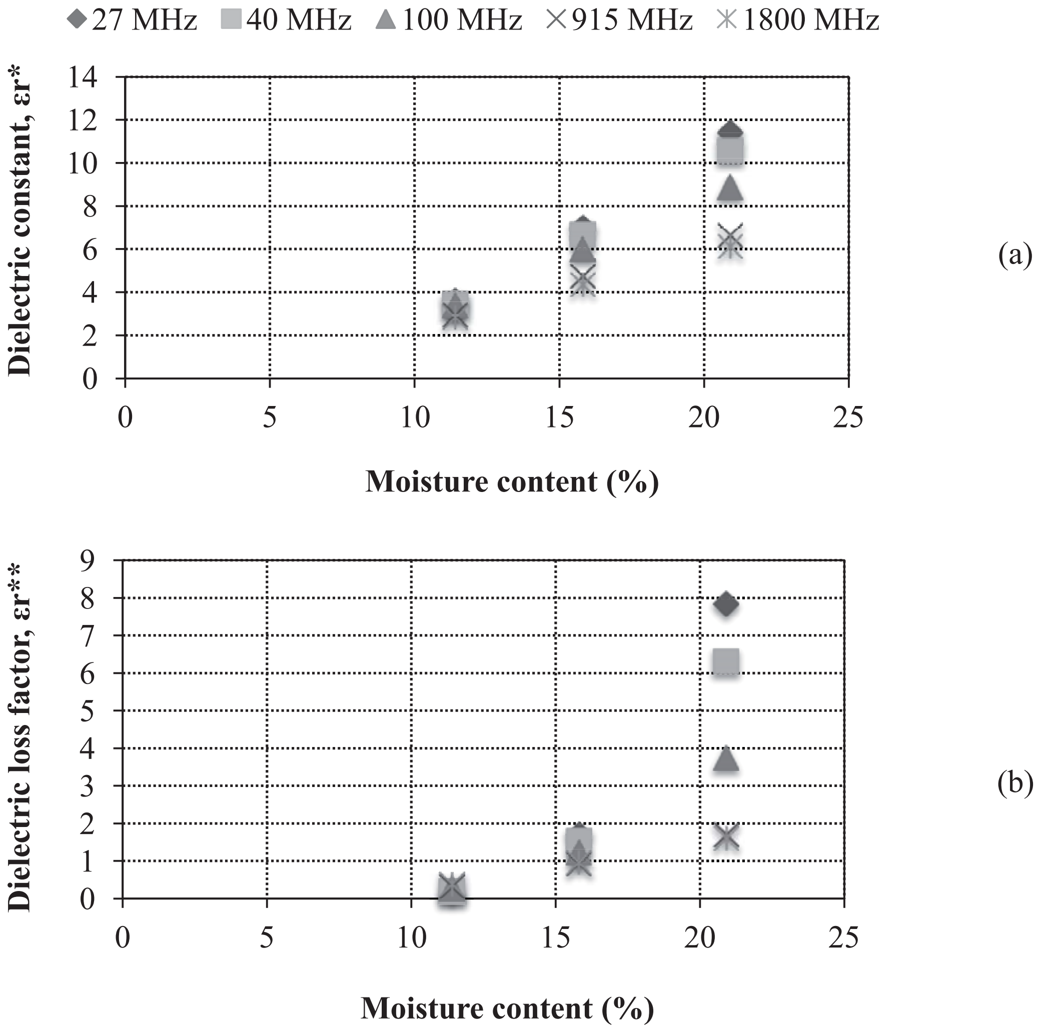


Figure 10: The dielectric constant (a) and loss factor (b) of chickpea flour at temperature 50 ° C (Guo *et al.*, 2008)

2.4.4. Density

Nelson and Stettson (1976) suggested that the bulk density and the kernel density of wheat are highly correlated to the moisture content. In another study conducted by Sokhansanj and Nelson (1988), it was also declared that the bulk density has a major influence on the dielectric constant but a lesser influence on the dielectric loss factor (Table 3). The bulk density and moisture on hard red winter wheat grain can be used to calculate the value of dielectric constant and dielectric loss factor at 2.45 GHz by using the Eq. 10 and 11 with the standard error of 1.419

and 0.060, respectively. The increase in moisture content will increase the kernel volume and then will cause the decrease in bulk and kernel density.

Table 3: The dielectric constant and loss factor of hard red winter wheat at frequency 2.45 GHz

MC (%)	Kernel density (g/cm^3)	Range of bulk density (g/cm^3)	ε_r^*	ε_r^{**}
10.4	1.429	Low: 0.764	2.55	0.26
		High: 0.860	2.90	0.30
14.5	1.399	Low: 0.722	2.84	0.42
		High: 0.829	3.29	0.51
18.2	1.383	Low: 0.719	3.39	0.69
		High: 0.824	3.94	0.75

(Sokhansanj and Nelson, 1988)

$$\varepsilon^* = \left\{ \frac{\rho \times (MC + 11.4)}{43.3} + 1 \right\}^3 \tag{10}$$

$$\varepsilon^{**'} = -0.08 + (5.07 \times M \times \rho) \tag{11}$$

where:

MC = the moisture content (wet basis) [%]

2.4.5. Other factors

The size would influence the dielectric properties of a material. The dielectric constant and loss factor of wheat grain sizing 4.19 x 2.29 x 1 cm (L x W x H) at frequency 10.365 GHz were about 2.43 and 0.66, respectively. In comparison, the dielectric constant and loss factor of *T. confusum* sizing 1.27 x 2.29 x 1 cm (L x W x H) at frequency 10.02 GHz were about 14.3 to 18.4 and 2.15 to 4.05, respectively (Hamid *et al*., 1968).

The dielectric constant and loss factor of *Sitophilus oryzae L*. (rice weevil) at frequency 9.4 GHz and temperature 24 °C were 31.5 and 2.7, respectively (Nelson and Stettson, 1976). Thus, the dielectric properties vary among the insect species.

Despite the information about the moisture contents is still incomplete, there is some evidence, however, that the moisture content of insect is higher than that of wheat grains. Nelson and charity (1972) had determined that the moisture content of *S. oryzae L*. was about 49 %. Therefore, the higher amount of moisture content in the insect body probably contributes to the higher level of its dielectric properties and later will benefit for the higher mortality rate.

The dielectric properties of fruits are also influenced by their structural parts. For instance, the inner orange peel layer has lower values of the dielectric constant and loss factor in comparison to the peel layer (Birla *et al*., 2008). These factors influencing the dielectric properties of a material are highly integrated to the others.

2.5. The potential of using microwave energy for insect control

There are many studies, which are conducted to find the potential of using MW energy in controlling the insect pest. Under the MW heating at frequency 2.45 GHz and power 600 W, the required time for 90 % mortality of *Tribolium confusum* (the confused flour beetle), *Sithopilus granaries* (granary weevil), and *C. ferrugineus* in wheat was about 30, 30, and 18 s, respectively (Hamid *et al*., 1968). At the same frequency and power of 0.0017 kWh/kg, about 100 % mortality of *S. oryzae L.* was obtained when the temperature of rice was above 55 ° C (Zhao *et al*., 2007).

The mortality of *T. castaneum* adults along with 50 g wheat with 3 level moisture contents (14, 16 and 18 %) reached 100 % after exposing in the MW heating at frequency 2.45 GHz, where the powers were 400 and 500 W for 56 and 28 s, respectively (Vadivambal, 2009). Lu *et al*. (2010) investigated that the MW heating at frequency 2.45 GHz can be used to kill the *T. castaneum* adults at a lower temperature than the conductive heating. In the further study, Lu *et al*. (2011) pointed out the detail effects of MW energy that probably caused the insect death, i. e. causing the destruction in epidermis, reducing and aggregating the fat body, leading to the appearance of a large cavity in the nucleus, and leading to the disappearance of mitochondria and Golgi bodies.

Singh *et al*. (2011) studied the mortality of *Callosobruchus chinensis L.* (the pulse beetle) under MW heating at frequency 2.45 GHz on 200 g of chickpea, pigeon pea and green gram, respectively (Table 4). The higher the power given led to the higher the temperature and the shorter the time needed to reach 100 % mortality of the beetles. The treatments did not change the cooking time significantly. Nevertheless, the heating was significantly reduced the viability and the germination of the seeds at probability of 5 %. For example, in the case of Cheakpea, by using the power 280, 420, and 700 W, the viability reduced from 98 to 86, 77 and 57 %, respectively, while the germination decreased from 97 to 87, 78 and 54 %, respectively. Those reductions were caused by the high temperature treatment at level 50, 65, and 80 °C, respectively.

Table 4: The time needed and quality affected to reach 100 % mortality of *Callosobruchus chinensis L.* under MW heating at different power levels and products

Products	**Power** (W)	**Temperature** (°C)	**Time** (s)	**Viability** (%)	**Germination** (%)	**Cooking time** (min)
Cheakpea	700	80	100	57	54	33.1
	420	65	200	77	78	34.5
	280	50	240	86	87	36.5
Control				98	97	39.6
Pigeon pea	700	80	90	53	64	21.9
	420	65	180	76	76	20.1
	280	50	240	69	86	20.7
Control				97	98	22.3
Green gram	700	80	70	62	78	15.2
	420	65	160	78	82	12.5
	280	50	240	87	87	13.3
Control				98	98	14.1

(Singh *et al*., 2011)

2.6. The quality of wheat flour

The end utilization of wheat is based on flour, and therefore, it is necessary to determine the flour quality. The main components of flour quality are moisture, protein, starch, damaged starch, water absorption, viscosity, enzymatic activity, granulation, grain hardness, minerals, color, responses to additives, nutritional fortification, rheological properties, and bread performance (Mailhot and Patton, 1988). Several traits that are commonly used for the flour quality assessment are moisture content, starch, Falling Number (FN), flour viscosity, damaged starch, gluten content, dough properties as well as baking properties (Pawelzik, 2010).

2.6.1. Moisture content

Moisture content of flour is important for making bread and it is related to the dough water absorption. Usually high water absorption values are desirable because they lead to the maximum loaf volume after baking. Water absorption is defined as the amount of water required to yield a dough of predetermined consistency and it can be measured by using the farinograph. The particle size has been proposed as a responsible factor influencing the water-holding capacity (Mailhot and Patton, 1988).

2.6.2. Starch

Starch is a polysaccharide consisting of amylose, a linear compound, and amylopectin, a branched component and is found as a storage carbohydrate in plants (Pawelzik, 2010 and deMan, 1999). It occurs as small granules with the size range and appearance characteristic to each plant species (deMan, 1999). Wheat composition is dominated by starch content ranging from 63 to 76% (McCance *et al.*, 1945). Since wheat is primarily used to produce flour for making bread, the importance of starch for bread quality would be pronounced.

2.6.3. Falling number

Falling Number (FN) is a useful tool in evaluating the quality of grains and other agricultural products containing starch and malted products. As it is firstly developed by Harberg in 1960, the name for this method is also known as Harberg Falling Number (HFN). The FN is defined as the time in seconds required to stir and to allow a viscometer stirrer to fall a measured distance through a hot aqueous flour gel undergoing liquefaction (Anonymous, 2005). The minimum value possible is 62 (Kettlewell and Adam, 1999).

2.6.4. Flour viscosity

The maximum viscosity can be used to estimate the enzyme activity i.e. α-amylase. The factors that influence the viscosity are starch and damaged starch (Mailhot and Patton, 1988).

2.6.5. Damaged starch

The damaged starch is the fraction from the native starch and it plays an important role in governing the performance of bread. The level of damaged starch is also related to kernel hardness and it can be controlled by tempering process and grinding practices. Normally, break flours have the least damaged starch, whereas the middlings flours have the most (Mailhot and Patton, 1988). The possibility to produce damaged starch by mechanical operation is because the starch has semicrystalline structure. The important of damaged starch is due to its high ability to absorp water at 5 to 10 times higher than the native starch (Dubat, 2004).

2.6.6. Gluten content

Determination of gluten content is employed to determine the quantity as well as the quality of protein. Gluten protein is the composite of glutelin and prolamin. Glutenins are the most common gluten proteins and they appear to contribute mixing time, strength, and elasticity, whereas gliadins are the wheat prolamin and contribute the extensibility and stickiness. Thus, gluten protein are essential for the bread production (Mailhot and Patton, 1988).

2.6.7. Dough properties and baking test

The dough properties are determined by using farinograph and the results are used for the dough ingredients in baking test. Farinograph results consist of water absorption, development time, stability and degree of softening (Pawelzik, 2010). The microbaking procedure was developed to evaluate the baking properties (Dubat, 2004). The advantages of the method are quite reproducible and very sensitive to the changes in flours and formulations (Hoseney *et al*., 1988). The baking properties are loaf volume, shape, crust color, crumb structure and crumb texture (Pawelzik, 2010).

III. Materials and methods

The research was conducted from February 2009 until February 2011 at the Section of Agricultural Engineering, Department of Crop Sciences, Faculty of Agriculture, Georg-August University Goettingen, Germany.

3.1. Laboratory microwave applicator

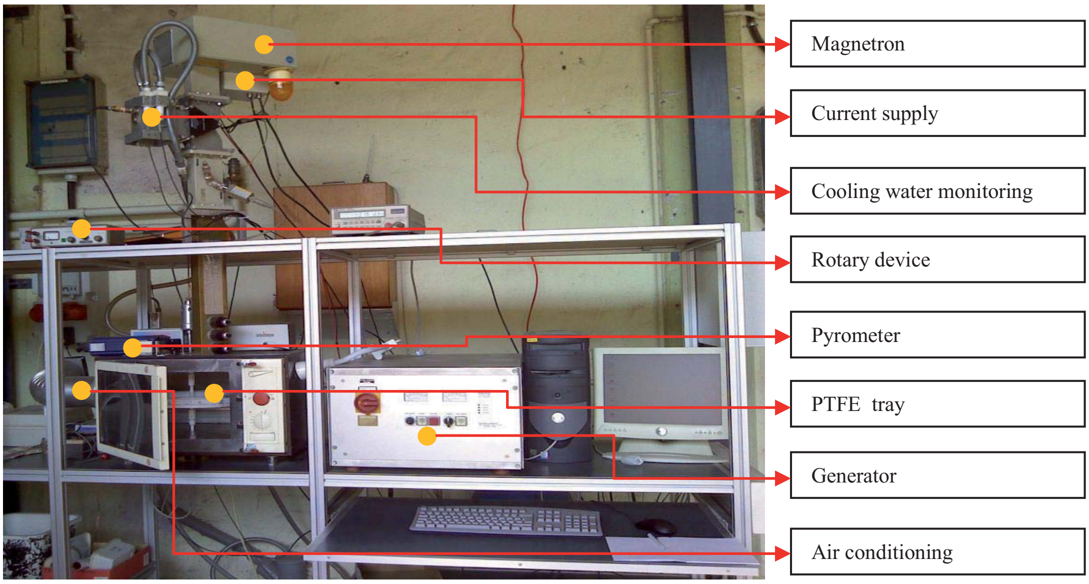


Figure 11: The MW applicator used in the experiment

A laboratory MW applicator batch system with the frequency of 2.45 GHz was used in this research, which is illustrated in Figure 11. The volume of its cavity was about 27 *l* (34.5 x 22.5 x 34 cm). The MW applicator has the power capacity between 120 and 1200 W and its power is operated continuously from its magnetron, as it is required for running an experiment. Therefore, the MW applicator is totally different from the domestic oven MW because the domestic oven MW is the multimode type, which works under frequency shift and damping pattern (Metaxas and Meredith, 1993).

The MW has a standard waveguide (R-26) coupled vertically into the resonant chamber and the electromagnetic waves are reflected into this chamber. A very low reflected energy in the space could damage the magnetron, thus a water flow system is integrated to the waveguide to absorb the reflected energy. Furthermore, the waveguide is also equipped with a directional coupling to detect the amount of reflected power. A power can be adjusted, and the phase and the wave ratio can be controlled as well. Those variables are important to optimize the MW application system (von Hoersten, 1995).

It has a ring-shaped tray made from polytetrafluor-ethylene (PTFE) with the internal and external radius of 10 and 15.5 cm, respectively. The height of the tray can be adjusted. The tray is connected to a rotary device thus there is a possibility to manage the speed of tray rotation. The tray is also integrated with a balance to measure the sample weight during the experiment accurately.

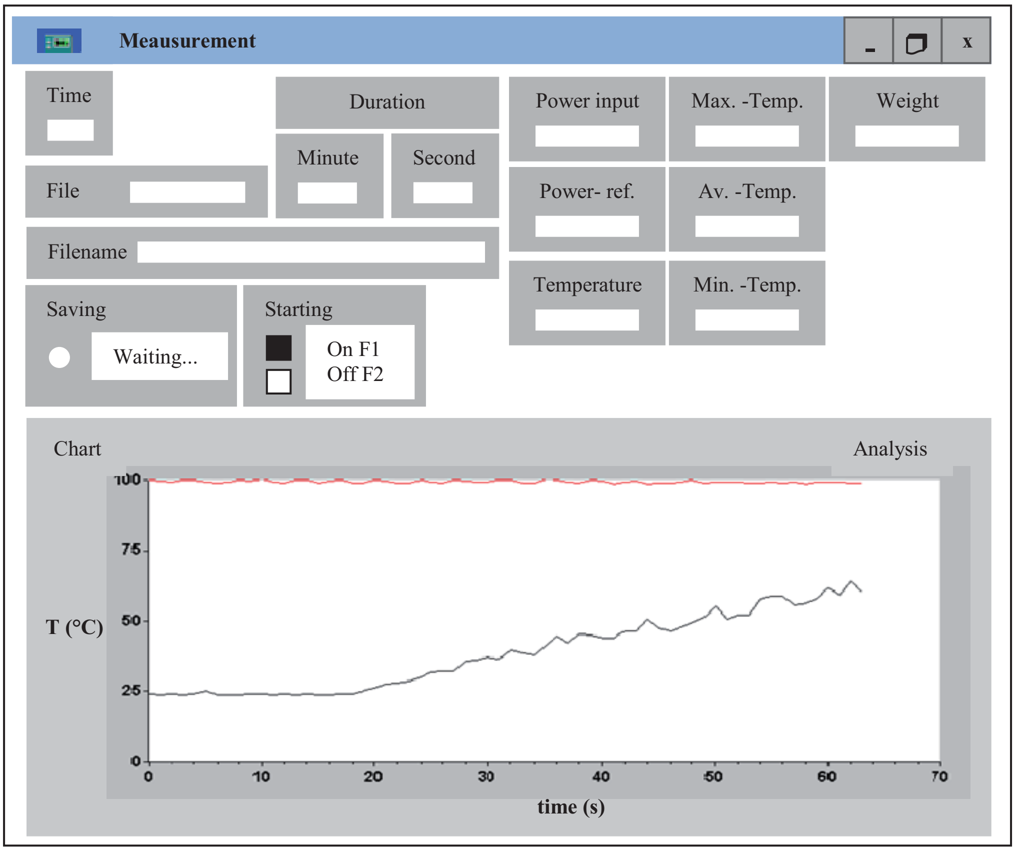


Figure 12: A control system screen display

An infrared radiation pyrometer (Heimann KT 19.82) was installed at an opening on the top of the cavity to measure the temperature on the product surface during the MW heating. The diameter of its lens is about 8 mm, thus the pyrometer will read the temperatures in diameter of 30 mm. The MW system is also associated with computer. The measured data were the temperature (maximum, minimum, and average), power (input and reflected), the time and the sample weight. All data were recorded per each 10 s and a control system screen display can be seen in Figure 12 (p. 25).

3.2. Materials

3.2.1. Grain preparation

Soft winter wheat c.v. Kranich harvested in 2009 was used in this study. The moisture contents of wheat grains were adjusted at 3 levels, 10, 14, and 18 %. Firstly, the moisture was measured by drying about 2 to 3 g of grounded grain at 130 °C for 8 h in a drying oven (Multon and Martin, 1988). The initial moisture ranged approximately from 12.5 to 13 %. The moisture content was estimated from the initial and final weights of the samples based on wet basis (wb) (Eq. 12).

$$MC = \frac{W_1 - W_2}{W_1} x100\% \tag{12}$$

where:

MC = the moisture content in wet basis [%]

W_1 = the initial weight [g]

W_2 = the final weight [g]

To have the sample at moisture 10 %, about 1500 g of grains were placed in stainless steel container and then dried in a climate chamber at 30 °C for about 2 days. The weight of the grains was controlled until the expected weight and the final moisture was measured (Eq. 13). On the other hand, to have the sample at moisture 14 and 18 %, about 650 g grains were placed in a 1000 ml polyethylene (PE) bottles. The amount of distilled water needed to improve the moisture was calculated by using the Eq. 13. The water was added to the grains by using a hand sprayer. The bottles were shaken by using an overhead shaker for 5 h and were transferred into the cold storage at temperature 4 °C to let the moisture equilibrium. After 2 days, the final moisture was measured again. If the final moisture was lower or higher than the desired moisture content, the same procedure was repeated to improve the results. The moisture content was controlled with the accuracy of ± 0.2 %.

$$W_1 \times (100 - MC_1) = W_2 \times (100 - MC_2) \tag{13}$$

where:

MC_1 = the initial moisture content [%]

MC_2 = the desired moisture content [%]

3.2.2. Insects preparation

From the literature review in Subchapter 2.1.2 (pp. 6-7), the insect can be reared at temperature ranging from 25 to 35 °C and at humidity ranging from 50 to 70 %. The average temperature 28 °C and the most humid environment 70 % were chosen for this study. Under this defined environment, it is expected to have the optimum population growth as well as the moderately development time.

A preliminary trial on rearing the insect was conducted on 2 diets, rolled oats and ground wheat. About 20 parental insects (n=15) were put on 25 g diets in glass jar for 10 days. It was found that the average number of new generation, which was calculated on the 30th day from the infestation day, was 169±38 and 356±89 in ground wheat and rolled oats, respectively. Later, rolled oats were chosen as the medium for rearing the insects with expectation to have a higher insect population. Moreover, the harvesting of the insects in rolled oats was also easier than the harvesting of the insects in ground wheat.

About 100 insects were cultured in a glass bottle filled by 19 g rolled oats and 1 g yeast. Six bottles were prepared and transferred to a climate chamber at 28 °C and 70 % r.h. The whole rearing process was in darkness. After 10 days from the infestation, the parental generations were removed from each bottle. The larvae were collected from the bottles on the 10th and 20th day, whereas the new adults were collected on the 35th and 46th day. It is difficult to collect the pupae because they are usually located under the cracks. Therefore, about 10 larvae were kept directly with 6 g grain in plastic wrap and transferred back to the climate chamber for 10 days to let them develop into pupae stage.

3.3. Study on heating uniformity

3.3.1. Experimental design

The measurement of product temperature during MW application is difficult to perform (von Hoersten, 1995). The measurement of product temperature in the present study was based on the surface grain temperature. Two sets of experiments were run. The first experiment was designed for 5 min exposure time under 3 levels of grain moistures (10, 14, and 18 %) as well as 3 levels of grain surface temperatures (45, 50, and 55 °C). While the second experiment was run at grain surface temperature of 50 °C, with 3 levels of grain moisture (10, 14, and 18 %) and 4 levels of exposure time (0, 1, 3 and 5 min). The experiments were done by 2 replications for each heating (Figure 13).

MC_i (%)	**Temperature (°C)**		
	45	**50**	**55**
10	**X**	**X**	**X**
14	**X**	**X**	**X**
18	**X**	**X**	**X**

(a) MW heating at 5 min exposure time

MC_i (%)	**Time (min)**			
	0	**1**	**3**	**5**
10	**X**	**X**	**X**	**X**
14	**X**	**X**	**X**	**X**
18	**X**	**X**	**X**	**X**

(b) MW heating at temperature 50 °C

Figure 13: The experimental design for two experiments (a, b)

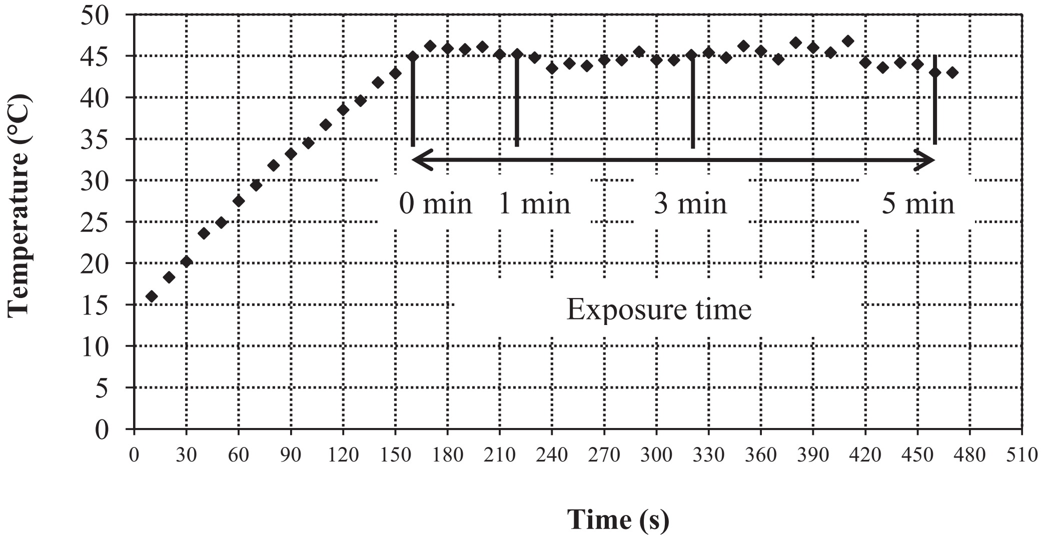


Figure 14: The temperature profile of MW heating for the treatment at temperature 45 °C

Figure 14 shows about the MW heating process. The initial temperature of the product was low ranging from 7 to 20 °C, and then it was increased to the desired temperatures (45, 50 and 55 °C) as it was proposed in the experimental design. The temperature profile of MW heating consists of 2 periods, that is, the period of temperature increase at constant power 300 W and the period of constant temperature by controlling the power. The starting point of exposure time was counted after the desired temperature was reached immediately. As it can be seen in Figure 14, the initial temperature is 16 °C and the desired temperature is 45 °C. The time needed to increase the temperature from 16 to 45 °C is about 160 s. Therefore, the starting point for the exposure time assumption is 160 s, while the 1, 3, and 5 min exposure time are counted at 220, 320, and 460 s, respectively.

3.3.2. Procedures

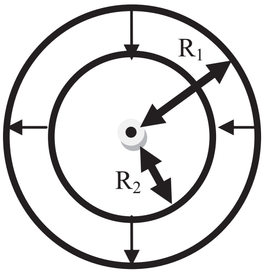
About 300 g grains were filled on the tray. Before the tray was transferred into the MW cavity, an image was taken by using the infrared camera. The speed of tray rotation was set at 19 rpm. The initial temperature ranged from 9 to 20 °C. The MW was operated at power 300 W to reach the desired surface temperature, and then to enhance the temperature profile at the desired level for a certain desired period, the power was controlled. Sometimes the power had to be reduced, and sometimes it had to be increased but it was controlled to be not higher than 300 W. The MW treatments were run following the experimental design in Figure 13 (p. 28). After the MW heating, another image was taken by using the infrared camera immediately. The treated grain samples were kept in the plastic at temperature 4 °C until the quality assessment.

