New strategy for improving heating uniformity and insect mortality in radio frequency treated mung beans

Rui Li[1], Xingyi Song[1], Xiangyu Guan[1], Bo Ni[1], Yu Gao[1], Lixia Hou[1], Xiaoxi Kou[1], Shaojin Wang[1,2*]

(1. *College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling 712100, Shaanxi, China*;
2. *Department of Biological Systems Engineering, Washington State University, Pullman, WA 99164-6120, USA*)

Abstract: Radio frequency (RF) heating is usually used to control insects while maintaining the quality of harvested grains. Different packaging conditions may influence RF heating uniformity, insecticidal efficacy, product quality, and energy efficiency. An RF unit was used for conducting thermal treatments to evaluate the heating uniformity, the mortality of *Rhizopathy dominica*, the main quality attributes of mung beans under four packaging conditions, and the energy efficiency. The results show that after the aluminum foil sheet was added at the top or bottom side of bags, the RF heating uniformity was improved. The mortality of *Rhizopathy dominica* in mung beans was 100% for vacuum-packaged bags added with aluminum sheets on the bottom side and ordinarily sealed bags. The fastest cooling rate was observed in vacuum-packaged bags with aluminum foil sheets added at the top side. The energy efficiency of the RF system for treating mung beans in Packaging A, B, C, and D were 54.8%, 56.0%, 53.6%, and 54.8%, respectively. The effective RF treatment protocol was developed using vacuum-packaged bags with aluminum sheets added at the bottom side, 54°C hot air assisted RF treatment under an electrode gap of 13.5 cm for 5 min, holding for 6 min, and placing bags upward for cooling. The suitable packaging condition could be explored for developing practical RF disinfestation treatments.

Keywords: heating uniformity, insect mortality, mung beans, packaging conditions
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1 Introduction

Productions of mung beans in 2018 were about 0.5 and 3.4 million t in China and World, respectively[1], and the global market value of mung beans reached 3.9×10^9 US dollars in 2020[2], showing that mung beans are the most important coarse grain[3]. Mung beans are rich in minerals, proteins, phytoestrogens, and vitamins[2,4,5] and have many health-beneficial effects, such as reducing blood pressure, preventing obesity, and regulating digestion[1]. However, about 20% of total mung beans could be infested by pests during storage, resulting in high economic losses[6]. Among the common pests in stored mung beans, the most heat-resistant insect was *Rhizopathy dominica* based on their thermal death kinetic results[7]. Physical methods are urgently needed to control this insect in postharvest mung beans.

Radio frequency (RF) treatments have been extensively used for controlling insects in postharvest agricultural products because of fast and volumetric heating without chemical residues[8]. Several researchers have applied RF heating for eliminating insects on laboratory and industrial scales. For example, 5 min of RF treatment assisted by hot air at 55°C could control fifth-instar *C. punctiferalis* completely in chestnuts without significant quality changes in the laboratory[9]. The RF heating of 52°C following a 55°C hot air holding for 2 min could cause 100% mortality of all fifth-instar *Indianmeal* moths in pistachios without quality changes in the laboratory[10]. Pegna et al.[11] reported that the RF treatment completely controlled larvae in dates while maintaining quality attributes. Liu et al.[12] reported that RF disinfestation treatments provided 100% mortality of insects in seven brands of rice with acceptable rice quality in laboratory. In addition, for industrial-scale RF processing, Hou et al.[13] developed an RF heating protocol to disinfest rice based on heating uniformity, insect mortality, and energy efficiency. These applications indicate that RF treatment could be a feasible physical method for disinfesting mung beans.