3.3.3. Determination of the linearity of the temperature increase

According to Wang *et al*. (2005), the increase of mean and standard deviation of temperature is expected to be linear in order to meet the procedure for the uniformity index calculation. They measured the temperature increase by using the infrared camera at a 3 min interval. However, the temperature data in this study were measured by using an infrared radiation pyrometer during the treatment completely. Therefore, the temperature increase is determined to be linear if the curve of the temperature increase follows a straight-line. The linearity relationship of temperature and time is considered by using the correlation coefficient, that is, a square root of the coefficient of determination (R^2). The linearity relationship is highly significant if the correlation coefficient closes to 1 or -1, while the linear relationship is insignificant if the correlation coefficient closes to 0.

3.3.4. Determination of temperature range on the image

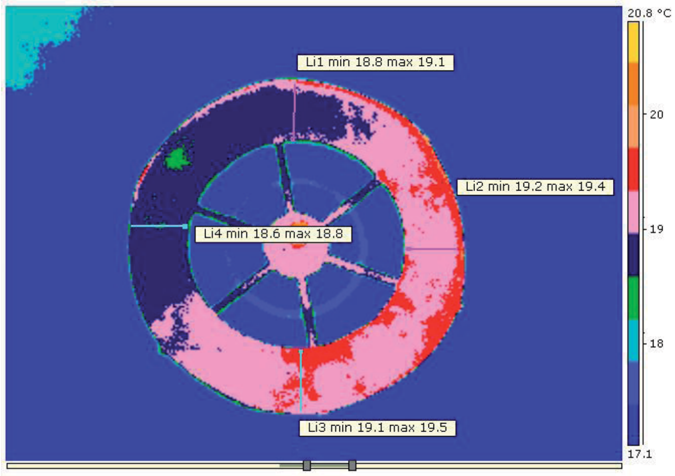
The analysis of temperature distribution on the images, which was captured by using a thermal infrared camera, was done by using FLIR quick report software. However, the software can only analyze the temperature distribution in a square area. Since the PTFE tray was in form of a ring (Figure 15), the analysis cannot be run directly inside the FLIR quick report software. The determination of temperature range becomes important and there is an idea to analyze the temperature distribution later by using the Microsoft Excel.



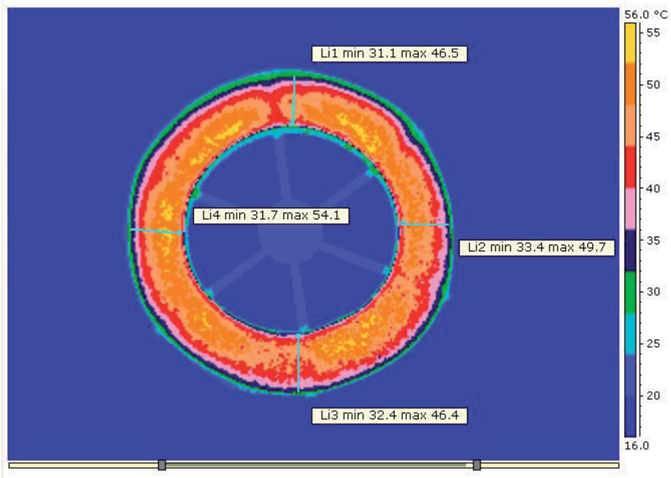
R_1 : external radius, (15.5) [cm]
R_2 : internal radius, (10) [cm]
→: line

Figure 15: The schematic view of tray

Several steps were done to have a precise decision on the temperature range inside the ring. First approach was done by drawing 4 lines inside the ring at 4 directions (Figure 15). Each line presented the information of the minimum and maximum values of data temperature through the line. Secondly, under the setting of isotherm and alarm tools, the area inside the ring can be isolated from the area outside the ring based on the temperature difference. The same as the line function, the isotherm and alarm tools will give the information about the minimum and maximum temperature. Based on this information, the data range for the temperature was determined. From a number of available palettes, medical palette was used to display the image because this palette could distinguish between the 10 colors clearly (Figure 16). After knowing the data range inside the ring, the image was cropped and exported into excel sheet, thus the temperature data were shown in detail at each pixel.



(a) Before MW heating



(b) After MW heating

Figure 16: The infrared image with medical palette before (a) and after (b) MW heating at surface temperature 45 °C, wheat moisture 10 %, and 5 min exposure time

3.3.5. Determination of temperature distribution

By using the logical function (IF), the experimental temperature data on the excel sheet were selected based on the temperature range, which was defined earlier in previous subchapter. Afterward, the descriptive statistics of the selected temperature data were determined, i. e. the mean value, the standard deviation, and the maximum and minimum value. The probability density frequencies (PDF) of the experimental temperature distribution were also studied by using the statistical function (PERCENTRANK). The PDF for normal temperature distribution was calculated by using Eq. 14. The experimental and normal temperature distributions were then plotted on a chart. If both curves matched each other, the experimental temperature was defined as a normal distribution.

$$PDF = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (14)$$

where:

PDF = probability density frequency

π = the mean temperature [°C]

σ = the standard deviation [°C]

x = the individual temperature [°C]

e = a mathematical constant, the unique real number (2.718)

3.3.6. Determination of uniformity index

Wang, *et al*. (2005) determined that the uniformity index is a unique parameter derived experimentally from the temperature measurement. Two fundamental assumptions should be met to allow the calculation of uniformity index, those are, (1) a linear relationship between the rise in standard deviation and the rise in mean temperature to the heating time, and (2) a normal distribution of the product temperatures. The uniformity index was calculated by using the following equations.

$$\Delta\mu = \mu_t - \mu_0 \quad (15)$$

$$\Delta\sigma = \sqrt{\sigma_t^2 - \sigma_0^2} \quad (16)$$

$$\lambda_{ui} = \frac{\Delta\sigma}{\Delta\mu} \quad (17)$$

where:

$\Delta\mu$ = the rise of mean of surface temperature [°C]

$\Delta\sigma$ = the rise of standard deviation of surface temperature [°C]

μ_o = the mean temperature of the initial image [°C]

μ_t = the mean temperature of the final image [°C]

σ_o = the standard deviation of the initial image [°C]

σ_t = the standard deviation of the final image [°C]

λ_{ui} = the uniformity index

3.3.7. Determination of hot and cold spot areas

A great importance in using the MW application is the evidence of hot and cold spots as a consequence of irregular temperature distribution. Alcolado *et al*. (2011) determined that the hot spots were the localized region of high temperatures. Therefore, in opposite to this definition, the cold spots can be defined as the localized region of low temperatures. Tang *et al*. (2007) suggested avoiding both hot and cold spots since they contributed to the loss of product quality. Moreover, the presence of cold spot will reduce the effectiveness of dielectric heating in controlling the pest.

In the present study, the hot and cold spot areas would be determined as the area that is higher and lower than one standard deviation of the mean, respectively. The mathematical expressions can be written as following equations (Eq. 18 and 19). The plot for a normal distribution is shown in Figure 17. The quality of the heating uniformity will be evaluated as the smaller the percentage of hot and cold spot areas.

$$Hot\ spot\ area > \mu + \sigma \tag{18}$$

$$Cold\ spot\ area < \mu - \sigma \tag{19}$$

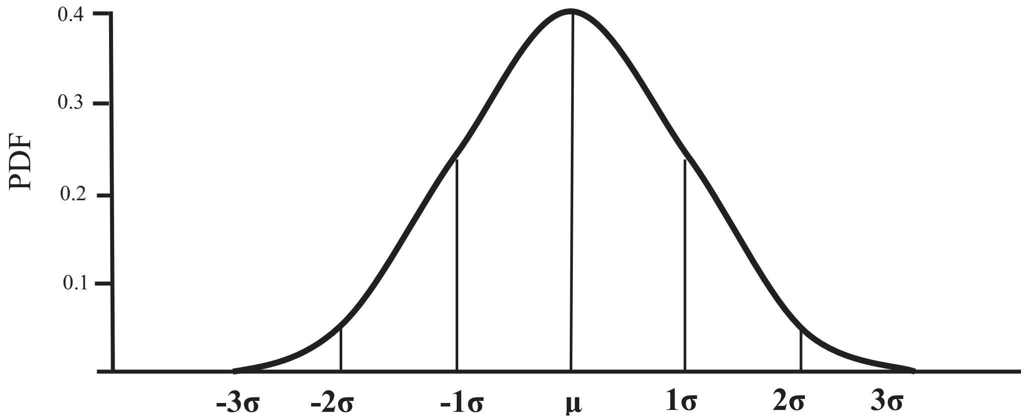


Figure 17: A plot of a normal distribution

3.4. Study on the mortality of *Oryzaephilus surinamensis*

3.4.1. Experimental design

In a preliminary research, which was conducted by using a drying oven (Figure 18), it was found that the lethal temperature to control adult stage of *O. surinamensis* was 50 °C for the exposure time longer than 5 min. However, at temperature 55 °C, the time needed to control the insects was reduced to 3 min. In addition, about 93 and 100 % of larvae died after 1 min exposing in the oven at temperature 55 and 60 °C, respectively. In contrast, only 10 % of adult died after 1 min exposure time at temperature 60 °C.

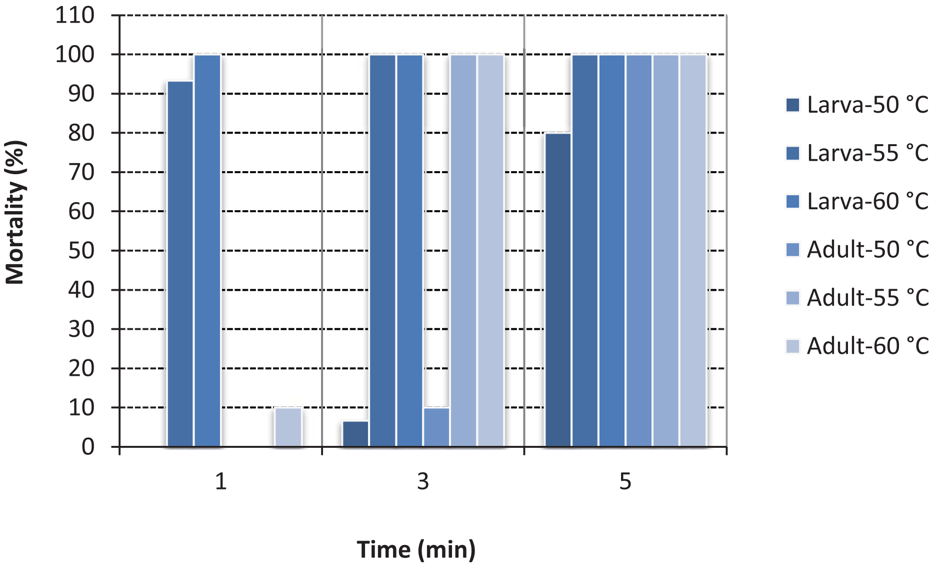


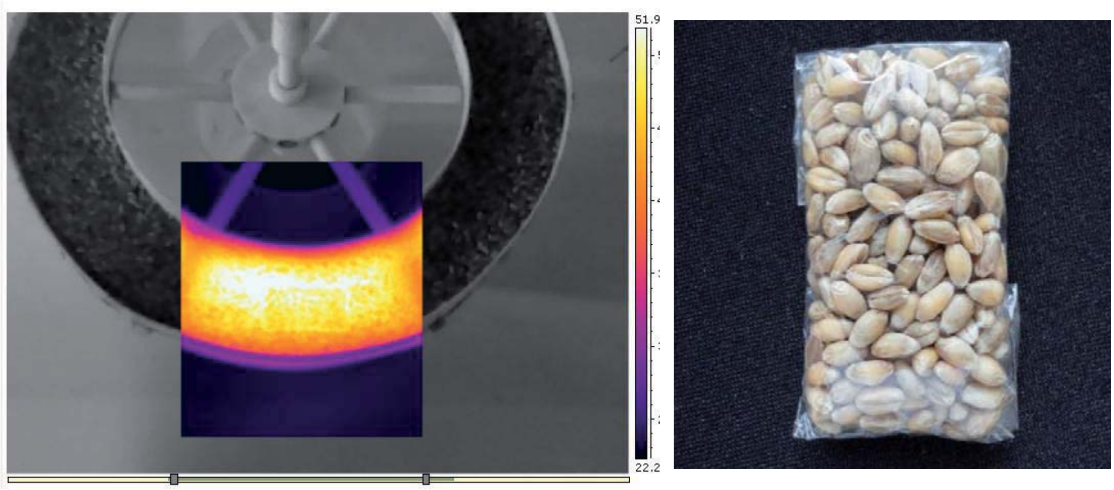
Figure 18: The mortality of larva and adult of *Oryzaephilus surinamensis* under heat treatment by using drying oven

According to this result, the experiments were designed as it was used for the study of temperature distribution shown in Figure 13 (p. 28). The experiments were conducted by 2 replications with the infestation of 60 individuals of *O. surinamensis* at different life stages separately. The study was conducted on larva, pupa and adult stage.

3.4.2. Procedures

3.4.2.1 Binding grains and insects with plastic wrap

As it was described in the literature review, the insects are small, highly mobile, and could hide in many places. From number of trials, a method by binding the insect and grain in plastic wrap was chosen (Figure 19b). Previously, the binding of the insects and grains in plastic wrap was convinced by the temperature evaluation by using a thermal infrared camera. It was found that there are no differences of temperature in the area with and without the use of plastic wrap to bind the grain (Figure 19a). Biglari *et al*. (1982) found that under MW heating, the temperatures of wrapped and unwrapped samples by a commercially available Saran Resin that is resistant to temperatures up to 143°C were similar and did not show a consistent pattern of differences. Therefore, it was concluded that the method was valid to be used.



(a) The infrared image

(b) The binding grains

Figure 19: The infrared image of grain in plastic wrap (a) and the photo of the binding grains

As can be seen in Fig 19b, about 10 adults and larvae were packed by using plastic wrap with 6 g grains, separately, and were treated in the MW heating following the experimental design. While for preparing pupae (Subchapter 3.2.2), about 10 larvae were covered with 6 g grain by using plastic wrap and then transferred to the climate chamber for 10 days in order to let them grow into pupae.

3.4.2.2 Microwave treatment

About 6 packs of binding grains along with un-binding grains were filled on the tray to reach the total weight of 300 g. The tray was then transferred into the MW cavity and the speed of tray rotation was set at 19 rpm. The MW was operated at power 300 W to reach the desired surface temperature, and then to enhance the temperature profile at the desired level for a certain desired period, the power was controlled. As soon as possible after the MW heating, the insects were transferred to the aluminium container at room temperature.

3.4.2.3 Determination of mortality

The mortality of adults was determined every day for 2 days after MW heating, while the mortality of larvae and pupae was determined every 2 day for 10 and 20 days, respectively. During this period, the insects were transferred to the climate chamber at temperature 28 °C and 70 % r.h. The signal for the mortality of adult is the mobility, thus an adult insect is considered to be died when there is no movement observed even after prodding it with a fine brush. The signals for the mortality of larvae and pupae are the development stage and the color changes. Larvae and pupae were assumed to be died when there is no development stage, or when the color of larvae and pupae turn to black, or when the molds grow on their body.

3.4.2.4 Statistical analysis

If the mortality in control was higher than 10 %, the Schneider-orelli formula (1947) was used as the correction procedure (Eq. 20). The analysis of variance (ANOVA) was run at confidence interval 95 % by using general linear model (GLM). If there is a significant influenced of the MW heating to the mortality, the least significant difference (LSD) t-test was used to show the significance differences at probability 5 %.

$$M_{corr} = \left(\frac{M_{\exp} - M_{cont}}{100 - M_{cont}} \right) x100\% \tag{20}$$

Where:

M_{corr} = the correction of mortality [%]

M_{exp} = the mortality in the experiment [%]
M_{cont} = the mortality in control [%]

3.5. Study on germination rate

3.5.1. Procedure

In order to analyze the grain quality, the germination test was carried out following the procedure from International Seed Testing Association (ISTA, 1999). Hundred seeds were distributed in 2 arrows of folded filter paper (50 x 33 cm) and saturated with 30 ml of distilled water. The paper was sealed in the plastic container and incubated at 25 °C. Three replications were applied for each MW heating following the experimental design in Figure 13. The test was also conducted for control at all moisture levels. The germination percentage was measured on the 4th and 8th day. The 4th day counting indicates the seedling vigor and germination energy while the 8th day counting showed the overall effect of the MW heating to the germination rate.

3.5.2. Statistical analysis

The ANOVA at confidence interval 95 % was run by using the GLM. If there is significant influence of MW heating to the germination rate, the LSD t-test was used to show the significance differences at probability 5 %.

3.6. Analysis on flour quality

3.6.1. Experimental design

The flour quality analyses were conducted on the flour milled from treated grains following the schedule in Figure 20.

MC_i (%)	**Temperature (°C)**		
	45	**50**	**55**
10	**X**		**X**
14			
18	**X**		**X**

(a) MW heating for 5 min exposure time

MC_i (%)	**Time (min)**			
	0	**1**	**3**	**5**
10	**X**			**X**
14				
18	**X**			**X**

(b) MW heating at temperature 50 °C

Figure 20: The experimental design for the quality assessment

Since the sample flour cannot be produced from the grain at initial moisture 18 %, the control was prepared at initial moisture 10 % (C10) and 12.5 % (C12.5). The samples for the quality analysis were milled to the size of 0.5 mm, in exception for the Falling Number (FN) analysis; the grains were milled to the size of 0.8 mm.

The samples were prepared from 3 replications of each MW heating because it was estimated that the effect of irregular MW temperature distribution will influence the flour quality. Following the procedure in the laboratory, 2 repetitions were applied for each sample, which was controlled to have the mean different less than 5 %. If the mean difference is higher than 5 %, the third or more repetition was recommended to improve the accuracy of measurement, but only the best fixed two data were chosen for the calculation.

The parameters observed by 2 repetitions were starch content, Falling number (FN), viscosity, and gluten content. As an exception, 3 repetitions were used in determining the damaged starch level. Finally, since the amount of sample needed for the micro-scale baking test was a lot, the samples from different MW replications were mixed and kept in desiccators for a week to assure the uniformity of moisture. Two repetitions were applied on these samples for the determination of dough properties and loaf volume.

3.6.2. Determination of starch content

Starch content was determined following the ICC-Standard No. 123. The apparatus and reagents used were polarimeter, water bath, 100 ml volumetric flasks, funnel, filter paper, 593.5 erlenmeyer flasks, 1.124 % hydrochloric acid (HCl), 10 % *wolframatophosphoric acid*, and distilled water. About 2.5 g of flour and 25 ml HCl were placed in a 100 ml volumetric flask and shaken to obtain the solution, and then further 25 ml HCl was added without shaking. The flasks were immersed in a boiling water bath for 15 min where they were shaken vigorously and steadily for the first 8 min to avoid the formation of agglomerates. The cold water was added until the volume of 90 ml and cooled immediately at the room temperature. Then about 5 ml of *wolframatophosphoric acid* was added and shaken again. The distilled water was added until the 100 ml line, mixed and then filtered into the volumetric flasks. The optical rotation of the filtrate was measured with the polarimeter at 589 nm, which is equal to the D-line of sodium.

$$d = \frac{\alpha}{[\alpha]_c^{20} \times l} \tag{21}$$

$$S = \left(d \times V_{ext} \times \frac{100}{W} \right) \div \frac{DM}{100} \tag{22}$$

where:

d = the concentration of solution [g/ml]

α = the optical rotation of the solution

$[\alpha]_c^{20}$ = the optical rotation of wheat at temperature 20 °C and c concentration (182.7°)

l = the polarimeter tube length (1.901) [dm]

S = the starch content in dry matter [%]

V_{ext} = the extraction volume (100) [ml]

W = the sample weight [g]

DM = the dry matter [g]

3.6.3. Determination of falling number

FN was determined by using ICC-Standard No. 107/1. The instruments used were FN apparatus consists of boiling water bath and micro switch counter, viscometer tubes, rubber stoppers, 25ml-pipette, and balance. The material used was distilled water. The sample was weighed based on 7 g sample at moisture 14 % and then transferred into viscometer tubes. Two repetitions were applied, 25 ml of distilled water was added to the tube and the tube was fitted by the rubber stopper and shaken vigorously to obtain the uniform suspension. Then the stopper was removed and any slurry coating in the upper part of tube was scraped down by using the viscometer stirrer. The tube was put into the boiling water bath. The test was started immediately by pushing the start button, and after 5 s the viscometer stirrer was picked up and down at rate 2 stirs per s for 55 s. At the last picking, the stirrer was placed at the upper position and locked. The stirrer was led to drop under its own weight and the micro switch signaled the completion of the test and noted the total time of FN. The viscometer tube was removed and washed immediately in cold water. The test must be conducted as soon as possible after having the suspension approximately within 30 to 50 s.

3.6.4. Measurement of flour viscosity

The viscosity was measured by using a Rapid Visco Analyzer (RVA). The method applied was the Newport Scientific Method 10, December 1997. The RVA is a microprocessor controlled instrument that is able to apply variable temperatures and shear rates of a sample whilst continually monitoring the viscosity of the sample. The measurement of flour viscosity is based on its starch behavior under heat treatment to gelatinize and to change its viscosity. The standard profile applied was mixing at speed 960 rpm over 1 min and later it was reduced to 160 rpm for the whole process, heating at temperature 50 °C for 1 min, heating up to 95 °C over 3 min 42 s, holding at 95 °C for 3 min 30 s, and cooling down to 50 °C in 3 min 48 s. The whole process needs time for about 13 min.

The samples were weighed with the standard of 4 g at 14 % moisture. The comprehensive results from the test were pasting temperature (T_{past}), peak time (t_{peak}), peak viscosity (PV), holding viscosity (HV), breakdown viscosity (BV), final viscosity (FV), and setback viscosity (SV). The units for the viscosity properties were Rapid Visco Unit (RVU).

3.6.5. Determination of damaged starch

The method applied was the rapid non-enzymic modified of McDermott method (1980). The equipments used were 100 ml conical flask, water bath, pipettes, 25 ml volumetric flask, filter paper, funnel, cuvettes, photometer, ultrasonic bath, and test tubes. The material needed were trichloracetic acid (TCA), potassium thiocyanate (KSCN), iodine crystals, potassium iodine (KI), and distilled water. The solution 1 was made from 10 g TCA in 300 ml distilled water and the solution 2 was made from 30 g KSCN in 300 ml distilled water. Both solutions were kept in cool and darkness. The solution 3 was the mixture of solution 1 and 2 in the ratio 1:1, where as the solution 4 was the mixture of 0.2 g iodine crystal and 2 g KI in 100 ml distilled water.

About 0.25 g of samples and 20 ml of solution 3 were added into a dry 100 ml conical flask and then transferred into a water bath at 30 °C for 15 min to equilibrate. The flasks were put in an ultrasonic batch for 5 min to have a good dispersion. The flasks were removed again to a water bath at 30 °C completed by a shaker for 15 min. The suspensions were filtered through 11 cm diameter No.1 Whatmann filter papers into test tubes to have 6 ml of the filtrate.

About 15 ml of distilled water was prepared in 25 ml volumetric flask. Then 2 ml of filtrate was transferred to the flask, and 1 ml of solution 4 was added to the filtrate until the blue-green color perfectly occurred. Additional distilled water was added until reached the maximum volume of the flask. The solution was mixed and left in water bath at temperature of 21 °C for 10 min.

The solution was transferred to the cuvettes to measure the color density at 600 nm wave length by using spectrophotometer. The blank was prepared following the same procedure without using filtrate. The optical density (OD) of amylose-iodine complex were read in a unit of blue value (BV), which was based on fresh mater (FM) and dry matter (DM) of 1 g flour by using the Eq. 23 and 24.

$$OD_{FM} = (Es - Eb) \times K = Abs_{600nm} \times K \qquad (23)$$

$$OD_{DM} = OD_{FM} \times \frac{100\%}{DM} \qquad (24)$$

where:

OD_{FM} = the optical density in fresh matter base [BV]

OD_{DM} = the optical density in dry matter base [BV]

E_b = the extinction of the blank

E_s = the extinction of the sample

K = the correction factor for 2 ml filtrate extracted from 0.05 to 1 g samples (20)

McDermott (1980) presented the high correlation (r = 0.81) of the rapid non enzymatic method (BV) and Farrand method (FU, Farrand unit) in determining the damaged starch (Eq. 25). Thus, it is presumable to use this equation to convert the BV into the FU.

$$FU = (0.97 \times BV) + 2.1 \tag{25}$$

3.6.6. Determination of gluten content

The gluten content was investigated by using ICC-Standard No. 106/2. The apparatus used were porcelain mortar, spoon, and 10 ml-pipette, container with adjustable outflow for sodium chloride solution (NaCl), glass plates with slightly roughened surface, watch-glass, and balance. The chemical materials used were NACl solution 2 %, and iodine solution (Lugol-solution).

About 10 g of sample and 6 ml of NaCl were mixed by using spoon until a dough ball presented. Then this ball was washed out by using NaCl for 10 to 12 min until the mixture of 1 or 2 drops of the wash water and iodine solution on the watch-glass was clear. It means that the gluten was approximately starch-free. After that, the gluten was washed with the cold water for 1 min and pressed by using two glass plates several times to dry the water as much as possible. The gluten was weighed and the gluten content was calculated by using the following formula.

$$G = \frac{w_{GM} \times 100}{w_F \times \left[100 - MC\right]} \times 100\% \tag{26}$$

where:

w_{GM} = the wet gluten mass [g]

w_F = the flour mass [g]

G = the gluten content [%]

3.6.7. Micro-scale baking test

3.6.7.1. Determination of dough properties with farinograph

Following the baking procedures, it is necessary to study about the dough properties by using farinograph (Pawelzik, 2010). A Brabender unit farinograph connected to a computer was used to determine some properties of dough. The sample was weighed based on its moisture content under the basis of 50 g at 14 % moisture. The amount of water uptake was estimated for the first test and entered to the input table. The sample was stirred without water for 1 min to assure the uniformity of temperature distribution at 30 °C, and then the water was added to the dough. The development curve was computed until the degree of softening was completed. The procedure was repeated until the development curve has the consistency value at 500±20 Farinograph Unit line (FU) because the value determines the optimum water uptake for the dough. The properties of dough measured were the consistency, the water absorption, the development time, the stability of dough, the degree of softening, the degree of softening (ICC), and the farinograph quality number.

3.6.7.2. Baking test

The apparatus and reagents needed were farinograph unit, spoon, towel, balance, noodle machine, proofing chamber, and baking oven. The ingredients of dough were 50 g flour at 14 % moisture, 5 % fresh yeast, 1 % fat, 1.5 % salt, 1 % sugar, and 0.002 % L-ascorbic acid. All ingredients were put into the farinograph and kneaded for 1 min, then continued by the adding of water.

The amount of water added and the kneading time were determined by using farinograph. The kneading was stopped 30 s earlier than the real development time in order to avoid the gluten breakdown. After kneading, the dough was covered for 20 min at 30 °C in the proofer. Then it was weight and divided into 5 pieces of the same mass. After that, the dough was kept at room temperature for 3 min to have relaxation. Then, it was rolled with noodle machine, folded to a shape similar to a croissant, covered with the towel, and transferred to the oven at 30 °C for 35 min. Finally, the dough was baked in a baking oven at 230 °C for 12 min.