However, the edge over-heating in the sample container remains a major problem for RF treatment applications in postharvest agricultural products[14] due to the different dielectric properties of the surrounding medium and samples, leading to unevenly distributed electric fields. Therefore, several methods for reducing the RF over-heating in the edge of the sample container and non-uniform temperature distributions over the agricultural products have been proposed. These methods include sample movement[15-17], using hot air assisted surface heating[18], adjusting the container shape[19], container size[20], or container material[21], and rearranging sample layers[22]. Since mung beans are widely sold in vacuum-packaged bags, single-layer aluminum coated bags, and ordinary sealed bags in the market, it's necessary

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Biographies: Rui Li, PhD, Senior Experimentalist, research interest: agricultural product processing technology using radio frequency heating, Email: ruili1216@nwafu.edu.cn; **Xingyi Song**, Undergraduate, research interest: radio frequency pesticide, Email: 2242218034@qq.com; **Xiangyu Guan**, PhD candidate, research interest: radio frequency pasteurization, Email: 673733218@qq.com; **Bo Ni**, Undergraduate, research interest: radio frequency drying, Email: 3438246270@qq.com; **Yu Gao**, Undergraduate, research interest: radio frequency pasteurization, Email: 885098593@qq.com; **Lixia Hou**, PhD, Associate Professor, research interest: radio frequency pesticide, Email: hlx0924hyx@163.com; **Xiaoxi Kou**, PhD, Associate Professor, research interest: radio frequency pasteurization, Email: 36125065@qq.com;
***Corresponding author: Shaojin Wang**, PhD, Professor, research interest: agricultural product processing technology using radio frequency energy. College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling 712100, Shaanxi, China. Tel: +86-29-87092391, Fax: +86-29-87091737, Email: shaojinwang@nwsuaf.edu.cn.

to determine the RF heating uniformity and energy efficiency under various packaging conditions.

For avoiding quality degradation, rapid cooling is also important after RF treatment. Forced room air and thin layer have been used for cooling. For instance, Wang et al.[23] reported the short cooling time of 1 cm thick lentil samples in forced ambient air compared with 2 cm and 10 cm thick samples. Hou et al.[13,24] and Ling et al.[10] proved that reducing sample thickness and introducing forced room air are effective ways to achieve a short cooling time. However, the sample thickness in packaged bags could not be reduced, resulting in cooling difficulties. Therefore, the effects of packaging conditions on cooling after RF heating need to be evaluated.

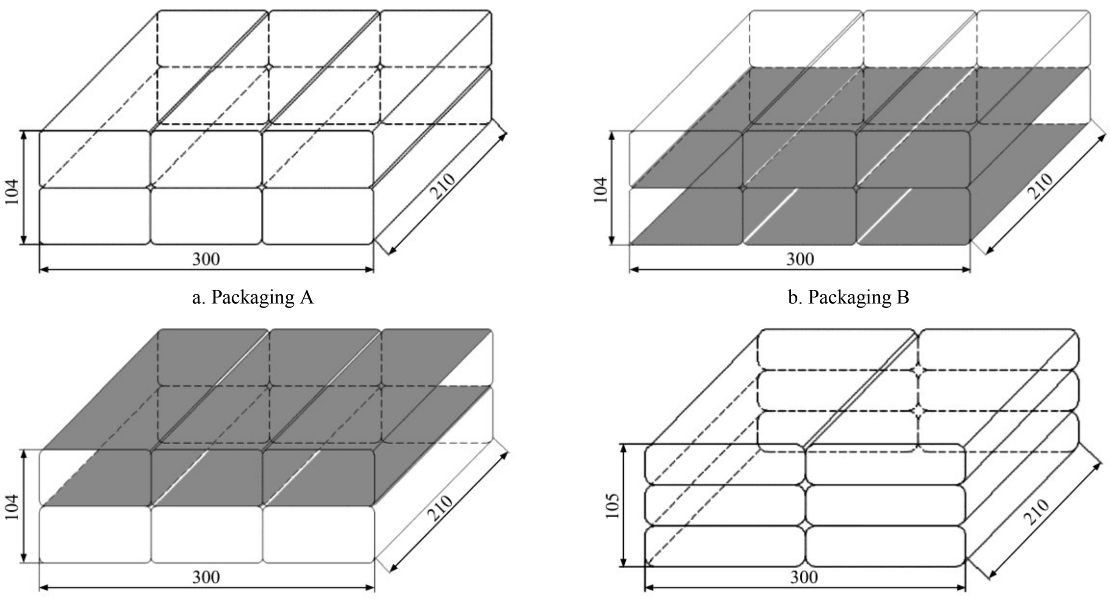
The objectives of this study were 1) to compare the heating uniformity in mung beans under four packaging conditions with various RF treatments; 2) to evaluate the effects of four different packaging conditions on insect mortality in RF-treated samples; 3) to explore an effective cooling method of mung beans after RF treatments; 4) to determine the energy efficiency under four packaging conditions with the given RF treatment.