Two replications were applied and 5 pieces of small bread were produced for each sample. The loaf volume of each piece of bread was determined by means of rapeseed displacement to find its density. About 80 ml rapeseed was used in a 100 ml graduated cylinder. Each piece of bread was transferred to the graduated cylinder along with rapeseed, thus the increase of rapeseed volume was determined as the loaf volume.

3.6.8. Statistical analysis

The ANOVA at confidence interval 95 % was run by using the GLM. If there is significant influence of MW heating to each quality parameters observed, the LSD t-test was used to show the significance differences at probability 5 %. The correlation among the quality parameters was studied by using Pearson correlation.

IV. Results

4.1. Heating uniformity

Heating uniformity is a major feature to be considered in using MW energy because the MW generates the irregular temperature distributions on the product.

Table 5: The desired and experimental temperatures during holding period

MC_i (%)	Time (min)	Desired temperature (°C)	Replication	Experimental temperature (°C)	Ratio
		μ_d		$\mu_e \pm \sigma$	$\mu_{e/}\ \mu_d$
10	5	45	1	44.93 ± 1.99	0.998
			2	44.93 ± 2.22	0.998
	5	50	1	49.95 ± 2.06	0.999
			2	50.06 ± 2.53	1.001
	5	55	1	55.26 ± 3.43	1.005
			2	55.11 ± 3.16	1.002
14	5	45	1	44.63 ± 2.55	0.992
			2	44.97 ± 2.13	0.999
	5	50	1	50.24 ± 2.03	1.005
			2	50.20 ± 2.53	1.004
	5	55	1	54.74 ± 2.52	0.995
			2	54.83 ± 3.53	0.997
18	5	45	1	44.60 ± 2.15	0.991
			2	44.72 ± 2.11	0.994
	5	50	1	49.85 ± 2.36	0.997
			2	50.04 ± 2.95	1.001
	5	55	1	53.18 ± 3.19	0.967
			2	54.94 ± 2.39	0.999
10	0	50	1	48.15 ± 3.89	0.963
			2	49.15 ± 6.72	0.983
	1		1	49.89 ± 2.93	0.998
			2	50.03 ± 2.32	1.001
	3		1	49.92 ± 2.92	0.998
			2	50.44 ± 2.29	1.009
14	0	50	1	48.90 ± 3.25	0.978
			2	49.85 ± 2.02	0.997
	1		1	50.18 ± 2.86	1.004
			2	50.23 ± 2.64	1.005
	3		1	49.83 ± 2.89	0.997
			2	49.91 ± 3.04	0.998
18	0	50	1	n.a	n.a
			2	48.75 ± 2.19	0.975
	1		1	50.18 ± 3.06	1.004
			2	48.89 ± 2.52	0.978
	3		1	49.98 ± 2.75	1.000
			2	49.91 ± 1.86	0.998

MC_i, initial moisture content; n.a., data was not available

In the present study, the experimental temperatures were recorded during the holding period by using a pyrometer for the surface temperature. It can be seen that the mean of the experimental temperatures matched well with the desired temperatures (Table 5), which is shown by the ratio values that close to 1 (ranging from 0.963 to 1.009). However, the standard deviations of the temperatures were considered to be high and irregular ranging from 1.86 to 3.53 °C.

4.1.1. Temperature profile during temperature increase period

It was found in the present study that the period of temperature increase was always shown as a straight-line indicating that the increased temperature was linear. However, this linear model can only be guaranteed until the temperatures 45, 50, and 55 °C because the model probably will be changed at higher temperature depending strongly on the characteristic of the products to be heated. According to this result, the first requirement for the uniformity index calculation as it was suggested by Wang *et al*. (2005) was met.

4.1.2. Temperature distribution

As it was described in Subchapter 3.3.5 (pp. 31-32), the study on the temperature distribution was done on the excel sheet. It was indicated that the standard deviation ranged from 4 to 7.5 °C. The temperature distribution is discussed for two representative images by using the probability density frequency (PDF) analysis. The first one is the PDF of the surface temperature between the experimental and normal distribution after 5 min MW heating on the treated wheat grains at initial moisture content 10 % and temperature 45 °C (Figure 21, p. 46). The experimental temperature distribution skewed to the left side of its normal distribution determining the temperature areas that are lower than the desired temperature and to the right side of its normal distribution representing the temperature areas that are higher than the desired temperature. It was found that the areas with low temperatures were larger than the area with high temperature.

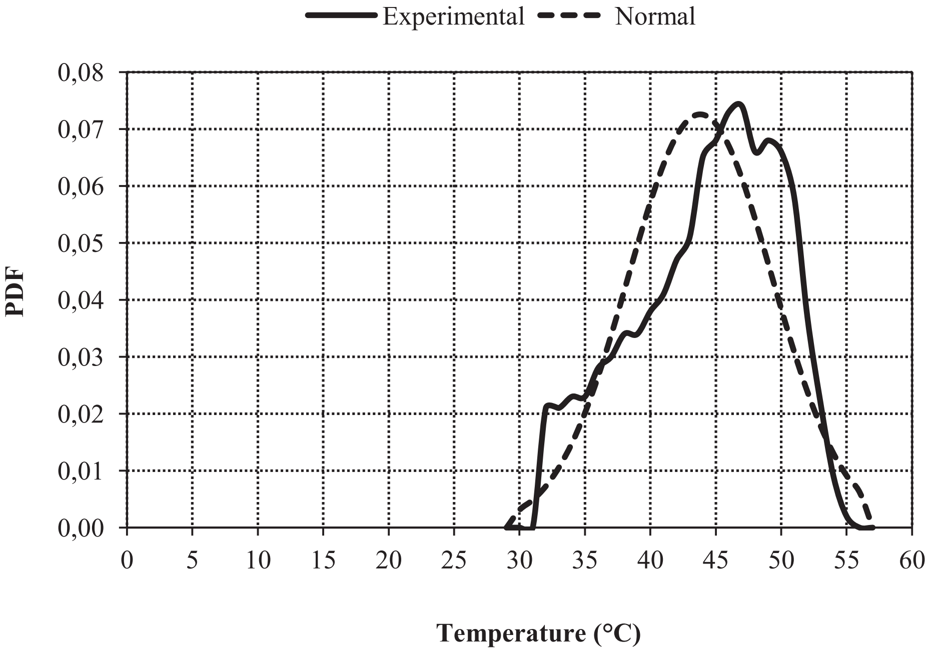


Figure 21: The probability density frequency (PDF) of wheat surface temperature between experimental and normal distribution after 5 min MW heating at 10 % MC_i and temperature 45 °C

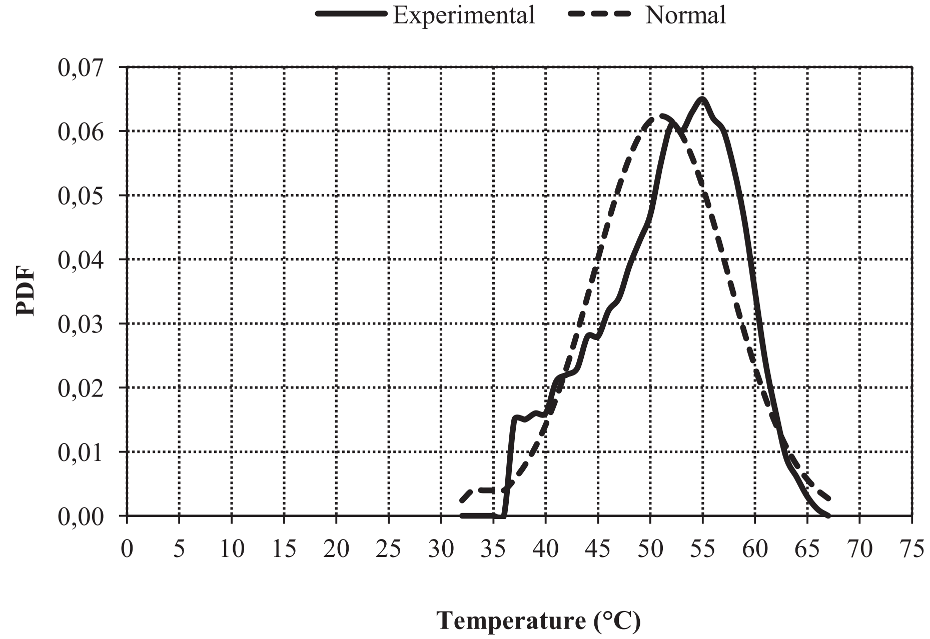


Figure 22: The probability density frequency (PDF) of wheat surface temperature between experimental and normal distribution after 5 min MW heating at 18 % MC_i and temperature 55 °C

The second is the PDF of wheat surface temperature between the experimental and normal distribution after 5 min MW heating on the treated wheat grains at initial moisture content 18 % and temperature 55 °C (Figure 22, p. 46). Figure 22 has the same trend as Figure 21 where the experimental temperature distribution skewed to the left and right side of its normal distribution.

Nevertheless, it can be seen in the Figure 22 that the distortion of the experimental temperature distribution to the normal distribution was smaller than in the Figure 21. Generally, the experimental temperature distributions of all MW heating were compatible with the normal distribution. Therefore, the second requirement for the uniformity index calculation was also met.

4.1.3. The uniformity index

4.1.3.1. The uniformity index after 5 min microwave heating with different initial moisture contents and surface temperatures

The uniformity indexes were calculated by using Eq. 15, 16 and 17 (p. 32). After 5 min MW heating with different initial moisture contents and surface temperatures, the uniformity indexes varied from 0.165 to 0.188 (Table 6).

Table 6: The uniformity index (λ_{ui}) after 5 min MW heating with different initial moisture contents and surface temperatures of wheat

MC_i (%)	**Temperature (°C)**	λ_{ui}
10	45	*0.183 ± 0.061*
	50	*0.188 ± 0.071*
	55	*0.175 ± 0.049*
14	45	*0.169 ± 0.027*
	50	0.182 ± 0.001
	55	0.177 ± 0.004
18	45	*0.172 ± 0.021*
	50	0.184 ± 0.011
	55	0.165 ± 0.006

The data were presented in mean ± standard deviation

By neglecting the treatments that have the high standard deviation due to the high variation of the uniformity index (the values are presented in italic), it can be seen that the increase in moisture content and temperature caused the decrease in the uniformity index. For example on the treated wheat grains at initial moisture content 14 %, the index decreased from 0.182 to 0.177 as the temperature increased from 50 to 55 °C. The lowest uniformity index was found about 0.165 on the treated wheat grains at initial moisture content 18 % and temperature 55 °C.

4.1.3.2. The uniformity index after microwave heating at temperature 50 °C with different initial moisture contents and exposure times

After MW heating at temperature 50 °C with different initial moisture contents and exposure times, the uniformity indexes varied from 0.152 to 0.244 (Table 7). The treatments with high standard deviation were also found on the treated wheat grains at initial moisture content 10 % combined with 1, 3 and 5 min exposure time (the values are presented in italic). On the treated wheat grains at initial moisture content 14 %, the uniformity index decreased as the exposure time was prolonged from 0.224 to 0.182. Although the uniformity indexes on the treated wheat grains at initial moisture content 18 % did not follow a regular change, in average their uniformity index were lower than the uniformity indexes on the treated wheat grains at initial moisture content 14 %, which indicate that the heating uniformity was better.

Table 7: The uniformity index (λ_{ui}) after MW heating at temperature 50 °C with different initial moisture contents of wheat and exposure times

MC_i (%)	**Time (min)**	λ_{ui}
10	0	0.163 ± 0.012
	1	*0.203 ± 0.040*
	3	*0.181 ± 0.018*
	5	*0.188 ± 0.071*
14	0	0.244 ± 0.008
	1	0.226 ± 0.008
	3	0.199 ± 0.006
	5	0.182 ± 0.001
18	0	0.162 ± 0.000
	1	0.152 ±0.003
	3	0.162 ±0.005
	5	0.184 ± 0.011

The data were presented in mean ± standard deviation

4.1.4. Hot and cold spot areas

The hot and cold spot areas were defined in Subchapter 3.3.7. (p. 33). The locations of the hot and cold spot areas were shown on the infrared image by using isotherm and alarm tools as a light green color (Figure 23, 24, 25, and 26). The distribution of the hot spot areas varied unevenly determining the irregular incident of the MW propagation. The hot spot areas were spread along the core part of the tray. In contrast, the cold spot areas were distributed along the edge part of the tray. It was found that the cold spot areas along the outer edge of the tray were larger than the cold spot areas along the inner edge of the tray. By using the PDF plot of experimental temperature distribution, the hot and cold spot areas could be analyzed quantitatively by using Eq. 18 and 19 (p. 33).

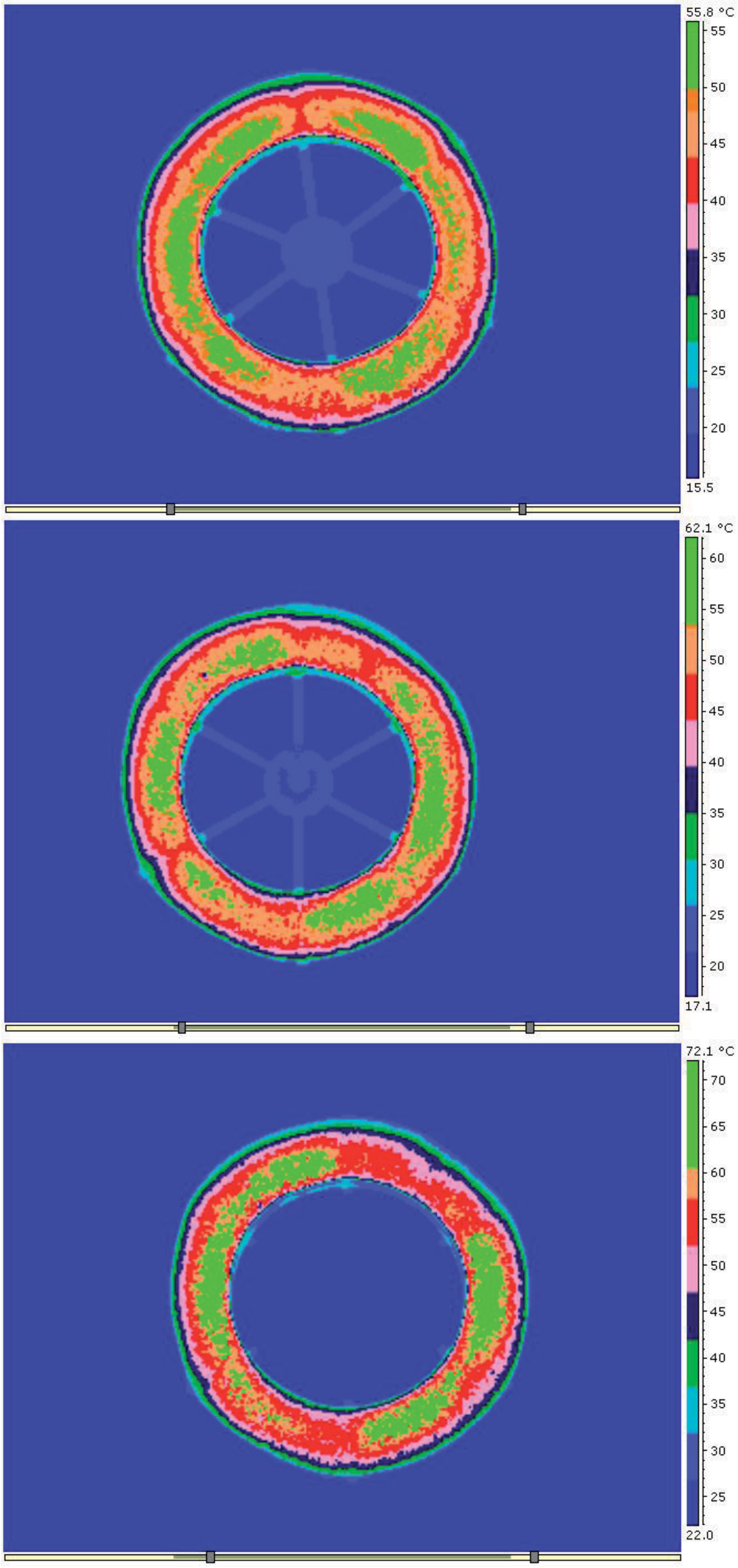
4.1.4.1. Hot and cold spot areas after 5 min microwave heating with different initial moisture contents and surface temperatures

After 5 min MW heating with different initial moisture contents and surface temperatures (Table 8), the hot and cold spot areas was found to be low on the treated wheat grains at initial moisture content 18 %, compared to the treated wheat grains at initial moisture content 14 and 10 %. The lowest hot and cold spot areas were indicated on the treated wheat grains at initial moisture content 18 % and temperature 55 °C; it was about 16 and 18 %, respectively.

Table 8: The percentage of hot and cold spot areas after 5 min MW heating with different initial moisture contents and surface temperatures of wheat

MC_i (%)	Temperature (°C)	Hot spot areas (%)	Cold spot areas (%)
10	45	18 ± 0.707	19 ± 0.000
	50	17 ± 2.121	19 ± 0.000
	55	17 ± 0.000	19 ± 0.707
14	45	18 ± 0.000	20 ± 0.707
	50	16 ± 0.000	19 ± 0.000
	55	17 ± 0.000	19 ± 1.414
18	45	17 ± 0.707	18 ± 0.000
	50	16 ± 0.000	18 ± 0.000
	55	16 ± 0.707	18 ± 0.707

The data were presented in mean ± standard deviation



Mean : 43.8 °C
Std : 5.5 °C
λ_{ui} : 0.14
Hot spot : 18 %

(a) 45 °C

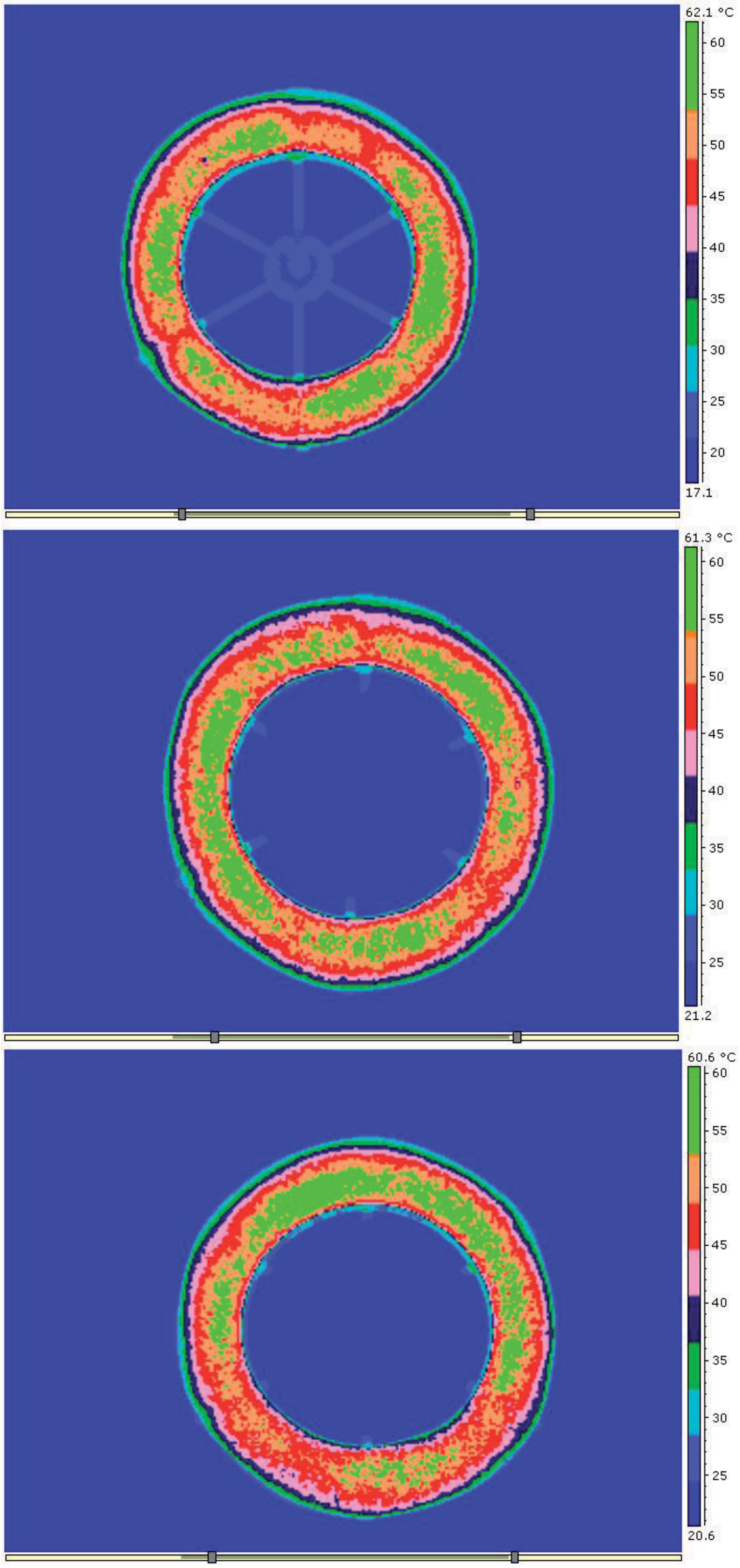
Mean : 47.1 °C
Std : 6.3 °C
λ_{ui} : 0.238
Hot spot : 17%

(b) 50 °C

Mean : 53.2 °C
Std : 7.1 °C
λ_{ui} : 0.210
Hot spot : 17%

(c) 55 °C

Figure 23: The distribution of hot spots (light green color) after 5 min MW heating at 10 % MC_i with surface temperature 45 °C (a), 50 °C (b) and 55 °C (c)



Mean : 47.1 °C
Std : 6.3 °C
λ_{ui} : 0.238
Hot spot : 17%

(a)10 %

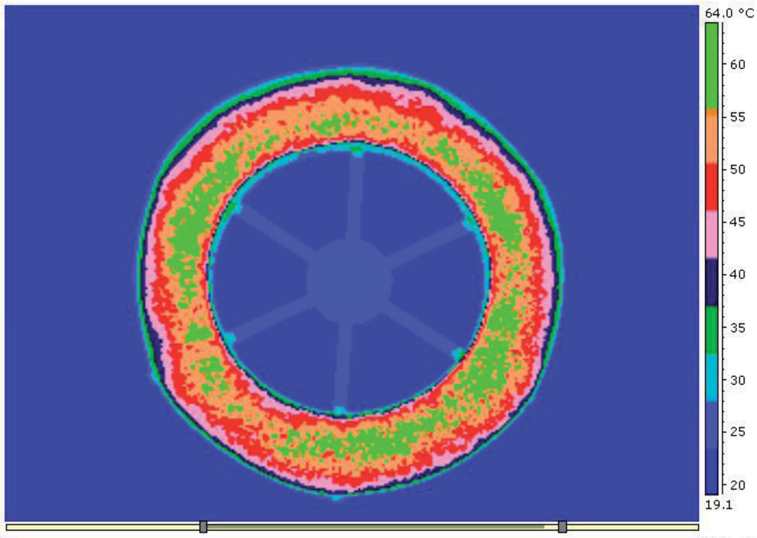
Mean : 48.2 °C
Std : 5.5 °C
λ_{ui} : 0.182
Hot spot : 16 %

(b) 14 %

Mean : 46.8 °C
Std : 5.8 °C
λ_{ui} : 0.176
Hot spot : 16 %

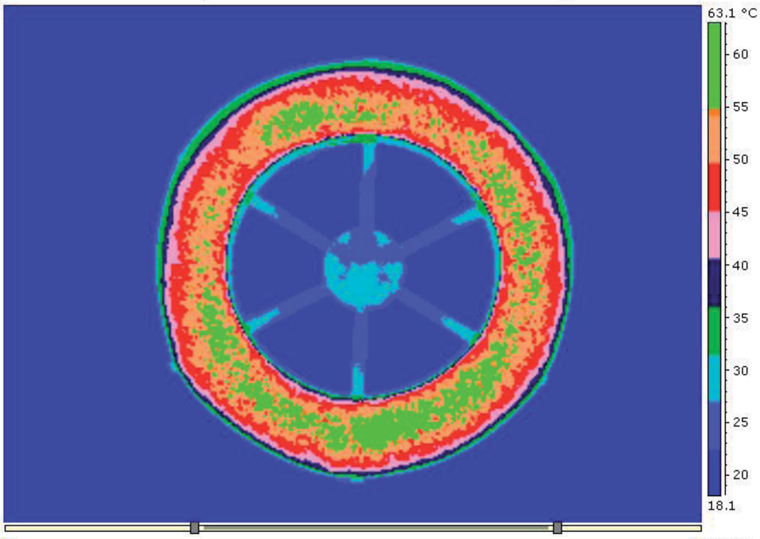
(c) 18 %

Figure 24: The distribution of hot spot areas (light green color) after 5 min MW heating at surface temperature 50 °C with 10 % MC_i (a), 14 % MC_i (b) and 18 % MC_i (c)



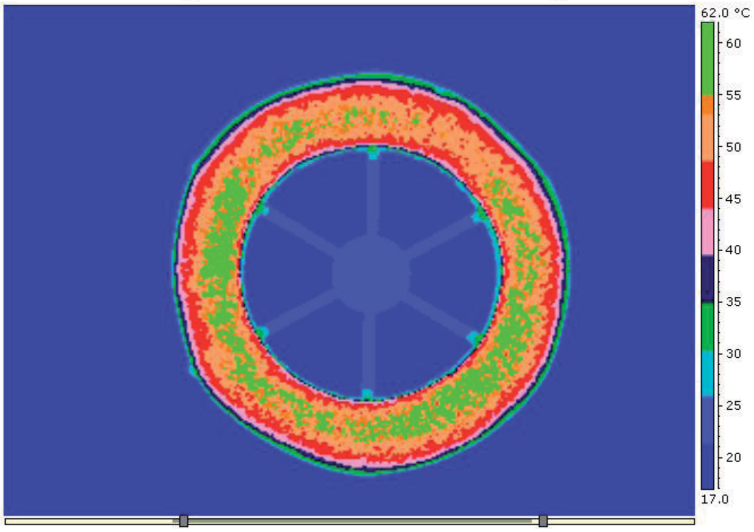
Mean : 49.6 °C
Std : 5.9 °C
λ_{ui} : 0.166
Hot spot : 16%

(a) 0 min



Mean : 49.0 °C
Std : 5.5 °C
λ_{ui} : 0.152
Hot spot : 15%

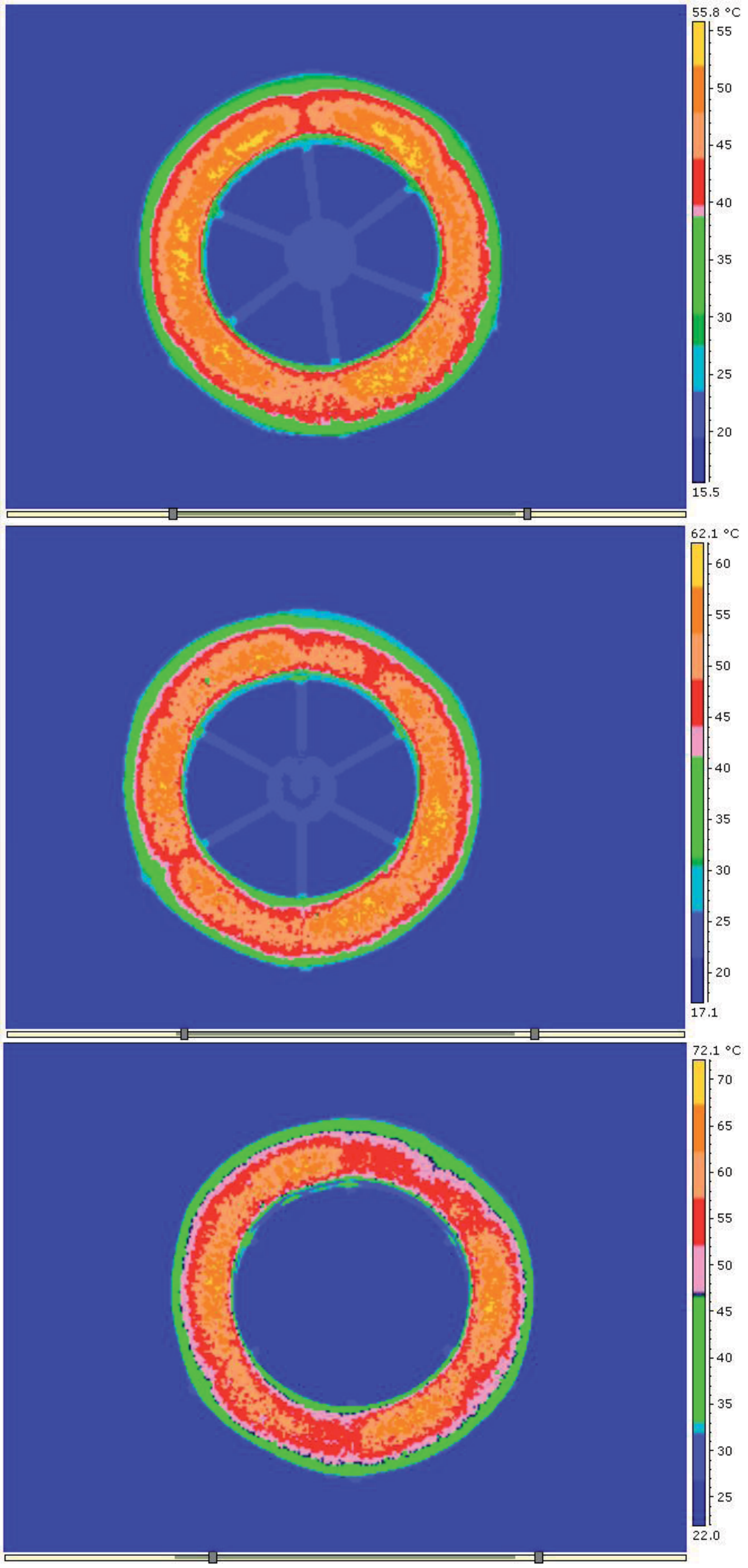
(b) 1 min



Mean : 48.9 °C
Std : 5.6 °C
λ_{ui} : 0.165
Hot spot : 15%

(c) 3 min

Figure 25: The distribution of hot spot area (light green color) at surface temperature 50 °C and 18 % MC_i with exposure time 0 min (a), 1 min (b) and 3 min (c)



Mean : 43.8 °C
Std : 5.5 °C
λ_{ui} : 0.140
Cold spot : 19%

(a) 45 °C

Mean : 47.1 °C
Std : 6.3 °C
λ_{ui} : 0.238
Cold spot : 19%

(b) 50 °C

Mean : 53.2 °C
Std : 7.1 °C
λ_{ui} : 0.210
Cold spot : 19%

(c) 55 °C

Figure 26: The distribution of cold spot areas (light green color) after 5 min MW heating at 10 % MC_i with surface temperature 45 °C (a), 50 °C (b) and 55 °C (c)

4.1.4.2. Hot and cold spot areas after microwave heating at temperature 50 °C with different initial moisture contents and exposure times

After MW heating at temperature 50 °C with different initial moisture contents and exposure times, the lowest hot and cold spot areas were noticed on the treated wheat grains at initial moisture content 18 % and exposure time for 1 and 3 min (Table 9). It can be seen that the increase in moisture and exposure time led to the decrease of the hot and cold spot areas.

Table 9: The percentage of hot and cold spot areas after MW heating at temperature 50 °C with different initial moisture contents and exposure times

MC_i (%)	Time (min)	Hot spot areas (%)	Cold spot areas (%)
10	0	18 ± 0.000	20 ± 0.000
	1	18 ± 0.707	20 ± 0.707
	3	17 ± 0.707	19 ± 0.000
	5	17 ± 2.121	19 ± 0.000
14	0	17 ± 0.000	21 ± 0.707
	1	18 ± 0.707	21 ± 0.707
	3	17 ± 0.707	20 ± 0.707
	5	16 ± 0.000	19 ± 0.000
18	0	16 ± 0.000	18 ± 0.000
	1	15 ± 0.000	17 ± 0.000
	3	15 ± 0.707	17 ± 0.000
	5	16 ± 0.000	18 ± 0.000

The data were presented in mean ± standard deviation

4.2. The mortality of *Oryzaephilus surinamensis*

4.2.1. The mortality after 5 min microwave heating with different initial moisture contents and surface temperatures

Table 10 shows the mortality from 3 life stages of *O. surinamensis* after 5 min MW heating with 3 levels of initial moisture contents and surface temperatures of wheat. The mortality of adults in the treated grains at temperature 45 °C and initial moisture content 10 % was low (17 %) and increased to 59 % as the moisture contents were increased to 18 %. In contrast, in the treated grains at temperature 50 °C, the increase in moisture contents from 10 to 18 % decreased the mortality from 90 to 75 %. However, at the temperature 55 °C, the mortality in the treated wheat grains at initial moisture content 10, 14 and 18 % was relatively high about 98, 100 and 99 %, respectively. The increase of mortality was shown as the temperature increase at each moisture level. The ANOVA showed that the mortality of adults was significantly influenced by the initial moisture contents and the surface temperatures of the treated grains.

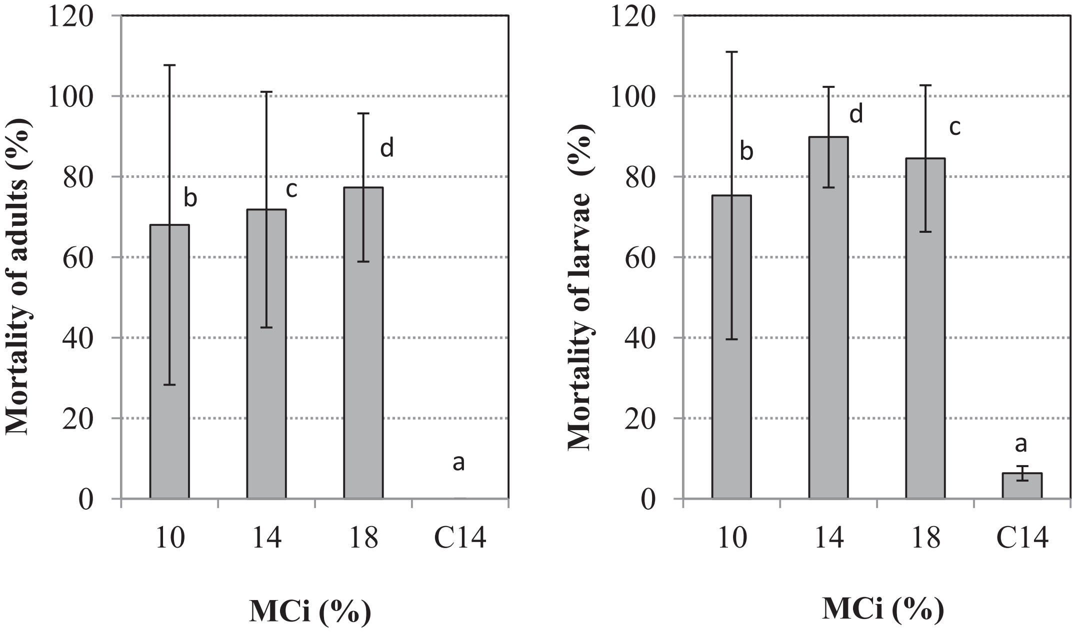
Table 10: The mortality of *Oryzaephilus surinamensis* after 5 min MW heating with different initial moisture contents and surface temperatures of wheat

MC_i (%)	**Temperature (°C)**	**Mortality (%)**		
		Adults	**Larvae**	**Pupae**
10	45	17 ± 0	30 ± 7.78	86 ± 9.19
	50	90 ± 3.54	97 ± 2.12	96 ± 5.65
	55	98 ± 3.54	100 ± 0	100 ± 0
14	45	36 ± 2.83	75 ± 2.12	84 ± 5.65
	50	80 ± 2.12	95 ± 7.07	100 ± 0
	55	100 ± 0	100 ± 0	100 ± 0
18	45	59± 2.12	62 ± 6.36	n.a
	50	75 ± 4.95	98 ± 0	n.a
	55	99 ± 1.41	94 ± 1.41	n.a
C14	CT	0 ± 0	6 ± 1.84	60 ± 0
ANOVA on MC_i		s	s	ns
ANOVA on temperature		s	s	s

n.a., data is not available; C14, control at 14 % MC_i; CT, no MW heating; s, significant; ns, not significant; the statistics were tested at $p<0.05$
The data were presented in mean ± standard deviation

The mortality of larvae on the treated grains at temperature 45 °C and initial moisture content 10 % was about 30 %. The increase of mortality at level 75 % was dramatically pronounced by increasing the initial moisture content of treated wheat grains up to 14 %, but then the mortality dropped to 62 % at moisture content 18 %. Hundred percent of mortality was obtained at temperature 55 °C and initial moisture content 10 and 14 %. In general, the mortalities of larvae in all treatments were higher than the mortality of adults, except at the initial moisture content 14 and 18 %, and temperature treatment 55 °C. However, there was about 6 % mortality of larvae occurred in untreated grains (control). Furthermore, the ANOVA showed that the larvae mortality was also significantly influenced by the initial moisture contents and the surface temperatures of the treated grains.

The mortality of pupae in the treated grains ranged from 84 to 100 %. The mortality test on the treated grains at initial moisture content 18 % was not conducted because 100 % mortality was obtained on the treated grains at initial moisture content 14 %. A mortality increase in the treated grains also pronounced as the moisture contents and temperatures increased. Unfortunately, the mortality of pupae in control was very high (60 %). The ANOVA showed that the mortality of pupae was not significantly influenced by the initial moisture contents of the treated wheat grains. In contrast, it was significantly influenced by the temperatures.

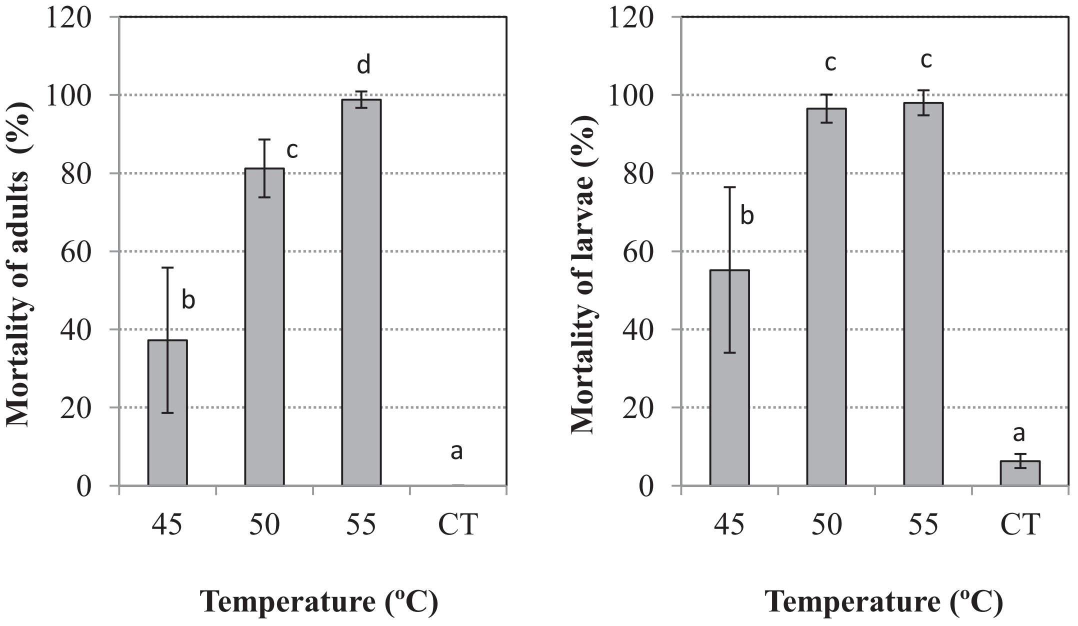


(a) Adults (b) Larvae

Figure 27: The LSD t-test for the mortality of *Oryzaephilus surinamensis:* adults (a) and larvae (b) after 5 min exposure time to the MW heating as the influence of the initial moisture contents (The same letter shows that there are no significant differences at $P<0.05$; C14, control at 14 % MC_i)

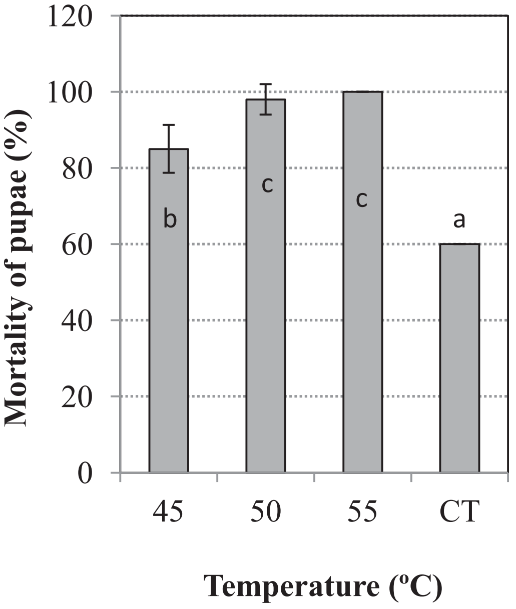
The least significant difference (LSD) t-test was run to determine the differences in the mortality. As the influence of the initial moisture content, the highest mortality of adults was evaluated in the treated wheat grains at initial moisture content 18 % (77.3 %), whereas the highest mortality of larvae was found in the treated wheat grains at initial moisture content 14 % (89.8 %) (Figure 27). The lowest mortalities of adults and larvae were 68 and 75.3 %, respectively, which were obtained in the treated wheat grains at initial moisture content 10 %.

Irrespective to Figure 28, as the influence of the temperature, the highest mortality for adults and larvae was in the treated grains at temperature 55 °C, which were obtained at level 98.8 and 98 %, respectively. While at temperature 45 °C, the mortalities of adults and larvae were 37.2 and 55.2 %, respectively.



(a) Adults

(b) Larvae



(c) Pupae

Figure 28: The LSD t-test for the mortality of *Oryzaephilus surinamensis:* adults (a), larvae (b) and pupae (c) after 5 min exposure time to the MW heating as the influence of temperatures (The same letter shows that there are no significant differences at $P<0.05$; CT, no MW heating)

However, no significant differences were found for the mortalities of larvae and pupae in the treated grains at temperature 50 and 55 °C. The mortalities of adults, larvae and pupae showed the same trend mortality where the increase in temperature led to the increase in mortality. In average, the mortality of larvae was higher than the mortality of adults while the mortality of pupae was higher than the mortality of adults and larvae.

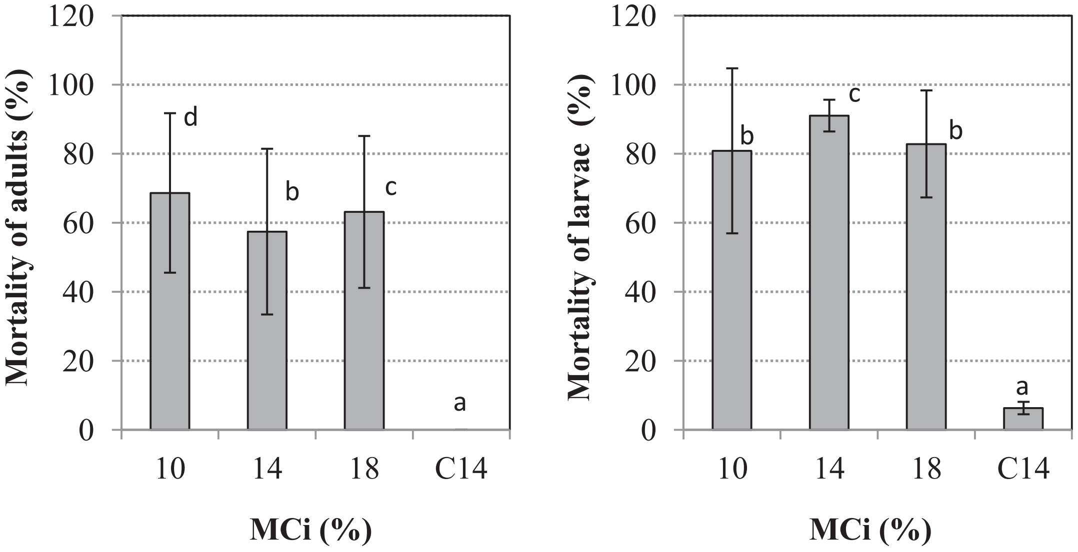
4.2.2. The mortality after microwave heating at temperature 50 °C with different initial moisture contents and exposure times

Table 11 shows the results from the second experimental design where the insects were treated at a constant targeted temperature 50 °C, but with different exposure times and initial moisture contents. The mortality of adults in the treated wheat grains increased dramatically as the exposure time was prolonged from 0 to 1 min exposure. However, the mortality of adults in the treated grains at initial moisture content 10 % (63 %) was higher than the mortality of adults in the treated grains at initial moisture content 14 % (41 %). Furthermore, in the treated wheat grains at initial moisture content 18 %, an aberrant data appeared since the mortality after 5 min exposing (75 %) in the MW heating was lower than that of after 3 min exposure (90 %).

Table 11: The mortality of *Oryzaephilus surinamensis* after MW heating at temperature 50 °C with different initial moisture contents and exposure times

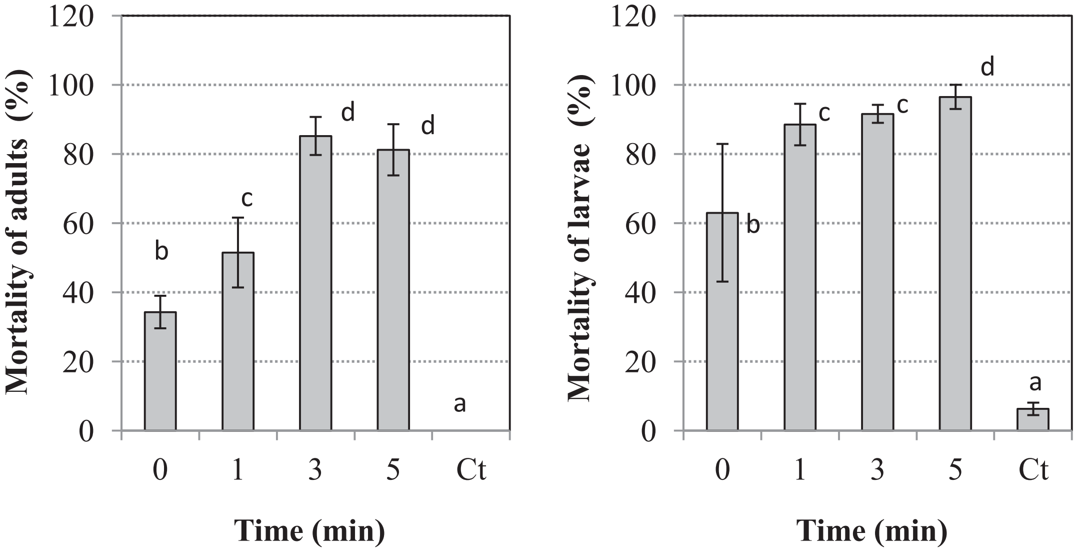
MC_i %	**Time min**	**Mortality (%)**		
		Adults	**Larvae**	**Pupae**
10	0	36 ± 7.07	43 ± 2.12	90 ± 14.84
	1	63 ± 1.41	94 ± 4.24	88 ± 0
	3	86 ± 4.24	91 ± 3.54	100 ± 0
	5	90 ± 3.54	97 ± 2.12	96 ± 5.65
14	0	30 ± 0	87 ± 4.95	77 ± 14.85
	1	41 ± 2.12	90 ± 0	94 ± 2.82
	3	80 ± 3.54	93 ± 0.71	93 ± 9.89
	5	80 ± 2.12	95 ± 7.07	100 ± 0
18	0	37 ± 1.41	60 ± 0	n.a.
	1	51 ± 1.41	82 ± 0.71	n.a.
	3	90 ± 2.82	92 ± 4.24	n.a.
	5	75 ± 4.95	98 ± 0	n.a.
C14	CT	0 ± 0	6 ± 1.84	60 ± 0
ANOVA on MC_i		s	s	ns
ANOVA on time		s	s	ns

n.a., data is not available; C14, control at 14 % MC_i; CT, no MW heating;
s, significant; ns, not significant; the statistics were tested at $p<0.05$
The data were presented in mean ± standard deviation



(a) adults (b) Larvae

Figure 29: The LSD t-test for the mortality of *Oryzaephilus surinamensis:* adults (a) and larvae (b) after MW heating at temperature 50 °C as the influence of the initial moisture contents (The same letter shows that there are no significant differences at P<0.05; C14, control at 14 % MC_i)



(a) adults (b) Larvae

Figure 30: The LSD t-test for the mortality of *Oryzaephilus surinamensis*: adults (a) and larvae (b) after MW heating at temperature 50 °C as the influence of exposure times (The same letter shows that there are no significant differences at P<0.05; Ct, no MW heating)

The mortality of larvae in the treated grain at initial moisture content 10 % and 0 min exposure was 43 %. The extension of exposure time to 1 min caused a dramatically increase of the mortality to the level of 94 %. In addition, the increase in initial moisture content also showed a sharp increase of the mortality at level 87 % after 0 min exposure. In comparison to the adult mortality, in average, the mortality of larvae was higher. However, there was an aberrant data detected on the treated wheat grains at initial moisture content 10 %, where the mortality after 1 min exposure was higher than the mortality after 3 min exposure.

Furthermore, the mortality of pupae in treated grains was high ranging from 77 to 100 %. However, the mortality in control grains was high. Thus, it is not reasonable to explain the mortality of them as the influence of the MW heating.

In general, the mortality in both adults and larvae increased as the exposure time was prolonged, but the effect of the initial moisture contents was found irregular. Nevertheless, both the initial moisture content and the exposure time significantly influenced the mortality. Higher number mortality of larvae also explained that the adult stage is more resistant to the MW heating than the larva stage. In case of pupa stage, the initial moisture content and the exposure time did not significantly influence the mortality.

As it is shown in Figure 29 (p. 59), the highest mortality of adults was found on the treated wheat grains at the initial moisture content 10 % (68.6 %), followed by 18 % (63.1 %) and 14 % (63.1 %). In contrast, the highest larvae mortality was indicated on the treated wheat grains at initial moisture content 14 % (91 %). However, there were no significant differences of larvae mortality on the treated wheat grains at initial moisture content 10 and 18 %, which were obtained at level 80.8 and 82. 8 %, respectively. Overall, the mortality of larvae was higher than the mortality of adult.

As the influence of the exposure time shown in Figure 30, the mortality of larvae in average was also higher than the mortality of adults. The LSD t-test showed that there were no significant differences of adult mortality at exposure time 3 and 5 min. The mortality of larvae at exposure time 1 and 3 min, which were obtained at level 88.5 and 91.6 %, respectively, had no significant differences as well. These results explained the aberrant data that were shown in Table 11 (p. 58). Finally, it is reasonable to presume that the prolongation of exposure time contributes to the higher mortality level. Especially for the adults, the longer time than 5 min is needed to reach 100 % mortality if the treatment temperature is about 50 °C.

4.3. Germination rate

4.3.1. Germination rate after 5 min microwave heating with different initial moisture contents and surface temperatures

The germination rates for the untreated (control) wheat kernels at initial moisture contents of 10, 14 and 18 % were 96, 98 and 96 %, respectively. However, after 5 min MW heating with different initial moisture content and temperature, the germination rates were still found high ranging from 94 to 99 % (Table 12).

Table 12: The germination rate of wheat after 5 min MW heating with different initial moisture contents and surface temperatures of wheat

	MC$_i$ %	**Temperature °C**	**Germination rate (%)**
	10	45	98 ± 2.08
		50	97 ± 2
		55	97 ± 3.79
	C10	CT	96 ± 3.61
	14	45	99 ± 0.57
		50	94 ± 3.06
		55	98 ± 0.57
	C14	CT	98 ± 0.58
	18	45	97 ± 1.53
		50	95 ± 2.52
		55	94 ± 2
	C18	CT	96 ± 1.73
ANOVA on MC$_i$			ns
ANOVA on temperature			s

C10, C14 and C18, control at 10, 14 and 18 % MC$_i$; CT, no MW heating;
s, significant; ns, not significant; the statistics were tested at $p<0.05$
The data were presented in mean ± standard deviation

Furthermore, the germination rates in the treated wheat grains at temperature 45 °C were higher than the germination rate in control. There was some evidence that the germination rate in the treated wheat grains at temperature 50 °C was lower or equal to the germination rate in the treated wheat grains at temperature 55 °C. The ANOVA showed that there was a significant influence of temperature on the germination rates, while the influence of the initial moisture content was insignificant.

The comparison of means in Figure 31 (p. 62) showed that there are significant differences of germination rates in the treated wheat grains at temperature 45 and

50 °C. The lowest incident of germination rate was occurred in the treated wheat grains at temperature 50 °C (95 %), but it has no significant differences from the germination rates in the treated wheat grains at temperature 55 °C (96.3 %) and untreated wheat grains (96 %). However, the germination rates in the treated wheat grains at temperature 55 °C were not significantly different from the germination rates in the treated wheat grains at temperature 45 and 50 °C, and control.