2 Materials and methods

2.1 Pests, samples, and four different packaging conditions

Rhizopathy dominica was obtained from Sinograin Chengdu Storage Research Institute Co., Ltd, Chengdu, Sichuan, China, in September 2020. The pests were reared in a glass bottle (d=9 cm with h=10 cm) containing coix seeds and maize flour. For air circulation, breathable filter paper was used for sealing the bottle. The pests in the glass bottles were kept at (28±1)°C and 60% relative humidity. Chinese standard sieve #40 was used for separating adult *Rhizopathy dominica* from seeds, which were then collected for RF disinfestation treatments.

Mung beans with a moisture content (MC) of 9.14% on wet basis (w.b.) were bought from Haoyouduo in Yangling, Shaanxi, China. The mung bean samples were placed at room condition (about (25±2)°C) before the experiment. Four packaging conditions (Packagings A, B, C, and D) (Figure 1) placed in the same plastic container were compared for RF heating uniformity evaluation. For Packagings A, B, C, and D, six 1 kg-vacuum-packaged bags, vacuum packaged bags with added aluminum foil sheet (0.06 mm thickness with glue on the back side) at the bottom side, vacuum packaged bags with added aluminum foil sheet at the top side, and ordinarily sealed bags were stacked vertically in the polypropylene (PP) plastic container, respectively. The total sample weight was 6 kg under each packaging condition. The total dimensions of Packagings A, B, and C were 300 mm ×210 mm×104 mm but those of Packaging D were 300 mm ×210 mm×105 mm.



a. Packaging A b. Packaging B

c. Packaging C d. Packaging D

Note: The shaded part represents the addition of aluminum foil sheets.

Figure 1 Four packaging arrangements of mung beans (mm)

2.2 RF system and electrode gap selection

A pilot-scale 6 kW, 27.12 MHz RF treatment equipment (SO6B, Strayfield International, Wokingham, UK) was used in this experiment. The mung beans in Packagings A, B, C, and D were placed over the bottom electrode without moving. The top electrode was adjustable to obtain different electrode gaps from 12 to 16 cm. Once the electrode gap was set, the RF system was turned on, and the electric current (I, A) was recorded from the displayed console of the RF system. Then the input power (kW) of the RF system was calculated based on the relationship $P_{input}=5\times I-1.5$ provided by the RF manufacturer[10,18]. The experiments were repeated three times.

The target temperature of 54°C for holding for 6 min was selected and used for disinfestation studies since this condition could achieve 100% mortality of adult *Rhizopathy dominica*[7]. The temperature-time history of mung beans in central Packaging A from 25°C to 54°C during the RF heating was monitored and recorded through the geometric center of the six bags with optical fiber temperature sensor system (HQ-FTS-D120, Heqi Technologies Inc., Xi'an, Shaanxi, China). According to the required suitable heating rate (5°C/min-6°C/min) during RF heating, the suitable electrode gap was selected for Packagings A, B, C, and D.

2.3 Heating uniformity determination

The top surface temperatures of mung beans in Packagings A, B, C, and D were mapped by a thermal imaging camera (FLIR A300, FLIR Systems Inc, Täby, Sweden) with an accuracy of ±2°C. By matching the measured sample temperature by the fiber-optic temperature sensor system (HQ-FTS-D120, Heqi Technologies Inc., Xi'an, Shaanxi, China), the surface emissivity of mung beans was set to 0.94 for the thermal imaging camera. After calibration, the thermal images were taken from a distance of 70 cm between the camera and the sample surface to cover the target area of the different packaging. The thermal images were transferred to a computer and analyzed for estimating the average, standard deviation, and uniformity index values.

The heating uniformity index (λ) was calculated from the initial and final temperature distributions of the top and bottom layers for Packagings A, B, C, and the top, middle, and bottom layers for Packaging D, respectively. The λ value could be estimated by the following equation[25]:

$$\lambda = \frac{\sqrt{\sigma^2 - \sigma_0^2}}{\mu - \mu_0} \quad (1)$$

where, μ_0 and σ_0 represent the initial average and standard deviations (°C) of mung beans' temperatures (T); μ and σ are the final average and standard deviations (°C) of mung beans' temperatures after RF heating, respectively. The smaller λ values indicate better RF heating uniformity.