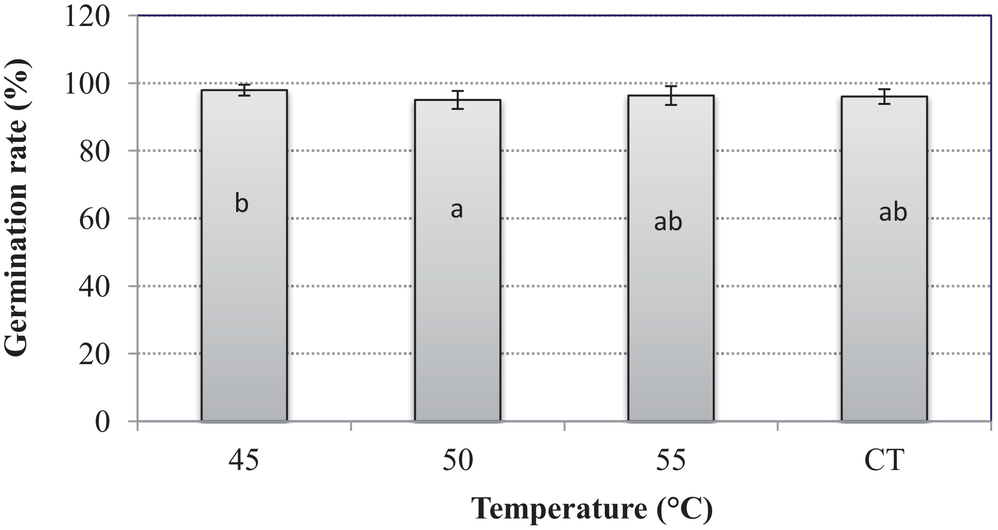


Figure 31: The LSD t-test for the germination after 5 min MW heating as the influence of temperatures (The same letter shows that there are no significant differences at P<0.05; CT, no MW heating)

4.3.2. Germination rate after microwave heating at temperature 50 °C with different initial moisture contents and exposure times

After MW heating at temperature 50 °C with different initial moisture contents and exposure times, the germination rates ranged from 93 to 98 % (Table 13, p. 63). At initial moisture content 10 %, there was evidence that the germination rates in the treated grains was higher than the germination rates in control. The ANOVA showed that the moisture contents significantly influenced the germination, but the exposure time did not influence the germination rates since the MW heating at 5 min was not reasonable for the degradation of germination rates.

Table 13: The germination rate of wheat after MW heating at surface temperature 50 °C with different initial moisture contents and exposure times

	MC_i %	Time min	Germination rate (%)
	10	0	96 ± 2.31
		1	98 ± 1
		3	97 ± 0
		5	97 ± 2
	C10	Ct	96 ± 3.61
	14	0	97 ± 1.15
		1	93 ± 4.16
		3	97 ± 2
		5	94 ± 3.1
	C14	Ct	98 ± 0.58
	18	0	95 ± 0
		1	97 ± 1.53
		3	91 ± 4.36
		5	95 ± 2.52
	C18	Ct	96 ± 1.73
ANOVA on MC_i			s
ANOVA on time			ns

C10, C14 and C18, control at initial moisture contents 10, 14 and 18 %; Ct, no MW heating; s, significant; ns, not significant; the statistics were tested at $p<0.05$
The data were presented in mean ± standard deviation

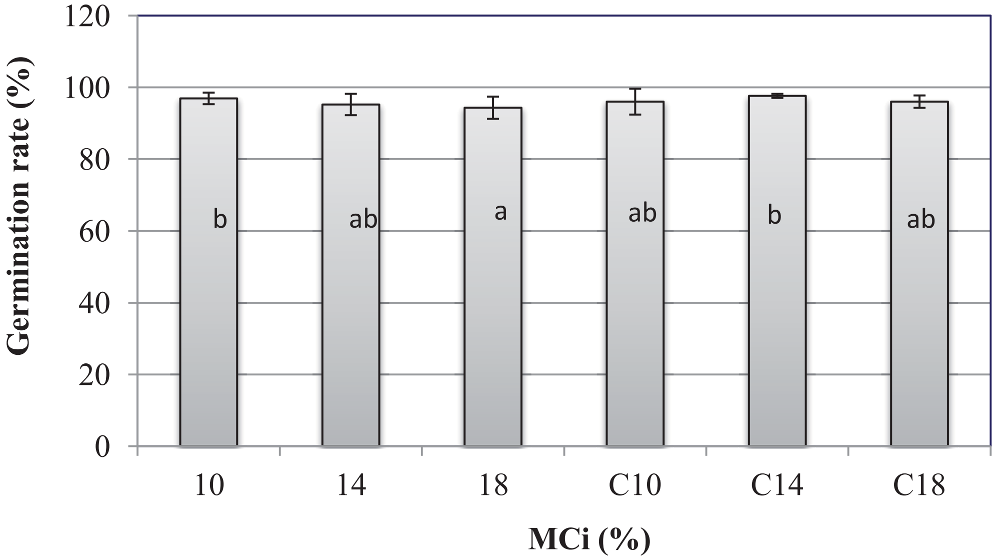


Figure 32: The LSD t-test for the germination rates after MW heating at temperature 50 °C as the influence of the initial moisture contents (The same letter shows that there are no significant differences at P<0.05; C10, C14 and C18: control at initial moisture content 10, 14 and 18 %)

As can be seen in Figure 32, the lowest germination rate was found in the treated wheat grains at initial moisture content 18 % (94.3 %) and it was significantly different from the germination rates in the treated wheat at initial moisture contents 10 % (96.9 %) and control at initial moisture content 14 % (97.6 %). Furthermore, there were no significant differences between the germination rates in the treated wheat grains and control at initial moisture content 10 and 14 %. The highest germination rate was obtained in control at initial moisture content 14 % (97.6 %), but it was not significantly different from the germination rates in the treated wheat grains at initial moisture content 10 and 14 %, and in untreated wheat grains (control) at initial moisture 10 and 18 %.

4.4. The quality of flour

4.4.1. The moisture loss under effect of microwave heating

The moisture content of wheat grains was measured by using the oven method (8 h at 130 °C) as it was used for preparing wheat grains (pp. 26-27) in order to improve the accuracy.

Table 14: The moisture loss due to MW heating with different initial moisture contents, surface temperatures and exposure times

MW treatments	MC_i (%)	Temperature (°C)	Time (min)	Moisture loss (%)	Final moisture range (%)
MC_i vs. temperature	10	45	5	0.21 ± 0.12	9.67 - 9.91
	10	50	5	0.36 ± 0.22	9.42 - 9.86
	10	55	5	0.33 ± 0.19	9.48 – 9.86
	14	45	5	1.24 ± 0.42	12.34 – 13.18
	14	50	5	1.46 ± 0.46	12.08 – 13.00
	14	55	5	1.73 ± 0.25	12.02 – 12.52
	18	45	5	2.51 ± 0.55	14.94 – 16.04
	18	50	5	3.03 ± 0.40	14.57 – 15.37
	18	55	5	3.51 ± 0.23	14.26 – 14.72
MC_i vs. time	10	50	0	0.18 ± 0.08	9.74 – 9.90
	10	50	1	0.24 ± 0.16	9.60 – 9.92
	10	50	3	0.34 ± 0.09	9.57 – 9.75
	14	50	0	0.97 ± 0.30	12.73 – 13.33
	14	50	1	1.19 ± 0.41	12.40 – 13.22
	14	50	3	1.39 ± 0.49	12.12 – 13.10
	18	50	0	2.68 ± 0.31	15.01 – 15.63
	18	50	1	2.77 ± 0.13	15.10 – 15.36
	18	50	3	2.83 ± 0.16	15.01 – 15.33

The values of moisture loss were presented in mean ± standard deviation

The weight information recorded in the control system were not used to determine the moisture content since the measurement of weight by digital balance was a bit disturbed by the application of rotating tray and the amount of weight loss was low.

As it is shown in Table 14 (p. 64), the moisture loss in treated wheat grains increased as the temperature increased. The moisture loss also increased as the initial moisture content was increased and the duration of MW application was prolonged. The decrease in moisture content more than 1 % was obtained when the initial moisture content was 14 and 18 %. In exception, after 0 min MW heating on wheat grains at initial moisture content 14 % and temperature 50 °C, the decrease in moisture content was lower than 1 %. It was noticed that the highest moisture loss was about 3.51 %, which was indicated on the treated wheat grains at initial moisture content 18 % and temperature 55 °C.

4.4.2. The quality of flour after 5 min microwave heating with different initial moisture contents and surface temperatures

4.4.2.1. Starch content

Starch content after 5 min MW heating with different initial moisture contents and surface temperatures ranged from 66.98 to 68.63 % (Table 15).

Table 15: The starch content after 5 min MW heating with different initial moisture contents and surface temperatures of wheat

	MC_i (%)	**Temperature (°C)**	**Starch (%)**
	10	**45**	68.10 ± 0.85
		50	67.32 ± 0.42
		55	66.98 ± 1.17
	18	**45**	68.02 ± 1.65
		50	68.63 ± 1.32
		55	67.27 ± 1.29
	C10	**CT**	66.60 ± 0.00
	C12.5	**CT**	68.10 ± 0.00
ANOVA on MC_i			ns
ANOVA on temperature			ns

s, significant; ns, not significant; the statistics were tested at $p<0.05$;
C10 and C12.5, control at initial moisture content 10 and 12.5 %; CT, no MW heating; the data were presented in mean ± standard deviation

The highest starch content (68.63 %) was indicated in the treated wheat grains at initial moisture content 18 % and temperature 50 °C. However, the ANOVA showed that the starch content was not significantly influenced by the initial moisture contents and the surface temperatures of the treated wheat grains (Table 15, p. 65).

4.4.2.2. Falling number

The FNs highly varied among the samples after 5 min MW heating with different initial moisture contents and surface temperatures of wheat grains. This high variation was shown by high standard deviations (Table 16). ANOVA showed that the initial moisture contents and the surface temperatures did not influence the FN results. The FN values in the flour produced from the treated wheat grains at initial moisture content 10 % ranged from 370 to 390 s, whereas the FN values in the flour produced from the treated wheat grains at initial moisture content 18 % ranged from 350 to 375 s. The FN in the flour produced from untreated wheat grains (control) at initial moisture content 10 % (386 s) was indicated lower than the FN in the flour produced from untreated wheat grains (control) at initial moisture content 12.5 % (427 s).

Table 16: The FNs after 5 min MW heating with different initial moisture contents and surface temperatures of wheat

	MC_i (%)	Temperature (°C)	FN (s)
	10	**45**	370 ± 47.1
		50	390 ± 14.4
		55	381 ± 37.5
	18	**45**	375 ± 17.9
		50	374 ± 40.0
		55	350 ± 61.0
	C10	**CT**	386 ± 7.1
	C12.5	**CT**	427 ± 5.6
ANOVA on MC_i			ns
ANOVA on temperature			ns

s, significant; ns, not significant; the statistics were tested at $p<0.05$;
C10 and C12.5, control at initial moisture content 10 and 12.5 %; CT, no MW heating; the data were presented in mean ± standard deviation

4.4.2.3. Flour viscosity

The rapid visco analyzer (RVA) viscosity profiles of the flour that was milled from the treated and untreated wheat grains after 5 min MW heating with different moisture contents and temperatures are given in Table 17. It can be seen that the pasting temperature varied from 78.2 to 80.7 °C, while the peak time ranged from 5.4 to 5.6 min. Overall, the peak, holding, breakdown, final and setback viscosities of the flour that was milled from the treated wheat grains at initial moisture content 18 % are higher than the viscosities of the flour that was milled from treated wheat grains at initial moisture content 10 %. Moreover, the final viscosity (FV) was also higher than the peak viscosity (PV).

Irrespective to Table 17, the ANOVA showed that the significant influence of moisture contents were investigated on all RVA viscosity profiles, except on peak time. On the other hand, the significant influence of temperature was indicated only on breakdown- and final viscosities (Table 18).

Table 17: The RVA viscosity profiles among replications after 5 min MW heating with different initial moisture contents, surface temperatures, and repetitions

Treatment			T_{past}	t_{peak}	Peak viscosity	Holding viscosity	Breakdown viscosity	Final viscosity	Setback viscosity
MC_i (%)	**T (°C)**	**R**	**(°C)**	**(min)**	**(RVU)**	**(RVU)**	**(RVU)**	**(RVU)**	**(RVU)**
10	**45**	**1**	78.7	5.6	236	129	107	233	104
		2	78.2	5.4	225	129	96	244	115
		3	78.7	5.4	220	121	99	228	107
	50	**1**	80.1	5.4	207	122	85	235	114
		2	79.6	5.4	212	128	84	244	116
		3	80.3	5.7	238	135	102	246	111
	55	**1**	80.0	5.5	222	126	96	236	110
		2	78.3	5.5	229	131	98	240	109
		3	78.3	5.5	209	117	92	223	106
18	**45**	**1**	80.0	5.5	243	137	107	255	118
		2	79.5	5.5	238	137	101	254	117
		3	79.9	5.5	249	138	110	257	119
	50	**1**	79.9	5.5	247	138	109	258	120
		2	80.4	5.5	238	138	100	255	117
		3	79.1	5.6	249	144	106	262	118
	55	**1**	80.3	5.6	255	142	113	261	119
		2	79.6	5.4	223	133	90	254	121
		3	80.7	5.4	201	123	79	245	122
C10	**CT**	**1**	79.9	5.6	218	128	90	233	106
C12.5	**CT**	**1**	79.6	5.4	203	122	81	239	117

MC_i, initial moisture content; T, temperature; R, MW repetition; T_{past}, pasting temperature; t_{peak}, peak time; RVU, rapid visco unit; C10 and C 12.5, control at initial moisture content 10 and 12.5 %; CT, no MW heating

Table 18: The ANOVA of RVA profiles after 5 min MW heating with different initial moisture contents and surface temperatures

RVA viscosity profiles	ANOVA	
	MC_i	Temperature
Pasting temperature	s	ns
Peak time	ns	ns
Peak viscosity	s	ns
Holding viscosity	s	ns
Breakdown viscosity	s	s
Final viscosity	s	s
Setback viscosity	s	ns

s, significant; ns, not significant; the statistics were tested at $p<0.05$

4.4.2.4. Damaged starch

The variation of damaged starch after 5 min MW heating with different initial moisture contents and surface temperatures were high, which is shown by high standard deviations. In the flour produced from the treated wheat grains at initial moisture content 10 %, the damaged starch increased as the temperatures were increased. On the other hand, in the flour produced from the treated wheat grains at initial moisture content 18 %, the damaged starch increased at temperature 50 °C, but then it decreased at temperature 55 °C. ANOVA showed that the moisture contents and temperature significantly influenced the damaged starch (Table 19).

Table 19: The damaged starch after 5 min MW heating with different initial moisture contents and temperatures

	MC_i (%)	Temperature (°C)	Damaged starch (BV)
	10	**45**	3.03 ± 0.23
		50	3.04 ± 0.23
		55	3.05 ± 0.19
	18	**45**	3.00 ± 0.16
		50	3.16 ± 0.05
		55	2.82 ± 0.26
	C10	**CT**	3.29 ± 0.12
	C12.5	**CT**	3.19 ± 0.14
ANOVA on MC_i			s
ANOVA on temperature			s

s, significant; ns, not significant; the statistics were tested at $p<0.05$
C10 and C 12.5, control at initial moisture content 10 and 12.5 %; CT, no MW heating; the data were presented in mean ± standard deviation

In Figure 33 (p. 69), it can be seen that the damaged starch in the flour produced from the treated wheat grains at initial moisture content 10 % (3.04 BV) was not significantly different from the damaged starch in the flour produced from the treated wheat grains at initial moisture content 18 % (2.98 BV). The highest damaged starch was indicated in the flour produced from untreated wheat grains (control) at initial moisture content 10 % (3.29 BV), and it was significantly different from the damaged starch in the flour produced from the treated wheat grains. However, the damaged starch in the flour produced from untreated wheat grains (control) at initial moisture content 10 % (3.29 BV) was not significantly different from the damaged starch in the flour produced from untreated wheat grains (control) at initial moisture content 12.5 % (3.19 BV). Thus, the results showed that the MW heating reduced the damaged starch.

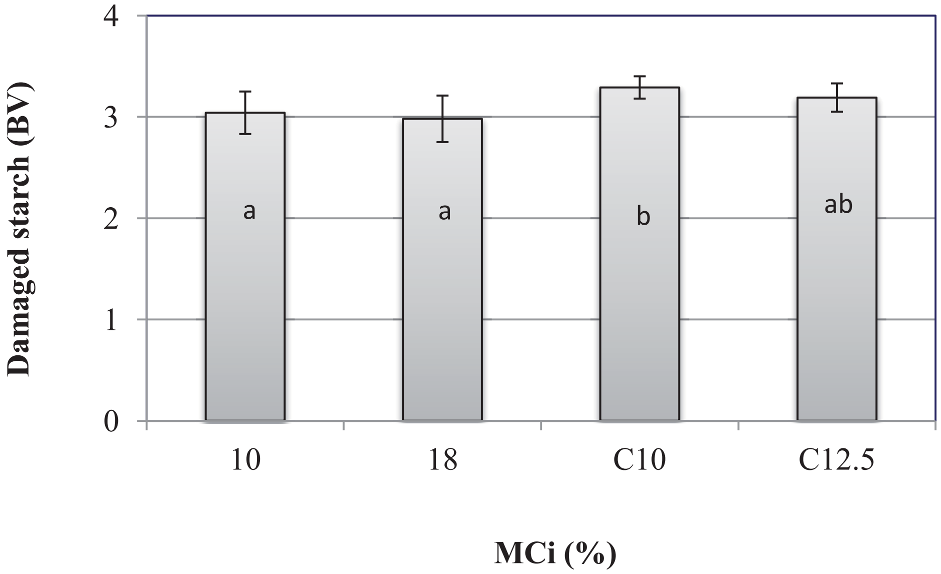


Figure 33: The LSD t-test for the damaged starch after 5 min MW heating as the influence of the initial moisture contents (The same letter shows that there is no significant difference at $P<0.05$; C10 and C12.5, control at initial moisture content 10 and 12.5 %)

Considering the influence of temperature, it is shown in Figure 34 that the damaged starch in the flour produced from the treated wheat grains at temperature 45 °C (3.02 BV) was not significantly different from the damaged starch in the flour produced from the treated wheat grains at temperature 50 and 55 °C, which were obtained at 3.09 and 2.94 BV, respectively. However, the damaged starch in the flour produced from the treated wheat grains at temperature 50 °C was significantly higher than the damaged starch in the flour produced from the treated wheat grains at temperature 55 °C and were not significantly different from the damaged starch in control wheat grains (3.24 BV). The highest damaged starch was found in control wheat grains (3.24 ± 0.13 BV). According to this result, the MW heating showed the tendency to decline the damaged starch.

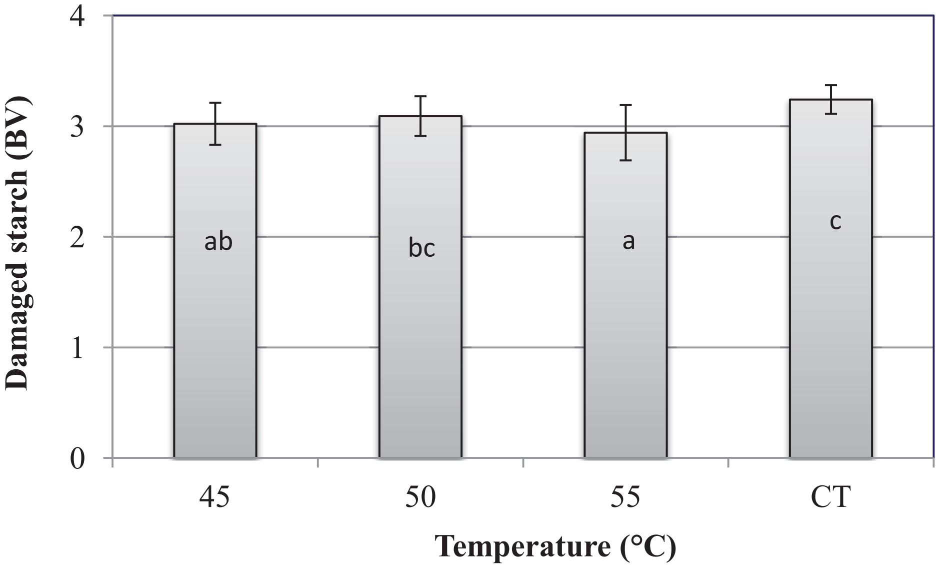


Figure 34: The LSD t-test for the damaged starch after 5 min MW heating as the influence of temperatures (The same letter shows that there are no significant differences at P<0.05; CT, no MW heating)

4.4.2.5. Gluten content

The gluten content varied after 5 min MW heating with different initial moisture contents and surface temperatures and it ranged from 23.1 to 26.66 % (Table 20). ANOVA showed that both moisture contents and temperatures significantly influenced the gluten content. The highest gluten content (26.66 %) was indicated in the flour that was milled from treated wheat grains at initial moisture content and temperature 10 % and 45 °C, respectively.

The LSD t-test for the gluten content in Figure 35 (p. 71) showed that the gluten in the flour that was milled from the treated wheat grains at initial moisture content 10 % (25.16 %) was higher significantly than the gluten in the flour that was milled from the treated wheat grains at initial moisture content 18 % (23.14 %). The same trend was found in 2 control grains studied while the gluten in control at initial moisture content 10 % (25.6 %) was higher significantly than the gluten in control at initial moisture content 12.5 % (22.9 %).

Table 20: The gluten content after 5 min MW heating with different initial moisture contents and temperatures

	MC_i (%)	Temperature (°C)	Gluten (%)
	10	**45**	26.66 ± 1.15
		50	25.33 ± 0.91
		55	23.47 ± 0.52
	18	**45**	25.07 ± 0.53
		50	24.09 ± 0.58
		55	23.10 ± 098
	C10	**CT**	25.57 ± 1.41
	C12.5	**CT**	22.92 ± 0.24
ANOVA on MC_i			s
ANOVA on temperature			s

s, significant; ns, not significant; the statistics were tested at p<0.05
C10 and C 12.5, control at initial moisture content 10 and 12.5 %; CT, no MW heating; the data were presented in mean ± standard deviation

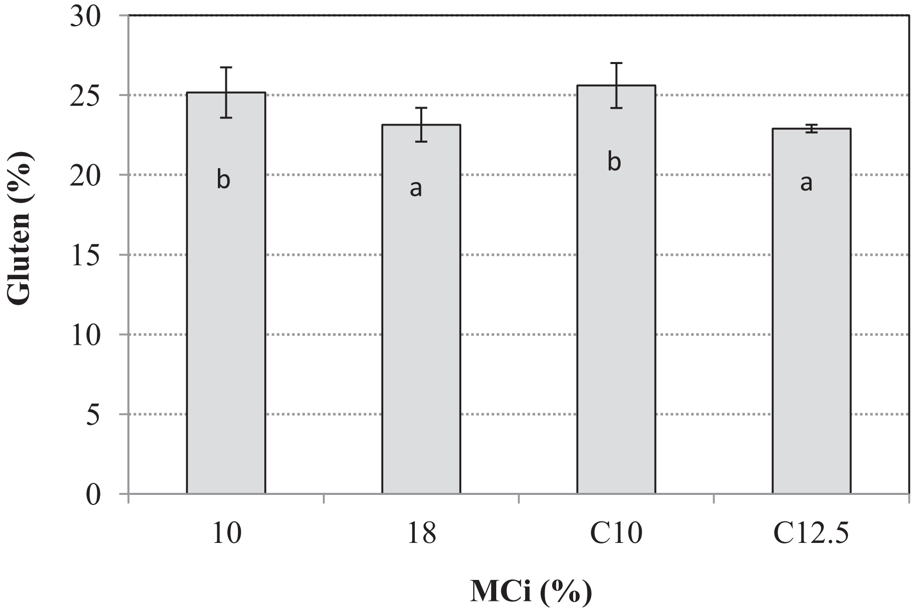


Figure 35: The LSD t-test for the gluten content after 5 min MW heating as the influence of the initial moisture contents (The same letter shows that there are no significant differences at P<0.05; C10 and C12.5, control at moisture 10 and 12.5 %)

The gluten in the flour produced from the treated wheat grains at initial moisture content 10 % was a little bit lower than the gluten in the flour produced from untreated wheat grains (control) at initial moisture content 10 %. In contrast, the gluten content in the flour produced from the treated wheat grains at initial moisture content 18 % was a little bit higher than the gluten in the flour produced from untreated wheat grains (control) at initial moisture content 12.5 %.

In Figure 36, it can be seen that the gluten content decreased significantly as the temperatures were increased. The highest gluten content was indicated in the flour that was milled from the treated wheat grains at temperature 45 °C (25.87 %) and the value was significantly different from the gluten content in control 24.24 %). In contrast, the lowest gluten content was indicated in the flour that was milled from the treated wheat grains at temperature 55 °C (23.31 %), but it was not significantly different from the gluten content in control.

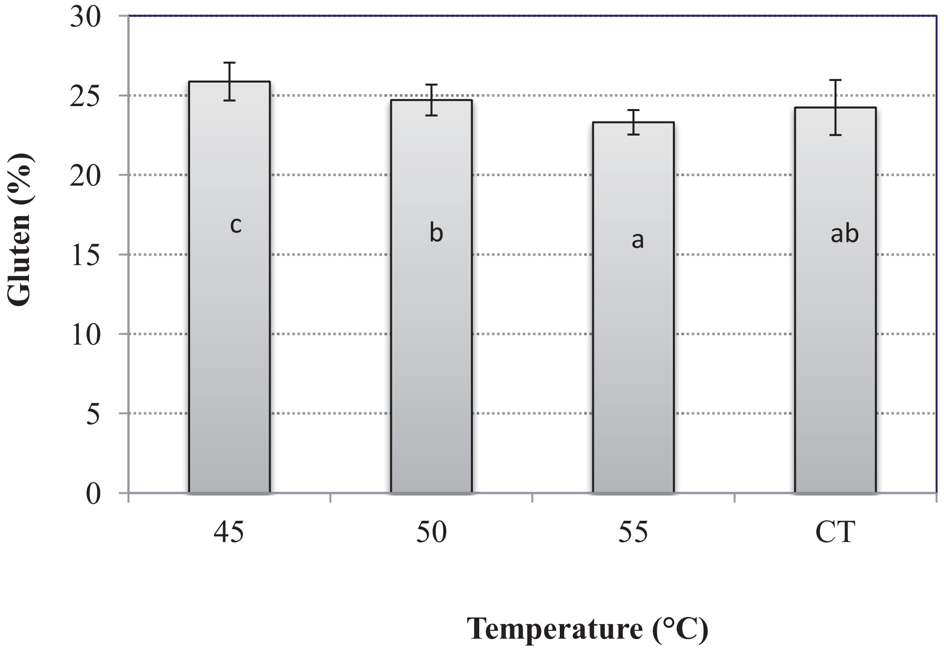


Figure 36: The LSD t-test for the gluten content after 5 min MW heating as the influence of temperatures (The same letter shows that there are no significant differences at $P<0.05$; CT, no MW heating)

4.4.2.6. Dough properties

The dough properties, which were determined by using farinograph, are listed in Table 21. The consistency of dough ranged from 490 to 516 FU. The ideal expected consistency is at 500 FU line, but the consistency at 500±20 was accepted.

Table 21: The mean value of dough properties after 5 min MW heating with different initial moisture contents and surface temperatures of wheat

MC_i (%)	Temperature (°C)	Consistency (FU)	Water absorption (%)	Dev. time (min)	Stability (min)	DOS (FU)	DOS (ICC) (FU)	Quality number (FU)
10	**45**	493	64.5	5.70	8.90	21	50	123
	50	511	64.5	6.35	9.60	27	50	119
	55	495	65.1	5.75	8.50	26	50	115
18	**45**	516	61.0	9.10	14.75	8	32	195
	50	507	61.2	12.85	20.50	8	26	277
	55	514	60.0	10.60	20.65	13	24	259
C10	**CT**	490	65.3	5.75	9.20	19	41	126
C12.5	**CT**	509	62.2	8.10	11.45	8	39	168

DOS, degree of softening; FU, farinograph unit; C10 and C 12.5, control at initial moisture content 10 and 12.5 %; CT, no MW heating

Table 22: The ANOVA of dough properties after 5 min MW heating with different initial moisture contents and surface temperatures of wheat

Dough properties	ANOVA	
	MC_i	Temperature
Consistency	s	ns
Water absorption	s	ns
Development time	s	ns
Stability	s	s
Degree of softening	s	ns
Degree of softening (ICC)	s	ns
Quality number	s	s

s, significant; ns, not significant; the statistics were tested at $p<0.05$

The water absorption decreased at the initial moisture content of the treated wheat grains increased. The development time and stability also took longer time in the flour produced from the treated wheat grains at the initial moisture content 18 %. Two types of degree of softening were displayed. The first one is the degree of softening after 10 min kneading, while the second is the degree of softening (ICC), which represents the degree of softening at 12 min after the peak time. Both of those degrees of softening were found higher in the flour produced from the treated wheat grains at the initial moisture content 10%. This finding indicates that the quality number increased as the moisture increased. It can be seen in ANOVA (Table 22) that the initial moisture content of the treated wheat grains influenced all dough properties significantly. In contrast, the temperature only significantly influenced the stability time and the quality number.