The λ value was calculated and then compared under two following conditions: 1) 54°C hot air assisted RF heating in Packagings A, B, C, and D; 2) 54°C hot air assisted RF heating and 6 min holding in Packagings A, B, C, and D.

2.4 Disinfestation procedure and pest mortality evaluation

Adult *Rhizopathy dominica* was chosen as the targeted pest to determine the efficacy of RF thermal treatments. 60 active adults of *Rhizopathy dominica* were collected and separated into 6 nylon mesh bags (30 mm×20 mm), and then placed on the surface center of each packaged bag for RF treatments. The nylon mesh bags were used because of little effect on RF heating behavior and pest mortality[13], but easy to collect the pests after RF treatments. After mung beans in four different packaging conditions were treated with and without (control) the given RF heating, the insects were collected and placed into the glass bottle with coix seeds and corn flour under suitable rearing conditions, and the mortality of pests was evaluated after 48 h of the treatments. If the pests did not move or react when touched with a small brush, the pests were judged dead. The mortality of insects was determined by the following equation:

$$\text{Mortality (\%)} = \frac{N}{N_0} \times 100\% \quad (2)$$

where, N_0 represents the number of total treated insects; N means the number of dead insects.

2.5 Cooling method

During this cooling experiment, the four packagings were heated to 54°C for holding 6 min, and then forced room air horizontally blowing from the side of the sample was used for cooling. Since the single packaging has a faster cooling rate, each horizontally oriented bag was used for cooling tests. An electric fan (FS-3015h7, Zhuhai Gree Electric Appliance Co., Ltd., Guangdong, China) was used for providing forced room air. The air velocity of 3.5 m/s[12] was used for cooling. The geometric center temperatures of each bag in Packagings A, B, C, and D were determined through the six-channel optical fiber temperature measurement system. When the temperature of mung beans dropped to 30°C, the shortest time was applied to develop the cooling process of RF-treated mung beans in Packagings A, B, C, and D.

2.6 Quality assessment of mung beans sample

The product quality of mung beans was evaluated for RF treatments to completely control adult *Rhizopathy dominica.* The quality evaluation of mung beans was conducted both for control and RF-treated samples. Physical attributes (water activity, MC, and color), chemical compositions (protein and starch contents), and biological index (germination rate) were chosen as the main quality indexes.

The water activity (Aw) of mung beans was measured by a water activity meter (Model 4 TE, Decagon Devices, Inc., Pullman, WA, USA). The MC of samples was measured by a moisture analyzer (Model HE53, Mettler Toledo International Inc., Nairobi, Switzerland). Computer vision system (CVS) was used for measuring the color value of L^*, a^*, and b^* to control and treated mung beans. The mung beans were first placed in the middle of the device studio, the camera was adjusted to AV mode, and the F4.5 was set up for taking color images. Finally, the color image was analyzed by Adobe Photoshop CS (Adobe Systems Inc., USA). Detailed information on CVS could be obtained from Liu et al.[12]

Protein and starch contents were measured based on the Chinese National Standard Methods of GB5009.5-2016[26] and GB5009.9-2016[27], respectively. The germination rate was determined according to GB/T 3543.4-1995[28,29].

2.7 Energy efficiency absorbed by mung beans as affected by packaging conditions

The energy efficiency (η, %) absorbed by mung beans as affected by the packaging of the samples was equal to the energy absorbed by mung beans (P_{output}, W) divided by the RF input power (P_{input}, W)[30]:

$$\eta = \frac{P_{\text{output}}}{P_{\text{input}}} \times 100\% = \frac{mC_p(\Delta T / \Delta t)}{(5 \times I - 1.5) \times 1000} \times 100\% \quad (3)$$

where, m is the weight of mung beans (kg) and remained unchanged during RF heating; C_p is the specific heat capacity of mung beans and equals 1630 J/kg·K[31]; ΔT is the increasing temperature (°C) over the RF treatment time (Δt, s).