4.4.2.7. Loaf volume

As a result of MW application for 5 min with different initial moisture contents and surface temperatures, it can be seen in Table 23 that the loaf volume of the bread, which was produced from the flour that was milled from the treated wheat grains at the initial moisture content 10 % was higher than the loaf volume of the bread, which was produced from the flour that was milled from the treated wheat grains at the initial moisture content 18 %. The highest loaf volume was obtained from the bread, which was produced from the flour that was milled from the treated wheat grains at temperature 45 °C. As the temperature was increased to 50 °C, the loaf volume decreased, but then it increased again at temperature 55 °C. ANOVA showed that the moisture contents strongly influenced the loaf volume, but the temperatures did not significantly influence the loaf volume.

Table 23: The loaf volume per 100 g flour after 5 min MW heating with different initial moisture contents and surface temperatures of wheat

	MC_i (%)	**Temperature (°C)**	**Loaf volume (ml/100 g flour)**
	10	**45**	215 ± 14.8
		50	201 ± 0
		55	212 ± 2.8
	18	**45**	195 ± 5.6
		50	184.5 ± 7.8
		55	188 ± 0
	C10	**CT**	217 ± 0
	C12.5	**CT**	201 ± 2.8
ANOVA on MC_i			s
ANOVA on temperature			ns

s, significant; ns, not significant; the statistics were tested at $p<0.05$
C10 and C12.5, control at initial moisture content 10 and 12.5 %; CT, no MW heating; the data were presented in mean ± standard deviation

It is shown clearly from Figure 37 (p. 75) that the loaf volume of the bread, which was produced from flour milled from the treated wheat grains at the initial moisture content 10 % (210 ml/100 g flour) was significantly higher than the loaf volume of the bread, which was produced from the flour that was milled from the treated wheat grains at the initial moisture content 18 % (189 ml/100 g flour). The lowest loaf volume was indicated in the bread, which was produced the flour that was milled from the treated wheat grains at the initial moisture content 18 %. In contrast, the highest loaf volume was obtained from the bread baked from the flour that was milled from control grains at the initial moisture content 10 % (217 ml/100 g flour), but it was not significantly different from the loaf volume of bread, which was produced from the flour that was milled from the treated wheat grains at the initial moisture content 10 %. The loaf volume of the bread, which was produced from the flour that was milled from the treated wheat grains at the initial moisture content 10 % was also not significantly different from the loaf volume in control flour at the initial moisture content 12.5 % (201 ml/100 g flour).

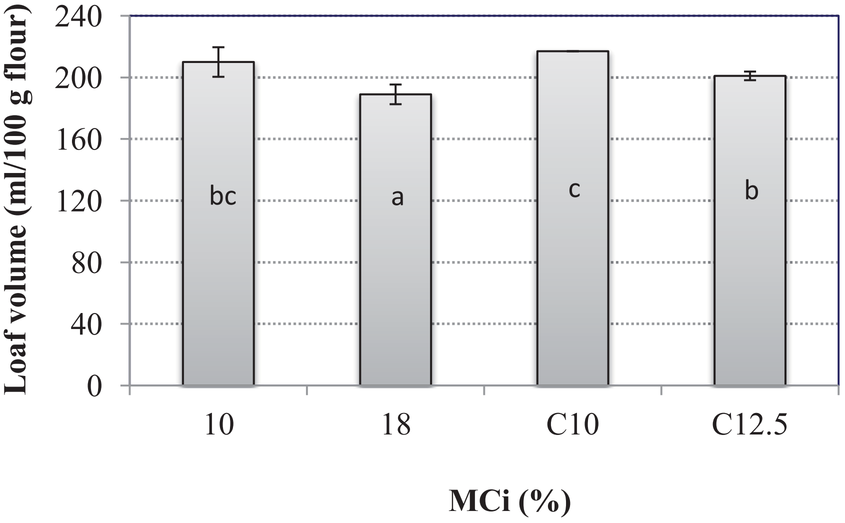


Figure 37: The LSD t-test for the loaf volume per 100 g flour after 5 min MW heating as the influence of the initial moisture contents of treated wheat grains (The same letter shows that there is no significant difference at P<0.05; C10 and C12.5, control at moisture 10 and 12.5 %)

4.4.3. The quality of flour after microwave heating at temperature 50 °C with different initial moisture contents and exposure times

4.4.3.1. Starch content

Starch content after MW heating at temperature 50 °C with different initial moisture contents of the treated grains and exposure times varied from 67.27 to 69.77 % (Table 24).

Table 24: The starch content after MW heating at surface temperature 50 °C with different initial moisture contents and exposure times

	MC_i (%)	**Time (min)**	**Starch (%)**
	10	**0**	67.27 ± 0.63
		5	67.32 ± 0.42
	18	**0**	69.77 ± 0.88
		5	68.63 ± 1.32
	C10	**Ct**	66.60 ± 0.00
	C12.5	**Ct**	68.10 ± 0.00
ANOVA on MC_i			s
ANOVA on time			ns

s, significant; ns, not significant; the statistics were tested at p<0.05
C10 and C12.5, control at initial moisture content 10 and 12.5 %; Ct, no MW heating; the data were presented in mean ± standard deviation

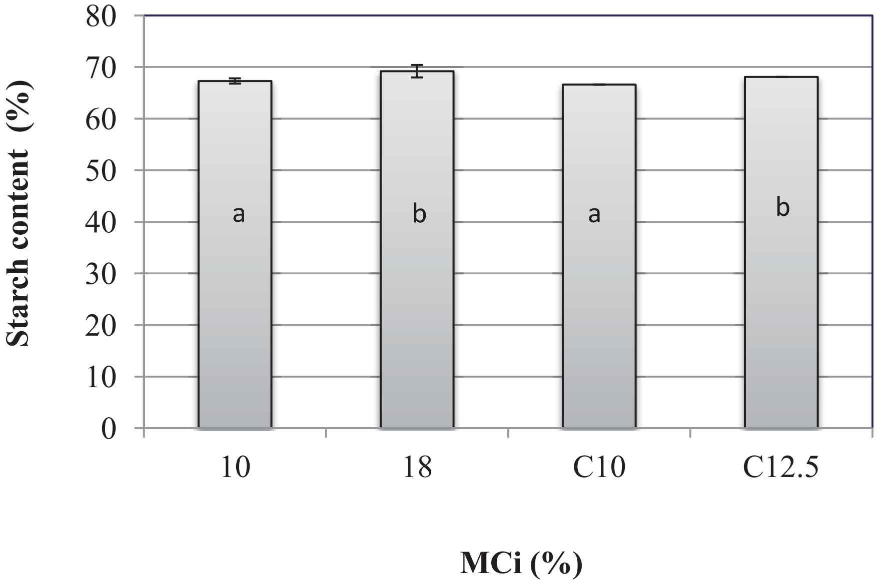


Figure 38: The LSD t-test for the starch content at different initial moisture contents of treated wheat grains (The same letter shows that there are no significant differences at P<0.05; C10 and C12.5, control at initial moisture content 10 and 12.5 %)

The ANOVA showed that the initial moisture content of the treated wheat grains significantly influenced the starch content, while the exposure time showed insignificant differences to the starch content. The LSD t-test (Figure 38, p. 76) showed that the starch content in the flour produced from the treated wheat grains at initial moisture content 18 % (69.2 %) is significantly higher than the starch content in the flour produced from the treated wheat grains at initial moisture content 10 % (67.3 %). However, it was insignificant different from the starch content in the flour produced from the untreated wheat grains at initial moisture content 12.5 % (68.1 %).

4.4.3.2. Falling number

The FNs after MW heating at temperature 50 °C with different initial moisture contents and exposure times highly varied. The FNs ranged from 374 to 375 s in the flour produced from the treated wheat grains at initial moisture content 18 %, and ranged from 390 to 412 s in the flour produced from the treated wheat grains at initial moisture content 10 % (Table 25).

Table 25: The FN after MW heating at targeted surface temperature 50 °C with different initial moisture contents and exposure times

	MC_i (%)	Time (min)	FN (s)
	10	**0**	412 ± 21.1
		5	390 ± 14.4
	18	**0**	375 ± 40.5
		5	374 ± 40.0
	C10	**Ct**	386 ± 7.1
	C12.5	**Ct**	427 ± 5.6
ANOVA on MC_i			ns
ANOVA on time			ns

s, significant; ns, not significant; the statistics were tested at $p<0.05$
C10 and C12.5, control at initial moisture content 10 and 12.5 %; Ct, no MW heating; the data were presented in mean ± standard deviation

The FNs dropped slightly as the moisture was increased as well as the exposure time was extended, but the decrease in FNs in the flour produced from the treated wheat grains at initial moisture content 10 % was higher than the decrease in FNs in the flour produced from the treated wheat grains at initial moisture content 18 %.

However, the ANOVA showed that the FNs were not significantly influenced by the initial moisture content and exposure time variables.

4.4.3.3. Flour viscosity

The RVA profiles after MW heating at temperature 50 °C with different initial moisture contents of grains and exposure times can be seen in Table 26 (p. 78). The pasting temperature ranged from 78 to 80 °C, except in the third repetition in the flour produced from the treated wheat grains at initial moisture content 10 % and 0 min exposure time, there was an evidence of pasting temperature at 66.1 °C. Furthermore, the peak time ranged from 5.4 to 5.7 min.

Table 26: The RVA viscosity profiles among replications after MW heating at temperature 50 °C with different initial moisture contents and exposure times

Treatment			**T_{past}**	**t_{peak}**	**Peak viscosity**	**Holding viscosity**	**Breakdown viscosity**	**Final viscosity**	**Setback viscosity**
MC_i (%)	**time (min)**	**R**	**(°C)**	**(min)**	**(RVU)**	**(RVU)**	**(RVU)**	**(RVU)**	**(RVU)**
10	**0**	**1**	79.6	5.5	239	137	102	256	119
		2	78.6	5.5	240	137	104	251	115
		3	66.1	5.6	235	133	102	244	111
	5	**1**	80.1	5.4	207	122	85	235	114
		2	79.6	5.4	212	128	84	244	116
		3	80.3	5.7	238	135	102	246	111
18	**0**	**1**	80.3	5.6	251	140	111	255	115
		2	80.3	5.5	233	136	97	255	119
		3	80.6	5.5	243	140	102	260	120
	5	**1**	79.9	5.5	247	138	109	258	120
		2	80.4	5.5	238	138	100	255	117
		3	79.1	5.6	249	144	106	262	118
C10	**Ct**	**1**	79.9	5.6	218	128	90	233	106
C12.5	**Ct**	**1**	79.6	5.4	203	122	81	239	117

MC_i, initial moisture content; R, MW repetition; T_{past}, pasting temperature; t_{peak}, peak time; RVU, rapid visco unit; C10 and C12.5, control at initial moisture content 10 and 12.5 %; Ct, no MW heating

The viscosity properties of flour produced from the treated wheat grains at initial moisture content 18 % were higher than the viscosity properties of flour produced from the treated wheat grains at initial moisture content 10 %. In average, the peak and final viscosities in the treated grains were higher than the peak and final viscosities in untreated grains (control). From Table 27 (p. 78), the ANOVA showed that the influence of the initial moisture content of treated grains was significant on the peak, holding, breakdown, final and setback viscosities, whereas the significant influence of exposure times was indicated on peak and breakdown viscosities only.

Table 27: The ANOVA of RVA viscosity profiles after MW heating at temperature 50 °C with different initial moisture contents and exposure times

RVA viscosity profiles	**ANOVA**	
	MC_i	**Exposure time**
Pasting temperature	ns	ns
Peak time	ns	ns
Peak viscosity	s	s
Holding viscosity	s	ns
Breakdown viscosity	s	s
Final viscosity	s	ns
Setback viscosity	s	ns

s, significant; ns, not significant; the statistics were tested at $p<0.05$

4.4.3.4. Damaged starch

The damaged starch among replications after MW heating at temperature 50 °C with different moisture contents and exposure times highly varied. From Table 28, the ANOVA showed that the initial moisture content of treated grains and exposure time significantly influenced the damaged starch. The highest damaged starch was obtained in the flour produced from control grains at initial moisture content 10 % (3.29±0.11 BV), followed by the flour produced from control grains at initial moisture content 12.5 % (3.19±0.14 BV).

Table 28: The damaged starch after MW heating at surface temperature 50 °C with different initial moisture contents and exposure time

	MC_i (%)	**Time (min)**	**Damaged starch (BV)**
	10	**0**	3.12 ± 0.22
		5	3.04 ± 0.23
	18	**0**	2.77 ± 0.13
		5	3.16 ± 0.05
	C10	**Ct**	3.29 ± 0.11
	C12.5	**Ct**	3.19 ± 0.14
ANOVA on MC_i			s
ANOVA on time			s

s, significant; ns, not significant; the statistics were tested at $p<0.05$

C10 and C12.5, control at initial moisture content 10 and 12.5 %; Ct, no MW heating; the data were presented in mean ± standard deviation

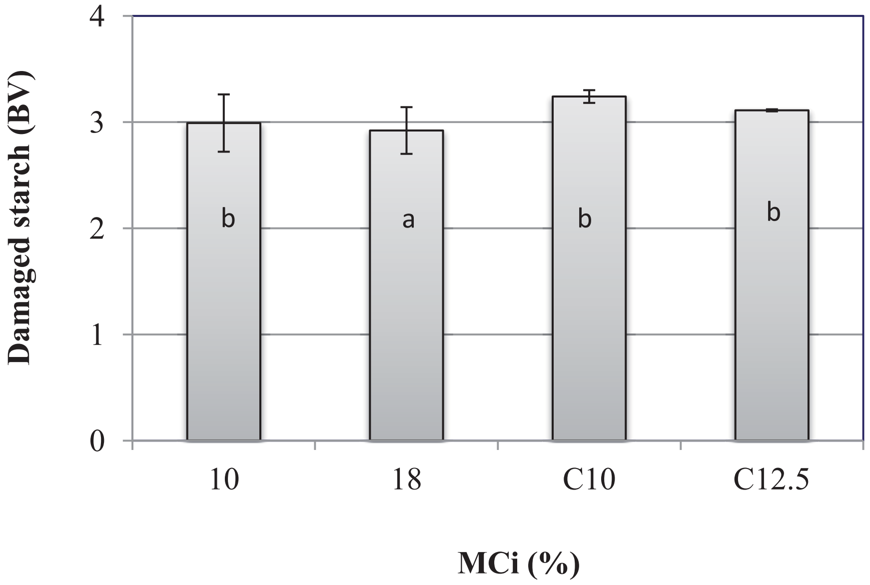


Figure 39: The LSD t-test for the damaged starch after MW heating at temperature 50 °C as the influence of the initial moisture contents (The same letter shows that there is no significant difference at P<0.05; C10 and C12.5, control at moisture 10 and 12.5 %)

The LSD t-test showed that the damaged starch in control flour was higher significantly than the damaged starch in the flour produced from the treated grains at initial moisture content 18 % (Figure 39). In general, the damaged starch in the flour produced from the treated grains was lower than the damaged starch in the flour produced from untreated grains (control). However, the damaged starch in the flour produced from the treated grains at initial moisture content 10 % (2.99 BV) has no significant differences from the damaged starch in the flour produced from untreated grains (control).

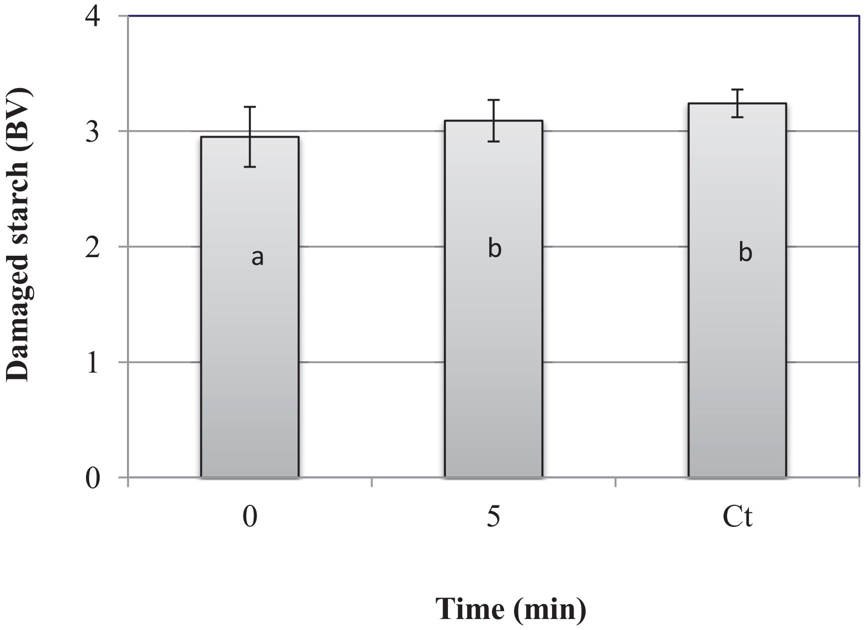


Figure 40: The LSD t-test for the damaged starch after MW heating at temperature 50 °C as the influence of exposure times (The same letter shows that there is no significant difference at $P<0.05$; Ct, no MW heating)

As the influence of exposure time (Figure 40), it can be seen that the extension of MW heating from 0 to 5 min increased the damaged starch significantly. However, the damaged starch in the flour produced from control grains (3.24 BV) were still higher than the damaged starch in the flour produced from the treated grains for 5 min exposure (3.09 BV). Therefore, it can be concluded that the MW heating declined the damaged starch.

4.4.3.5. Gluten content

After MW heating at temperature 50 °C with different initial moisture contents of treated grains and exposure times, the gluten content ranged from 23.86 to 25.33 %. It is clear shown in Table 29 that the gluten contents in the flour produced from the treated and untreated grains at initial moisture content 10 % was above 25 %. However, the gluten content in the flour produced from the treated grains at initial moisture content 18 % was higher than the gluten content in the flour produced from untreated grains at initial moisture content 12.5 %. The ANOVA showed that the influence of moisture to the gluten content appeared significantly, but the influence of exposure time was not significant.

Table 29: The gluten content after MW heating at surface temperature 50 °C with different initial moisture contents and exposure times

	MC_i (%)	Time (min)	Gluten (%)
	10	**0**	25.25 ± 1.21
		5	25.33 ± 0.91
	18	**0**	23.86 ± 0.57
		5	24.09 ± 0.58
	C10	**Ct**	25.57 ± 1.41
	C12.5	**Ct**	22.92 ± 0.24
ANOVA on MC_i			s
ANOVA on time			ns

s, significant; ns, not significant; the statistics were tested at $p<0.05$
C10 and C12.5, control at initial moisture content 10 and 12.5 %; Ct, no MW heating; the data were presented in mean ± standard deviation

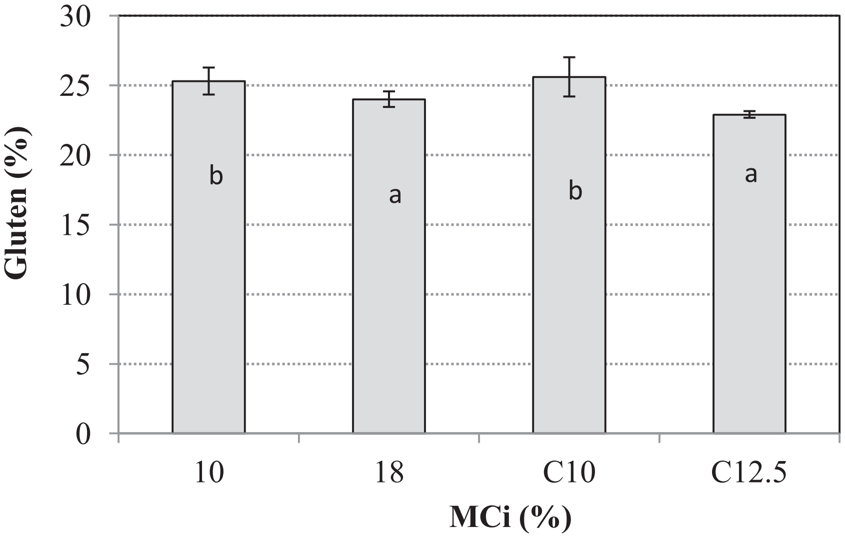


Figure 41: The LSD t-test for the gluten content after MW heating at temperature 50 °C as the influence of the initial moisture contents (The same letter shows that there are no significant differences at P<0.05; C10 and C12.5, control at initial moisture content 10 and 12.5 %)

The LSD t-test in Figure 41 showed that the gluten content in the flour produced from the treated grains at initial moisture content 10 % (25.3 %) is higher significantly than the gluten content in the flour produced from the treated grains at initial moisture content 18 % (24 %), but it was not significantly different from contents in the flour produced from untreated grains (control) at initial moisture content 10 % (25.6 %).

4.4.3.6. Dough properties

It can be seen in Table 30, the water absorption of flour produced from the treated grains at initial moisture content 10 % was approximately 64.5 %, while the water absorption of flour produced from the treated grains at initial moisture 18 % ranged from 60 to 61 %. The highest water absorption was indicated in the flour produced from untreated grains (control) at initial moisture content 10 %. The development time and stability of flour produced from the treated grains at initial moisture 18 % was about 2 fold than the development time and stability of flour produced from treated grains at initial moisture 10 %.

Table 30: The mean value of dough properties after MW heating at temperature 50 °C with different moisture contents and exposure times

MC$_i$ (%)	**time (min)**	**Consistency (FU)**	**Water absorption (%)**	**Dev. time (min)**	**Stability (min)**	**DOS (FU)**	**DOS (ICC) (FU)**	**Quality number (FU)**
10	**0**	491	64.6	6	10.10	19	45	134
	5	511	64.5	6.35	9.60	27	50	119
18	**0**	509	60.4	12.15	20.30	12	27	327
	5	507	61.2	12.85	20.50	8	26	277
C10	**Ct**	490	65.3	5.75	9.20	19	41	126
C12.5	**Ct**	509	62.2	8.1	11.45	8	39	168

DOS, degree of softening; FU, farinograph unit; C10 and C 12.5, control at moisture 10 and 12.5 %; CT, no MW heating

Table 31: The ANOVA of dough properties after MW heating at temperature 50 °C with different moisture contents and exposure times

Dough properties	**ANOVA**	
	Moisture	**Exposure time**
Consistency	ns	ns
Water absorption	s	ns
Development time	s	ns
Stability	s	ns
Degree of softening	s	ns
Degree of softening (ICC)	s	ns
Quality number	s	ns

s, significant; ns, not significant; the statistics were tested at $p<0.05$

ANOVA showed that the significant influence of moisture was indicated in all dough properties, except for the consistency (Table 31). In contrast, the influence of exposure time was insignificant for all dough properties.

4.4.3.7. Loaf volume

The loaf volume of bread per 100 g flour after MW heating at temperature 50 °C with different initial moisture content of the treated grains and exposure times are listed in Table 32.

Table 32: The loaf volume per 100 g flour after MW heating at surface temperature 50 °C with different initial moisture contents and exposure time

	MC_i (%)	Time (min)	Loaf volume (ml/100 g flour)
	10	**0**	204 ± 0
		5	201 ± 0
	18	**0**	180 ± 19.8
		5	184.5 ± 7.8
	C10	**CT**	217 ± 0
	C12.5	**CT**	201 ± 2.8
ANOVA on MC_i			s
ANOVA on time			ns

s, significant; ns, not significant; the statistics were tested at $p<0.05$
C10 and C 12.5, control at initial moisture content moisture 10 and 12.5 %; Ct, no MW heating; the data were presented in mean ± standard deviation

The loaf volume of bread produced from the flour that was milled from the treated grains at the initial moisture content 10 % decreased as the exposure time increased. In contrast, the loaf volume of bread produced from the flour that was milled from the treated grains at the initial moisture content 18 % increased as the exposure time prolonged. ANOVA showed that the initial moisture content of treated grains significantly influenced the loaf volume, but the exposure time did not significantly influence the loaf volume.

Irrespective to Figure 42 (p.84), the LSD t-test showed that the loaf volume of bread produced from the flour that was milled from the treated grains at the initial moisture content 10 % (202 ml/100 g flour) was higher significantly than the loaf volume of bread produced from the flour that was milled from the treated grains at the initial moisture content 18 % (183 ml/100 g flour). The highest loaf volume was indicated from the bread produced from the flour that was milled from untreated grains (control) at the initial moisture content 10 % (217 ml/100 g flour), but it was not significantly different from the loaf volume of bread, which was produced from the flour that was milled from the treated grains at the initial moisture content 10 %

and untreated grains (control) at the initial moisture content 12.5 % (201 ml/100 g flour).

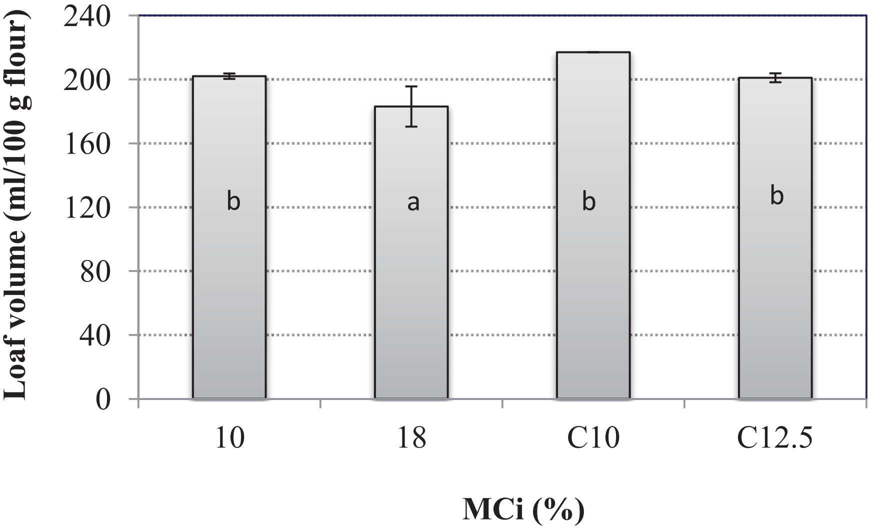


Figure 42: The LSD t-test for the loaf volume per 100 g flour after MW heating at temperature 50 °C as the influence of moisture contents (The same letter shows that there is no significant difference at $P<0.05$; C10 and C12.5, control at initial moisture content 10 and 12.5 %)

4.4.4. The correlation between quality parameters

The Pearson correlation was used to determine the correlation between 2 parameters observed. All combination was tested and only the significant correlation were displayed and later discussed.

4.4.4.1. The correlation between flour quality parameters and dough properties after 5 min microwave heating with different initial moisture contents and surface temperatures

As can be seen in Table 33, the starch has a significant correlation with the peak viscosity (r = 0.393), holding viscosity (r = 0.367) and final viscosity (r = 0.371) at significant level 5 %. Furthermore, it is shown that starch has significant correlation with gluten content (r = 0.322) at significant level 5 %, whereas the FN has significant correlation with the damaged starch (r = 0.450) at significant level 1 %.

The pasting temperature has significant correlation with the final viscosity (r = 0.332) at significant level 5 %. The peak viscosity has stronger correlation with the holding viscosity (r = 0.901) and the final viscosity (r = 0.716) at significant level 1 %. The holding viscosity has significant correlation with the final viscosity (r = 0.897) at significant level 1 %. The negative correlation of loaf volume was indicated significantly with the final viscosity (r = -0.828) at significant level 1 %.

Table 33: The Pearson correlation flour quality parameters after 5 min MW heating with different initial moisture contents and temperatures of wheat grains

Parameters	Correlation
Starch vs. Peak viscosity	0.393*
Starch vs. Holding viscosity	0.367*
Starch vs. Final viscosity	0.371*
Starch vs. Gluten content	0.322*
Falling number vs. Damaged starch	0.450**
Pasting temperature vs. Final viscosity	0.332*
Peak viscosity vs. Holding viscosity	0.903**
Peak viscosity vs. Final viscosity	0.716**
Holding viscosity vs. Final viscosity	0.897**
Loaf volume vs. Final viscosity	-0.828**

*, Correlation is significant at the 0.05 level; **, Correlation is significant at the 0.01 level

Table 34: The Pearson correlation between loaf volume and dough properties after 5 min Mw heating with different initial moisture contents and temperatures of wheat grains

Parameters	Correlation
Loaf volume vs. Consistency	-0.719**
Loaf volume vs. Water absorption	0.834**
Loaf volume vs. Development time	-0.845**
Loaf volume vs. Stability	-0.826**
Loaf volume vs. Degree of softening	0.505*
Loaf volume vs. Degree of softening (ICC)	0.701**
Loaf volume vs. Quality number	-0.822**

*,. Correlation is significant at the 0.05 level; **, Correlation is significant at the 0.01 level

It can be seen from Table 34 that the loaf volume was indicated to have a strong correlation at significant level 1 % with all dough properties, except for the degree of softening. The fact determines that those dough properties are relatively important to be considered in producing the high quality of bread.

4.4.4.2. The correlation between flour quality parameters and dough properties after microwave heating at temperature 50 °C with different initial moisture contents and exposure times

As it is shown in Table 36, the starch has a correlation with peak viscosity (r = 0.417) at level 5 %, holding viscosity (r = 0.424) at level 5 % and final viscosity (r = 0.520) at level 1 %. Furthermore, the starch has negative correlation with the damaged starch (r = 0.386) and gluten content (r = 0.380) at significant level 5 %. The pasting temperature has significant correlation with peak viscosity (r = 0.598) and holding viscosity (r = 0.582) at level 1 %. The peak viscosity has strong correlation with holding viscosity (r = 0.953) and final viscosity (r = 0.840) at level 1 % and the holding viscosity has significant correlation with the final viscosity (r = 0.895) at level 1 %.

Table 35: The Pearson correlation between flour quality parameters after MW heating at temperature 50 °C with different initial moisture contents and exposure times

Parameters	Correlation
Starch vs. Peak viscosity	0.417*
Starch vs. Holding viscosity	0.424*
Starch vs. Final viscosity	0.520*
Starch vs. Damaged starch	-0.386*
Starch vs. Gluten content	-0.380*
Pasting temperature vs. Peak viscosity	0.598**
Pasting temperature vs. Holding viscosity	0.582*
Peak viscosity vs. Holding viscosity	0.953**
Peak viscosity vs. Final viscosity	0.840**
Holding viscosity vs. Final viscosity	0.895**
Loaf volume vs. Starch	-0.763**
Loaf volume vs. Damaged starch	0.645*
Loaf volume vs. Peak viscosity	0.594*
Loaf volume vs. Final viscosity	0.664*

*,. Correlation is significant at the 0.05 level; **, Correlation is significant at the 0.01 level

It was also indicated that the loaf volume was found to have negative correlation with starch (r = 0.763) at significant level 1% and positive correlation with damaged starch (r = 0.645) at significant level 5 %. The negative correlation of loaf volume was also indicated with peak viscosity (r = 0.594) and final viscosity (r = 0.664) at significant level 5 %. The significant correlation of loaf volume with dough properties is listed in Table 36, but there is no significant correlation between the loaf volume and the degree of softening of the dough.

Table 36: The Pearson correlation between loaf volume and dough properties after MW heating at temperature 50 °C with different initial moisture contents and exposure times

Parameters	Correlation
Loaf vs. Consistency	-0.668*
Loaf vs. Water absorption	0.816**
Loaf vs. Development time	-0.889**
Loaf vs. Stability	-0.757**
Loaf vs. Quality number	-0.610*

*,. Correlation is significant at the 0.05 level; **, Correlation is significant at the 0.01 level

V. Discussion

5.1. Heating uniformity

According to literatures, the MW applicator generates an irregular temperature distribution inside the products (Metaxas and Meredith, 1993), resulting in low quality of heating uniformity. Considering this disadvantage of using the MW applicator, the heating uniformity was studied as a main interest with the expectation to improve its quality.

5.1.1. Heating uniformity based on the uniformity index

In some treatments, it was found that the uniformity indexes highly varied among the replications, which was signed high standard deviations (Table 6, p. 47 and Table 7, p. 48). The evidences were probably caused by the high variation in the initial temperatures among the MW repetitions ranging from 7 to 23 °C since the uniformity index as it was suggested by Wang *et al*. (2005) was influenced by the increase of mean and standard deviation of temperatures. Therefore, to avoid such problem in further experiment, it is necessary to apply a certain level of initial temperatures uniformly.

The uniformity indexes in this study ranged from 0.152 to 0.244 while the lowest uniformity index was indicated at moisture 18 % and temperature 50 °C. It can be seen that the increase in moisture led to the decrease in the uniformity index. Wang *et al*. (2007a) confirmed that the smaller the uniformity index the better the heating uniformity. Thus, it can be concluded that the best heating uniformity is obtained in treated grain at initial moisture content 18 %.

Furthermore, Wang *et al*. (2007a) suggested that the operational conditions could influence the heating uniformity of the final product temperature. They found that the unwashed pre-condition for walnuts had better heating uniformity than the washed pre-condition. The lowest uniformity index was obtained about 0.062 at following operational conditions of the walnuts: unwashed pre-condition, moving, mixing, and using hot air. In the recent study, Wang *et al*. (2008) clarified that the heating uniformity is also influenced by size, geometry, and properties of agricultural products. They investigated that the small-size crops performed better heating uniformity than the large-size crops, which could explain the obtained heating uniformity in present study.

The uniformity index is expected to be a quality control for the heating uniformity. However, irrespective to our experience, the uniformity index from Wang *et al*. (2005) is relatively influenced by the level of the initial temperature. It seems that the comparison of indexes between two or more different studies is not reasonable. Moreover, many factors could be a constraint in using this analysis such as the size and shape of the tray, and the instrumentation for the temperature measurement to be used.

Nevertheless, the study of the uniformity index is very important to be used as a parameter for improving the quality of heating uniformity under the application of MW as well as RF energy. Therefore, the further experiments should be conducted with the expectation to find the standardized uniformity index procedure for the heating uniformity assessment.

5.1.2. Heating uniformity based on hot and cold spot areas

From the infrared images with medical palette, the location of hot and cold spot can be seen clearly (Figure 23, 24, 25 and 26, pp. 50-53). In contrast to the uniformity index study, the variation of the initial temperature did not cause the variation on the size of hot and cold spot areas. The independence of initial temperature to the final temperature is probably affected by the MW heating procedure applied in this study (Figure 14, p. 28). Our results showed that the hot and cold spot areas decreased as the initial moisture content of treated grains increased (Table 8, p. 49 and Table 9, p. 54).

The hot spot area was always found smaller than the cold spot area because the hot spot areas are only produced along the core part of the tray. In contrast, since the tray has a ring-shape, the cold spot areas are produced along the inner and outer edge of the tray. It is estimated that the heat convection and radiation loss occurred in the edge part of the tray (Figure 43). The heat loss by convection was caused by the rotation of the tray while the heat loss by radiation was caused by the MW heating. However, according to Metaxas and Meredith (1993), the benefit of using the rotating tray was to improve the heating uniformity.

Furthermore, the cold spot area along the outer edge of tray was found higher than the cold spot area along the inner edge of the tray indicating that the heat loss in the outer edge was higher, which was caused by the convection and radiation heat transfer on its surface (Figure 43). In addition, the length of the outer edge circumference was longer than the length of the inner edge circumference. Therefore, the higher circumference velocity was also estimated to cause the higher heat loss.

The smallest hot and cold spot areas were obtained in treated grains at initial moisture content 18 %, with the hot spot area ranged from 15 to 18 %, and the cold spot area varied from 18 to 21 %. The sump up of hot and cold spot areas varied from 31 to 38 %, while with respect to the normal distribution (Figure 17, p. 33), the area under the definition of hot and cold spot is about 32 %. This cold spot area should be reduced as much as possible since it will lead to the failure of insect pest control.

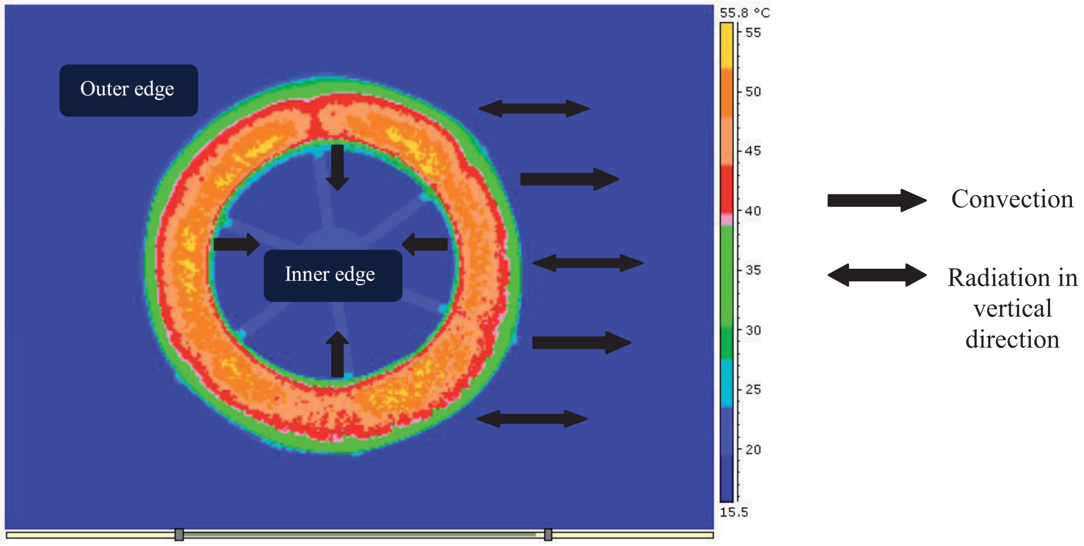


Figure 43: The heat convection and radiation loss

The temperature increase and the prolongation of exposure time also contributed to the decrease in hot and cold spot areas. Taken together, there is a correlation between the uniformity index and the hot and cold spot areas analyses, where the best heating uniformity was found at the same treatment condition, that is, on treated grains at initial moisture content 18 %, temperature 55 °C and exposure time 5 min.

However, compared to the uniformity index, the hot and cold spot analysis would be more comfortable to be used since the definition of hot and cold spot areas can be modified according to the need, and the result can be shown both qualitatively and quantitatively. Qualitatively, the level of heating uniformity can be suggested based on the percentage of hot and cold spot area, while quantitatively; the experimental data distribution can be shown in detail since the analysis is made by using the PDF of the experimental temperature distribution.

5.1.3. Improving the quality of heating uniformity under microwave heating

There are several approaches, which can be used to improve the quality of heating uniformity under MW heating by reducing both the hot and cold spot areas.

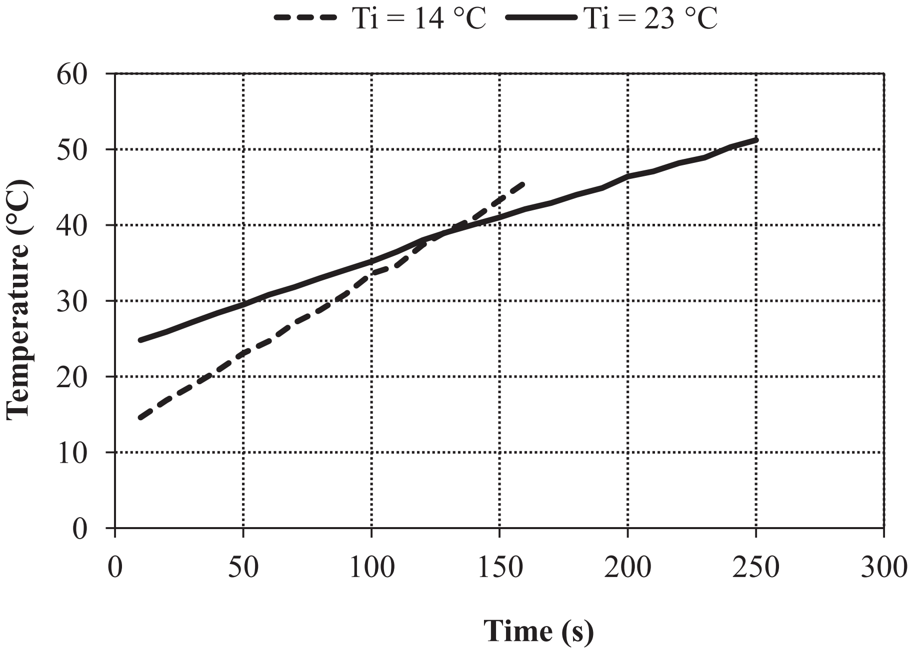
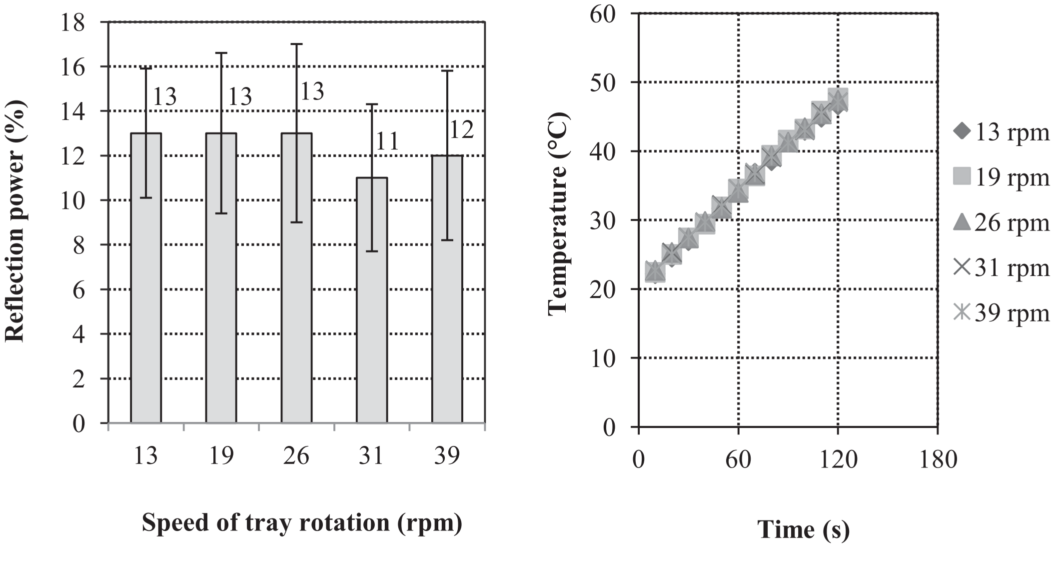


Figure 44: The differences in heating rates due to the differences in initial temperatures

Firstly, starting the MW heating at properly initial temperature could contribute the improvement of the heating uniformity quality. Irrespective to Figure 44, it can be seen that the differences in initial temperature lead to the differences in heating rates. The sharper the slope of the curve determines the higher the heating rate. The fact probably could be explained by the differences in energy absorption because it was noticed that the lower the initial temperature the higher the energy absorption was obtained.

It was derived from the experimental data that with the initial temperature 14 °C, the absorption power was about 87 %, while with the initial temperature 23 °C, the absorption power was 70 % (Figure 44). However, according to Semenov and Zharova (2006), when the MW heating control is based on the surface temperature of the product, a stable heating uniformity on the product can only be achieved if the increases of absorption power and temperature are not too sharp.

Secondly, the use of a wall heater is expected to improve the heating uniformity by means of reducing the heat conduction and convection loss. As it was studied by von Hoersten (1995), with the use of wall heater, the temperature increased to 75 °C after 180 s MW heating at constant power 300 W, while without using the wall heater, the time needed was longer than 300 s. He suggested that the use of wall heater reduced the heat radiation loss in the cavity. Irrespective to the investigation of von Hoersten (1995) study, it seems that the heating rate was also improved resulting the faster the temperature increase.



(a) (b)

Figure 45: The average reflection power (a) and the temperature profile (b) as the influence of different tray rotation speed

The higher the energy absorption determines the lower the heat loss. If the wall temperature is higher than the product temperature, the energy absorption will be higher and in consequence, the heat radiation and convection loss will be reduced. In relation to the result from von Hoersten (1995) study, it can be concluded that the benefit of using wall heater is the same as the benefit of starting the MW heating at low initial temperature, which is shown in Figure 44.

Thirdly, under batch system of MW, the heating uniformity can be improved with the use of a wave stirrer or a rotating tray (Metaxas and Meredith, 1993). However, the optimum speed rotation of the tray should be determined. As can be seen in Figure 45b, it was found that the temperature profiles at different speed rotation were not different. In contrast, the reflection power was influenced by the speed rotation of tray (Figure 45a). The lowest reflection power (11 %) was obtained at speed 31 rpm. Moreover, it should be considered that the relatively high speed rotation is not reasonable and will disturb the temperature measurement.

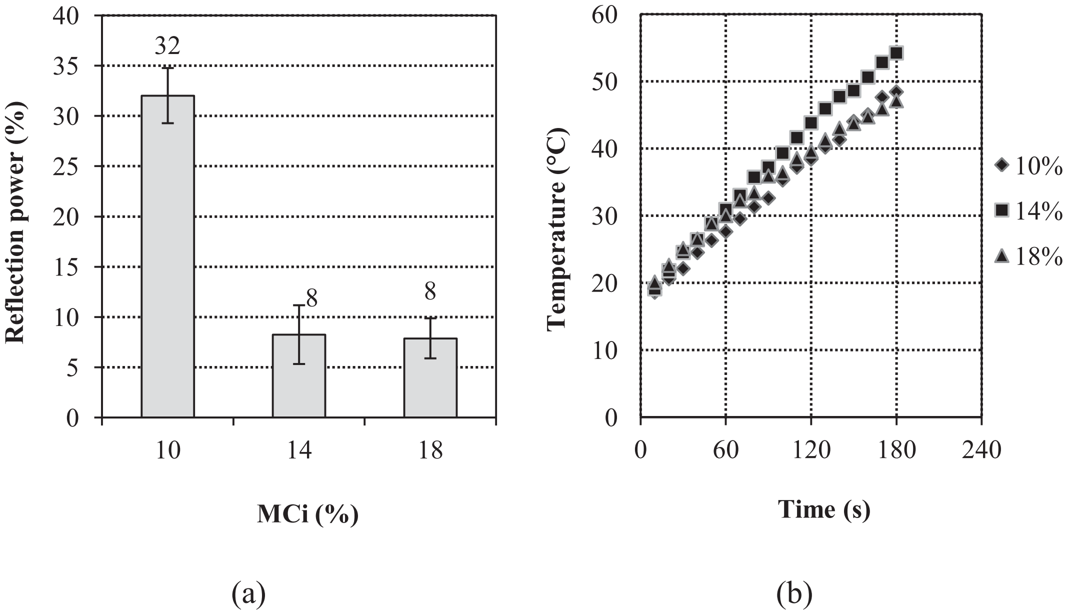
Moreover, the heating uniformity can be improved by controlling the uniformity of the initial moisture content (Mitcham *et al*., 2005). Irrespective to this suggestion, the moisture content of grain in our study was controlled with the accuracy ± 0.2 %.

5.2. The mortality of *Oryzaephilus surinamensis*

The MW heating effect on the mortality of the insects could not be explained simply. In the recent research, Lu *et al*. (2011) found that the MW heating caused the destruction in epidermis, the reduction and aggregation of the fat body, and the destruction of the mitochondria and Golgi bodies. Those destructions are believed to cause the death.

5.2.1. The mortality of *Oryzaephilus surinamensis* as the influence of initial moisture contents

Many studies displayed that the dielectric properties are influenced by the moisture content (Nelson and Stettson, 1976; Ajibola, 1985; Sokhansanj and Nelson, 1988; and Guo et al., 2008). Furthermore, the results of the present study showed that the initial moisture content of treated grains significantly influenced the mortality of adult and larva stages of *O. surinamensis*. This finding was confirmed by Vadivambal (2009), who found that the increase in moisture content led to the increase in mortality of *T. castaneum*. That could be explained by the correlation of the moisture content with the dielectric properties. Many studies described that the increase in moisture content will lead to the increase of the dielectric loss factor of the grain. For example, Sokhansanj and Nelson (1998) investigated that the increase of wheat moisture from 10.4 to 18.2 % led to the increase of dielectric loss factor from 0.26 to 0.75. Irrespective to the Eq. 3 (p. 10), as the dielectric loss factor increase, the higher energy absorption would be expected or in other words the lower the energy would be reflected.



(a) (b)

Figure 46: The average reflection power (a) and the temperature profile (b) as the influence of the initial moisture contents

It was noticed in this study that the average of reflection power in treated grains at initial moisture content 10 % was about 32 %. By increasing the moisture contents to 14 and 18 %, the average reflection power dramatically decreased to 8 % (Figure 46a). Based on this experimental data, it can therefore be proved that the increase in moisture content contributes to the increase of energy absorption. However the absorption power at moisture 14 and 18 % was not different. Irrespective to Figure 46b, the differences in initial moisture contents also influenced the differences in heating rate. The highest heating rate was obtained in treated grains at initial moisture content 14 %, followed by treated grains at initial moisture content 18 and 10 %. This result probably could be used to explain about the incident of higher mortality of larvae at moisture 14 % compared to the mortality of larvae at moisture 18 % (Figure 27b, p. 56 and 29b, p. 59).

However, Nelson (1996) noted that the increase of moisture content will lead to the decrease in penetration depth (Eq. 8, p. 12). The reduction of penetration depth can be illustrated by using the data from Sokhansanj and Nelson (1988) as shown in Figure 47. It can be seen that the penetration depth was declined from 12 to 5.2 cm by increasing the moisture contents from 10.4 to 18.2 %. Nevertheless, the factor of penetration depth for this study can be neglected since the depth of wheat grains used was about 1.5 cm.

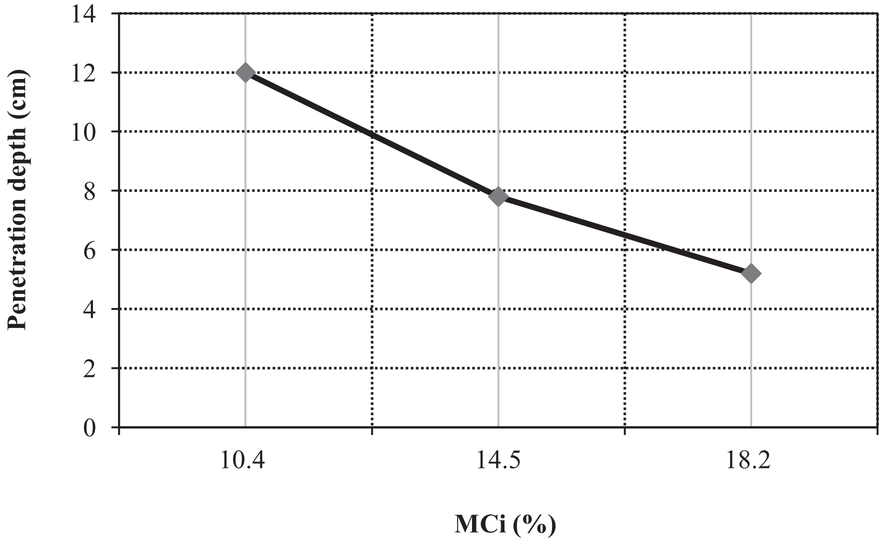


Figure 47: The decrease of penetration depth as the increase of moisture content for hard red winter wheat at frequency 2.45 GHz (Calculated by using the data from Sokhansanj and Nelson, 1988)

5.2.2. The mortality of *Oryzaephilus surinamensis* as the influence of surface temperatures

The next important variable to cause the mortality is the temperature. The results showed that with different initial moisture contents of treated grains and constant exposure time 5 min, the temperatures significantly influenced the mortality of adults, larvae and pupae of *O. surinamensis* (Figure 28, p. 56), which increased as the temperature increased. This result can be explained by the incident that the increased temperature will lead to the increase of the dielectric properties in the solid materials (Ndife *et al*., 1998 and Guo *et al*., 2008)

In average, the highest mortality was obtained at pupa stage, followed by the larva and adult stages. It can be concluded that the adult stage is the most resistant stage to the heat treatment generated by using MW energy. Irrespective to Figure 28 (p. 57), the adult mortality increased sharply with the temperature increase showing that the mortality was affected strongly by the temperature. About 100 % mortality of adults and larvae was reached at temperature 55 °C after 5 min exposure time.

The temperature range to reach the mortality of the insect is determined as the lethal temperature and this lethal temperature depends on the specific species. However, in general the zone of lethal ranging from 50 to 60 °C will cause the death in minutes while the lethal temperature at 45 °C will cause the death in hours (Fields, 1992). By using MW energy at frequency 2.45 GHz, Zhao *et al*. (2007) controlled 100 % of *S. oryzae* L. at temperature 55 °C, while Singh *et al*. (2011) killed 100 % of *C. chinensis L.* at temperature ranging from 50 to 80 °C.

Many studies by means of conventional heating methods had also shown the effect of temperature ranging from 40 to 90 °C on the mortality of pest insects (Bell, 1983; Sokhansanj *et al*., 1992; Smith and Lay-Yee, 2000; Wang *et al*., 2002). Beckett *et al*. (2007) confirmed that the mortality of an insect was a function of temperature as well as exposure time. Therefore, there is no doubt that the use of thermal heating either with the conventional or MW heating could be applied to control the insect pests.

Considering the mechanism of dielectric heating as the volumetric heating, the dielectric heating by using MW applicator is expected to reach the lower lethal temperature than the conventional one and it is reasonable with the findings from Lu *et al*. (2010). Lu *et al*. (2011) studied that the MW heating caused the destruction of insect body structure that is believed to be the cause of the death. However, the conventional heating affected the higher destruction on the insect body structure.

Regarding the mortality test under conventional heating by using air oven (Figure 18, p. 34), it was found that the adult and larva stages of *O. surinamensis* can be controlled at 50 °C after 5 min exposure time. The comparison of conventional and MW heating method in controlling *O. surinamensis* after 5 min exposure time can be seen in Figure 47. It shows that the mortality of adults treated by using MW heating is lower than that of treated by using the conventional heating. In contrast, the mortality of larvae treated by using MW heating is higher than that of treated by using the conventional heating. These results show that the body structure of the insect react differently to those two heating methods. Fields (1992) confirmed that the lethal temperature vary considerably and depend on species, stage life, acclimation and humidity.

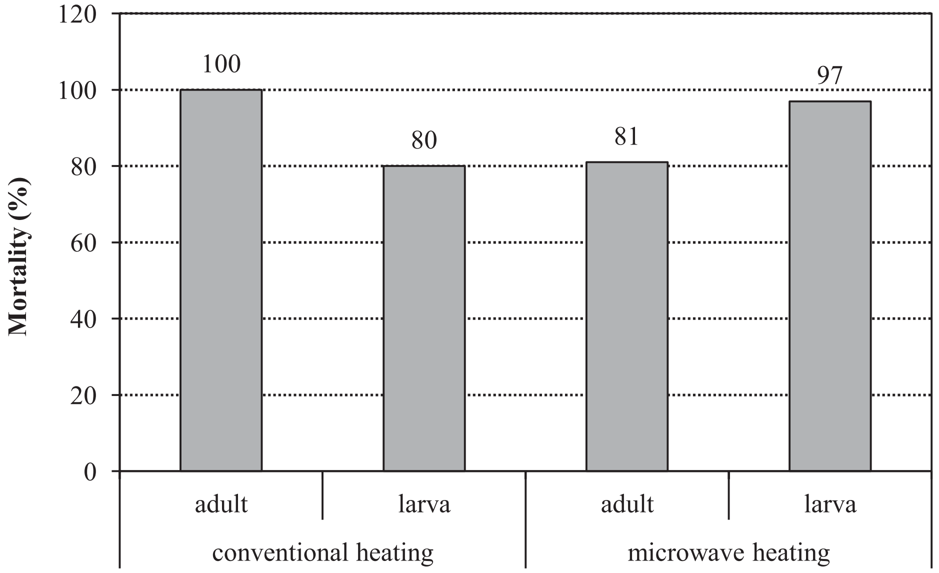


Figure 47: The mortality of *Oryzaephilus surinamensis* with different heating methods at temperature 50 °C and 5 min exposure time

5.2.3. The mortality *Oryzaephilus surinamensis* as the influence of exposure times

Results showed that with different moisture contents and constant temperature, the exposure times significantly influenced the mortality of adult and larva stages of *O. surinamensis* (Figure 30, p. 59). In average, it was found that the mortality of larvae was higher than the mortality of adults.

As it was confirmed previously, there is a negative correlation between the temperature and the exposure time to the mortality rate, that is, the higher the temperature the shorter the time needed to have 100 % mortality of the insect pests (Bell, 1983; Sokhansanj *et al*., 1992; Smith and Lay-Yee, 2000; Wang *et al*., 2002). It was shown in Figure 3 (p. 9) that the time required to achieve 100 % mortality of 600 fifth-instar *A. transitella* decreased with increasing temperature in a logarithmic manner (Wang *et al*., 2002). According to the literatures, under conventional heating

(Subchapter 2.2., pp. 8-10), the time needed to reach 100 % mortality of insect pests ranged from 3 min to 96 h, while by using MW heating (Subchapter 2.5., pp. 19-20), the time needed to control the insect pests varied from 18 to 240 s. However, since this study with the variation of moisture contents and exposure times was conducted only at temperature 50 °C, it is not possible to draw the correlation between the temperatures and exposure times.

5.2.4. The mortality at different life stages of *Oryzaephilus surinamensis*

The adult of *O. surinamensis* were found to be more resistant to the MW heating than the larvae since the mortality of adults was lower than that of larvae. This finding was confirmed by Vadivambal (2009) who found that the adult of *T. castaneum* was the most resistant stage to the MW heating. In addition, he found that pupae stage of *T. castaneum* was as strong as the adult, whereas the least resistant stage was the egg.

In contrast, Wang *et al*. (2007) found that the fifth instar larvae of *A. transitella* [*Walker*]) were most resistant to the heat treatment. It is estimated that the different reaction of adults and larvae to the MW irradiation probably is caused by the difference in their body structures. Moreover, as it was reported in many studies, the MW heating is relatively sensitive to the dielectric properties of material.

This study cannot explain the effect on MW heating to the mortalities of pupae and eggs. The experiments on pupa and egg stages were conducted, but the results were not satisfactory due to the high number of mortality in control. The result on pupae mortality was shown, but the result on eggs mortality was not presented (since it was the worst one). A high number of pupae mortality was estimated due to the preparation process to meet the treatment procedures. Naturally, the pupae were installed below the broken grain or inside the groove of wheat kernel. It was estimated that they are very sensitive to any vibration or movement. Therefore, it is recommended for the further study to find the better method for preparing pupae as well as eggs.

Considering the efficiency of controlling the insects by using MW applicator, probably the most effective stage to be controlled is egg. The suitable time of grain disinfestations could be investigated by studying the life cycle of the insects to prevent their infestation. Moreover, for the industrial application, the continuous system is preferable than the batch system. Thus, the further research in controlling the insect pests by using the MW applicator under a continuous system is recommended

5.2.5. The effect of heating uniformity on the mortality of *Oryzaephilus surinamensis*

The heating uniformity is believed to support the mortality of the insects. In the real storage environment, the insect is distributed well and randomly. There is also the ability of the insect, especially in adult and larva stages, to protect themselves by moving as soon as they recognize the heat or other hazardous condition.

According to our results, the quality of heating uniformity and the mortality rate increased as the initial moisture contents and surface temperatures were increased, and as the exposure times were prolonged. It can be concluded that the heating uniformity contributed positively to the mortality rate.

It must be mentioned that since the treated insects in our study were covered by using plastic wrap, the insects could not move to the cold spot areas. However, in the practical application, the present of cold spot areas would be a constraint in controlling the insect pest, especially in their active life stage. Therefore, as it was suggested by Tang *et al*. (2007), the present of cold spot areas should be reduced.

5.3. The influence of microwave heating on germination rate

5.3.1. The influence of initial moisture contents on germination rate

Under MW heating for 5 min exposure time at different moistures and temperatures, our results showed that the initial moisture contents of treated grains did not significantly influence the germination rate. In average, the germination rates in treated grain were above 95 %, while the germination rate in control was 96 %. However, after the MW heating at temperature 50 °C with different moistures and exposure times, it was found that the initial moisture contents of treated grains significantly influenced the germination rate.

The increase in the initial moisture contents of treated grains led to the decrease in germination rate. This finding is in agreement with the investigation of Vadivambal (2009), who found that the germination rate in treated grains at initial moisture content 14 % is significantly higher than the germination rate in treated grains at initial moisture content 16 and 18 % (Figure 48, p. 101). The higher the energy absorption in the treated grains by using MW heating at higher initial moisture content could be contributed to the lower the germination rate. Moreover, according to El Balla *et al*. (2011), the higher moisture content also decreased the seed maturity and resulted in the decrease in germination rate.

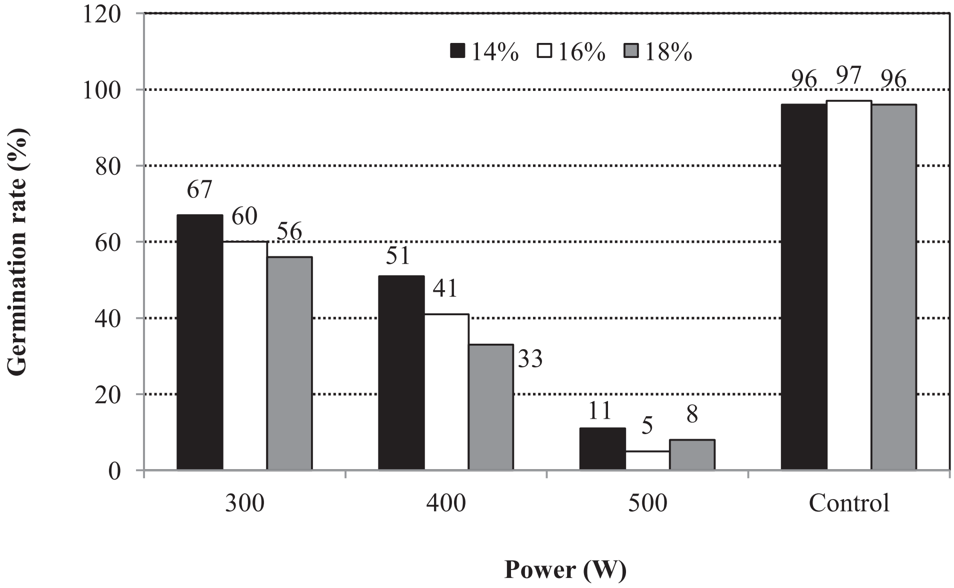


Figure 48: Germination rate of wheat treated by using MW heating at 28 s with different powers and moistures (Vadivambal, 2009)

5.3.2. The influence of surface temperatures on germination rate

After 5 min MW heating with the variation of moistures and temperatures, ANOVA showed that the germination rates were significantly influenced by the temperature increase (Figure 31, p. 61). According to Warchalewski *et al*. (2011), the temperature above 64 °C would destroy the grains quality. Since the temperatures in our study were controlled at 3 levels 45, 50 and 55 °C, the germination rates of grains were high above 95 %. However, the present of hot spot areas is estimated to influence the germination rate.

As it is shown in Figure 48, Vadivambal (2009) investigated that the germination rates decreased significantly as the powers increased. In contrast to our study, Vadivambal (2009) noticed relatively high reduction in germination rates. For example at power 300 W, the germination rates at moisture 14 and 18 % were about 67 and 56 %, respectively. Since he reported that the average temperature of wheat surface at 500 W was 93 °C, it could be estimated that the low germination rate in Vadivambal's experiment was caused by the uncontrolled temperature above 64 °C.

Considering Vadivambal (2009) results, it can be concluded that the use of relatively high temperature should be avoided. The temperature should be targeted to reach both disinfestations and quality protection. It is recommended to control the temperature in the region that is safe to the product but is lethal to the insect pest (Figure 4, p. 10). If the temperatures were controlled under the quarantine region as it was applied in our study, even the application of MW heating up to 5 min exposure time did not show any significant reduction in germination rates. While if the temperature is not controlled at the safe level, the application of MW heating for 28 s will reduce the germination rate dramatically (Vadivambal, 2009).

Manickavasagan *et al*. (2007) also confirmed that the germination of wheat grain after MW heating (laboratory scale MW, industrial continuous type at frequency 2.45 GHz) was reduced significantly, especially above the power 300 W. It was noticed that the temperatures ranged widely from 37.5 to 117 °C and 44 to 131 °C for 28 and 56 s heating treatment, respectively. They also determined the germination rates under hot spot and normal heating zones. It was found that the germination rate of grains collected from hot spot zone was lower significantly than the germination rate of grains collected from normal heating zone. This finding suggests that the temperature influences the germination rate significantly.

5.3.3. The influence of exposure times on germination rate

The results of germination rate can be seen in Table 13 (p. 63). In contrast to our result, Manickavasagan *et al*. (2007) and Vadivambal (2009) suggested that the exposure time significantly influenced the germination rate. Since the MW operation at a constant power will lead to the temperature increase in linear manner, the longer the exposure time the higher the temperature will be obtained. Thus, the significant reduction in germination rates by prolonging the exposure times is strongly correlated to the temperature increase.

However, as the temperature can be controlled accordingly to the quarantine region (Figure 4, p. 10), the germination rate in treated grains in our study can be enhanced. In addition, the MW application until 5 min exposure time did not reduce the germination rates significantly.

5.4. The influence of microwave heating on the flour quality

Results showed that the MW heating contributed to the moisture loss higher than 1 % when the initial moisture content of treated grains was higher than 10 %. In general, it was found that the initial moisture contents influenced the quality parameters more dominant than the surface temperatures and exposure times. The fact was expected to be due to the strong influence of moisture content on the physical properties of grains such as length, width, thickness. The increase in moisture content influenced the increase of the thousand-kernel weight, and porosity. In contrast, the increase in moisture decreased the bulk density (Tabatabaeefar, 2003; Karimi *et al*., 2009). Moreover, under the eradication of MW heating, the increase in moisture content was also indicated to cause the increase in the dielectric properties of the solid materials (Nelson and Stettson, 1976; Ajibola, 1985; Sokhansanj and Nelson, 1988; Ndife *et al*. 1998; and Guo *et al*., 2008) and probably to cause the higher temperatures within the grains.

The high variations among MW repetitions were indicated for all parameters observed. It is estimated that the irregular temperature distribution is responsible to these obtained results. Irrespective to the infrared image (Figure 23, 24, and 25), it can be seen that the standard deviation ranged from 4 to 7 °C, and there was a distance between the highest and the lowest temperatures ranging from 20 to 35 °C.

However, there is a possibility to enhance product quality treated by using MW energy compared to those treated by conventional heating. Tang *et al*. (2000) investigated that the MW and RF heating left a lower cumulative thermal effect on the product than that of conventional heating methods. Moreover, Lu *et al*. (2010) investigated that a lower lethal temperature was needed to control *T. castaneum* by using MW heating than by using the conduction heating method. Furthermore, Lu *et al.* (2011) investigated that the MW heating caused lower destruction on the material structure (insect body structure) than the conventional heating.

Kaasova *et al*. (2002) also observed that the falling number increased with increasing absorbed energy during MW heating, especially when the end temperature reached 80 °C. In contrast, in the present study the increase of FNs was not recognized as the moisture contents, temperatures, and exposure times were increased and even the FNs in the flour that was milled from treated grains was lower than the FNs in the flour that was milled from untreated grains (control). It must be mentioned that in this study, the temperatures were controlled with the mean temperatures ranging from 45 to 55 °C. However, these obtained FN values were considered to be high and above 200 s, which was recommended by Mailhot and Patton (1988) because these high FNs determine the low α-amylase activity. The optimum FNs, which is expected was about 200 to 250s and the FNs above 300 s will lead to the production of dry crumbly bread and small loaf volume (Pawelzik, 2010). Nevertheless, the FNs is strongly influenced by the variety of wheat grains, and in the case of c.v. Kranich, since the variety is belonged to the soft winter wheat, the common used of this flour is for home baking, cake doughnuts, biscuits, crackers, pastry, cookies, cakes, and soups (Mailhot and Patton, 1988). Thus, these high obtained FNs are acceptable for the production of those products.

Johansson (2002) had investigated that the FNs of c.v. Kosack and c.v. Tarso were 230 and 350 s, respectively. Beside cultivars, he also confirmed that the FNs could be influenced by the location of cultivation and the weather. In addition, the FN is also influenced by the hardness of the grain, for instance the medium hard wheat grain has the FN about 449 s whereas the hard wheat has about 385 s (Prabhasankar *et al*., 2000).

Lewandowicz *et al*. (2000) observed that the MW irradiation was evidenced to increase the gelatinization temperature. Irrespective to Table 17 (p. 67), the increase of pasting temperatures were significant, but irrespective to Table 26 (p. 78), the increase of pasting temperatures were not significant. However, the significant increase of pasting temperature in the present study was not too high. It can be explained that by controlling the MW heating temperatures in region of 45 to 55 °C, the increase of pasting temperature could be reduced. Furthermore, Kaasova *et al*. (2002) investigated the improvement effect on baking quality pronounced as a consequence of increasing amylographic maximum. The irradiation of MW energy at frequency 2.45 GHz for 60 min (0.5 W/g) to the wheat starch at moisture 30 % caused the alteration of the physic-chemical properties and structure, and resulted in reducing the crystallinity, solubility, and swelling characteristic.

The small increase of flour viscosity was found significant as the initial moisture contents of treated grains increased. It can be explained by the low amount of α-amylase enzyme activity in the flour (Batey and Curtin, 2000). Moreover, these results are in agreement with the obtained high FNs that also reflected the low α-amylase enzyme activity (Mailhot and Patton, 1988).

In relation with the utilization of soft winter wheat flours, Mailhot and Patton (1988) recommended that the expected water absorption is higher than 52 %, the development time ranges from 1 to 5 min, while the stability ranges 1 to 6 min. However, irrespective to our result (Table 21, p. 72 and Table 30, p. 82), the water absorption ranged from 60 to 65 %, the development time and stability in treated grain with the initial moisture 10 % varied from 5 to 7 min and 8 to 10 min, respectively. Since the treated grain with the initial moisture 18 % has a high moisture content about 14 to 16 % (Table 14, p. 64), the development time and stability ranged longer from 9 to 13 min and 14 to 21 min, respectively.

Tara (1972) had determined the damaged starch on 63 flours of a number of varieties of Indian wheat by using enzymatic AACC, Stewart method, Farrand method, and colorimetric procedures of Williams and Fegol. The results of Farrand method in FU were changed into BV unit by using the Eq. 25 (p. 41), thus the damaged starch level was 12.5 ± 5.46 BV. In contrast, according to the results of present study, the damaged starch level was low, ranging from 2.7 to 3.16 BV. Hoseney *et al*. (1988) stated that the damaged starch level in the soft winter wheat flour was low because their starch granules are soft and are easily released in the milling process. In relation to this fact, the differences in the initial moisture contents of treated grains would be suggested to cause the variation in the obtained damaged starch values.

It was observed in the present study that the damaged starch levels were below 20 %, even the damaged starch in the flour that was milled from the treated grains was lower significantly than the damaged starch that was milled from control grains. These results are in agreement with the finding of Carl *et al*. (1988), who investigated the starch damaged level of soft wheat flour ranging from 10 to 20 % from the total native starch. It must be mentioned that the wheat grains that were used in the present study was the soft winter wheat c.v. Kranich. It was suggested that for the general used of soft winter wheat flour, the damaged starch level ranges from low to moderate, in except of making cakes (layer), which needs a high damaged starch (Mailhot and Patton, 1988).

The MW heating caused the negative effect by reducing the gluten content (Kaasova *et al*., 2002). The MW heating was also responsible to the changes in the structural and functional characteristic of wheat protein gluten and later reduced the elasticity and strechtability of the dough (Walde *et al*. 2002). However, the results in the present study showed that the MW heating at temperature 50 and 55 °C did not decline the gluten content. Furthermore, there was evidence that the MW heating at temperature 45 °C had increased the gluten content.

In agreement to the results that the gluten content in the flour that was milled from the treated grains at initial moisture content 18 % was significantly lower than the gluten content in the flour that was milled from the treated grains at initial moisture content 10 %, it was obtained that the loaf volume of the bread, which was baked from the flour that was milled from treated grains at initial moisture content 18 % was significantly lower than the loaf volume of the bread, which was baked from the flour that was milled from treated grains at initial moisture content 18 %. According to Czuchajowska *et al*. (1996), the gluten is important because it can increase the water absorption ability up to 12 % and later by increasing 1 % of gluten content, the loaf volume could be increased from 45.5 to 65 m^3.

The study on correlation showed that there were some correlations indicated between the obtained quality parameters. However, the form of this correlation is influenced by the condition of MW heating, for example the correlation of starch and gluten content after MW heating for 5 min with moisture contents and temperatures of the grains was positive, while the correlation of them after MW heating at temperature 50 °C with different moisture contents and exposure times was negative. Furthermore, the correlations of starch with the flour viscosities were recognized reflecting the influence of MW heating to the starch structure through the possibility of gelatinization process.

There were correlations of loaf volume with damaged starch, peak viscosity and final viscosity. Thus, it can be explained that the loaf volume is highly supported by the damaged starch level in relation to the water binding capacity. Furthermore, the flour viscosity is also important because it determines the quality of starch in the flour as the effects of post harvest handling. There is no doubt about the correlation between the loaf volume and the dough properties since the significant correlation was indicated at level 1 %. Thus, the determination of dough properties before the baking is very important to determine the suitable water absorption and the correct kneading time.

The high correlation between water absorption and damaged starch was observed (r = 0.83) (Tara, 1972), indicating a significant contribution of damaged starch to the flour water absorption capability. In contrast, such correlation was not found in the present study and it is estimated to be due to a very low damaged starch observed.

Finally, it can be suggested that the MW heating at temperatures ranging from 45 to 55 °C for 5 min exposure time could be used. Although several changes occurred, the MW heating did not considerably change the flour quality, which was milled from soft winter wheat c.v. Kranich. Nevertheless it is important to consider based on the results from the present study that the treated grains at initial moisture content 18 % is responsible for the low flour quality.

VI. Recommendation

Since the heating uniformity is a very important parameter, which could improve the MW heating performance, the heating uniformity was studied in the present study. It was found that the procedure for analyzing the heating uniformity from Wang *et al*. (2005) contained big uncertainty and thus the results cannot be used to evaluate the heating uniformity among different studies. Therefore, the modified procedure is needed to improve the usefulness of this study for the practical consideration in the future.

The use of hot and cold spot analysis is suggested to be used as an alternative method to the uniformity index analysis. From the technical view, the use of a wall heater is also recommended to reduce the heat convection and radiation loss. Later, the reduction in heat loss will improve the heating uniformity.

However, the target of the present study that is to find the optimum temperature for controlling *O. surinamensis* at different life stages as well as to enhance the quality of grains was reached. Although the experiment on egg stage was not success, it was estimated that the eggs are the least resistant stage to the MW heating. However, the further experiment is recommended to test the mortality of pupa and egg stages against the MW heating.

It is also important to consider about the implementation of the method for the industrial scale. The analysis of energy consumption and economic cost would be an interesting part to be discussed. Therefore, it is recommended to include the energy consumption and economic analysis in the future study.

VII. Summary

The incident of *Oryzaephilus surinamensis* as the insect pest insects, which rise to the level of the important secondary pests, was firstly detected in Germany in 1953. Even though this insect is small, it has high multiplication rate, resulting in the dramatically increase of its population in a short time. Moreover, the insect is highly mobile and could live in all cereal products. The common method used to control this insect is by the application of insecticides, but this insect was found to build resistance against a number of insecticides. The application of biological method by using fungus *Beauveria bassiana* (Bals.) was also studied, but presently this method is not used commercially. Since the use of thermal method by using conventional heating was found effective for controlling some insect pests, it is expected that the dielectric heating by using microwave (MW) energy can be used for disinfestations grain products in the storage against the infestation of *O. surinamensis*.

Therefore, this study was aimed to study the heating uniformity on the product after MW heating based on surface temperature, to determine the potential of MW heating for controlling *O. surinamensis*, to investigate the germination rate of grain after the MW heating, and to analyze the quality of flour produced from the grain treated in the MW. These objectives are integrated in the field of agricultural engineering, entomology science, and food protection.

A laboratory MW applicator batch system with the frequency of 2.45 GHz was used in this research. The volume of its cavity is about 27 *l* (34.5 x 22.5 x 34 cm). The MW applicator was operated with the maximum power 300 W, which was controlled, based on the surface grain temperature. The grains were spread on a rotating-ring-shaped tray made from polytetrafluor-ethylene/PTFE. Soft winter wheat c.v. Kranich harvested in 2009 was used with about 300 g for each MW heating. Before the MW heating, the moisture contents of wheat grains were adjusted at 3 levels, 10, 14, and 18 %. Two MW treatments were conducted by two repetitions. The first was the treatment at temperature levels, 45, 50 and 55 °C for 5 min exposure time and the second is the treatment for exposure times 0, 1, 3 and 5 min at constant temperature 50 °C.

The study on heating uniformity was done following the Wang *et al*. (2005) procedures. The images were taken by using infrared camera before and after the MW heating. The study on heating uniformity was developed by using the hot and cold spot analysis, which was based on the probability density frequency (PDF) of experimental temperature distribution. The study on mortality was conducted for adult, larva and pupa stages of *O. surinamensis*. About 60 individuals from each life stage were treated per each trial, separately. The germination tests were run for all MW heating following the ISTA procedures (1999). Starch content, falling number, flour viscosity, damaged starch, gluten, dough properties and loaf volume were investigated to determine the flour quality produced from the treated grain under MW heating.

It was observed that the uniformity index in this study ranged from 0.152 to 0.244, while the lowest uniformity index was 0.152 indicated at moisture 18 % and temperature 50 °C. The best condition with the lowest hot and cold spot area was also indicated at moisture 18 %, with the hot spot area ranged from 15 to 18 %, and the cold spot area varied from 18 to 21 %. The increase in temperature and the prolongation of exposure time also contributed to the decrease in uniformity index and hot and cold spot areas.

With different temperatures and constant exposure time the mortality of adult of *O. surinamensis* increased as the initial moisture contents of treated grains increased from 10 to 18 %, while the highest mortality of larva reached at initial moisture contents 14 %, followed by 18 and 10 %. On the other hand, with different exposure times and constant temperature, it was found that the highest adult mortality was reached at initial moisture contents 10 %, followed by 18 and 14 %, while the highest mortality of larva was at initial moisture contents 14 %, followed by 18 and 10 %. The mortality of adults, larvae and pupae increased as the temperature increased. About 100 % mortality of adults and larvae was reached at temperature 55 °C after 5 min exposure time. The prolongation of exposure time significantly influenced the increase in mortality of adult and larva stages of *O. surinamensis*. It was observed that the adult stage was the most resistant stage to the MW heating.

After MW heating with different temperatures and constant exposure time, the initial moisture contents did not significantly influence the germination rate, but the temperatures significantly influenced the germination rate. However, after the MW heating at temperature 50 °C with different exposure times, it was found that the initial moisture contents significantly influenced the germination rate, but the exposure time did not influenced the germination rate. It was observed that the germination rates in treated grains were above 94 %.

With different temperatures and constant exposure time, the MW heating did not significantly change the starch content as well as FNs. However, under the study on the flour viscosity by using the rapid visco analyzer (RVA), the influence of MW heating was investigated. The damaged starch was significantly influenced by the initial moisture contents and temperatures. The increase in initial moisture content of treated grains and temperature led to the decrease in gluten content in the flour significantly.

On the other hand, with different exposure time and constant temperature, it was found that the increase in initial moisture contents significantly improved the starch content, but the exposure times did not. Under the same MW heating, FNs were not significantly influenced by the initial moisture contents and exposure times. The significant influence of the MW heating on flour viscosity was also investigated. The increase in initial moisture contents significantly decreased the damaged starch, but the prolongation of exposure times led to the increase of damaged starch. In case of gluten content, the increase in initial moisture contents led to the decrease in gluten content significantly, but the exposure time did not significantly influence the gluten content. Upon the conditions of applied experiments, it was observed that the increase in initial moisture contents significantly influenced the decrease in loaf volume, but the temperature and exposure time did not significantly influence the loaf volume. However, overall the quality of flour was enhanced, which was proved by no significant influence of loaf volume in the flour that was milled from the treated grains at initial moisture content 10 % and untreated grains (control).

Irrespective to the results in the present study, it can be concluded that the use of MW heating for disinfestations of the grains in controlling *O. surinamensis* is promising to be used if the temperature is controlled at secure level for the product quality. Absolutely, the further work is suggested to improve these results, especially for the study of heating uniformity and for the study of mortality of pupae and eggs.

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