2.8 Statistical analysis

All treatments in each test were conducted three times to get average values and standard deviations (SD). SPSS 21.0 version statistical software was used for statistical analyses with a probability level of $p<0.05$.

3 Results and discussion

3.1 Selection of appropriate electrode gap

Figure 2 shows that the electric current in Packagings A, B, C, and D decreased rapidly with the increase of electrode gap from 12 to 16 cm. Similar trends of electric currents were reported when the container was filled with almonds[18]. In the pre-experiment, when the electrode gap was 13 cm, the heating rate was (7.31±0.10)°C/min, which was slightly higher than the appropriate heating rate of 5°C/min-6°C/min. The larger electrode gap resulted in lower heating rates. Therefore, electrode gaps of 13.0, 13.5, and 14.0 cm were selected for achieving appropriate heating rates. Figure 3 shows the temperature-time history of mung beans heated by RF energy in Packaging A under electrode gaps of 13.0, 13.5, and 14.0 cm. About 4.0, 5.0, and 5.8 min were needed to heat mung beans in Packaging A from 25°C to 54°C at electrode gaps of 13.0, 13.5, and 14.0 cm, respectively, resulting in heating rates of (7.31±0.10)°C/min, (5.85±0.22)°C/min, and (5.03±0.18)°C/min. The electrode gap of 13.5 cm was chosen for further comparisons of RF heating uniformity in four different packaging conditions due to the similar electric current shown in Figure 2 and the suitable heating rate.

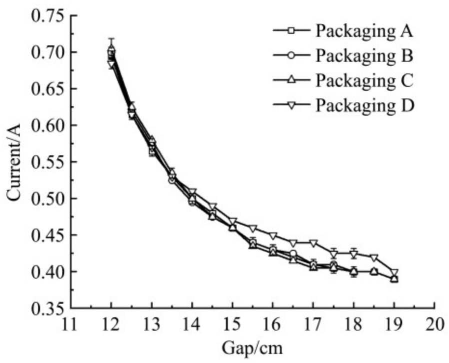


Figure 2 Electric current of RF-treated mung beans as influenced by electrode gaps under Packagings A, B, C, and D without hot air heating

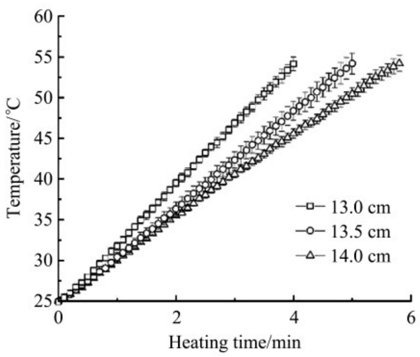


Figure 3 Time-temperature history of RF-heated mung beans in the center of Packaging A under different electrode gap

3.2 Heating uniformity under four packaging conditions

Table 1 lists T and λ values of mung beans in Packagings A, B, and C after different RF treatment conditions. Because of heat loss to ambient air, the T of the top layer was lower than that of the bottom layer in Packagings A, B, and C. A similar result was observed by Hou et al.[13] The T of top and bottom layers in Packaging B was the highest compared with that in Packagings A and C due to the aluminum foil sheet added at the bottom side of vacuum-packaged bags in Packaging B, which enhanced RF energy absorbed in the samples. For Packaging C, the T of the bottom layer was lower than that in Packaging A due to the reduced RF energy absorption. That is because the aluminum foil sheet added at the top side of the vacuum packaged bag reflected the partial RF electromagnetic wave in Packaging C. A similar phenomenon was found in the research of Lin et al.[32]

The λ value of both layers in Packaging A, B, and C was lower after holding 6 min in hot air due to the temperature difference among the samples reduced by heat conduction. For Packaging C, the λ value of top and bottom layers was reduced compared to Packaging A since the electromagnetic field in RF systems was distributed more evenly. This phenomenon could be explained by an aluminum foil sheet added to the top side of the vacuum-packaged bag, and the oblique electric field decreased[33]. The λ value of both layers in Packaging B was much lower than that in Packaging A since the partial RF electromagnetic wave was reflected slightly when the aluminum foil sheet was added at the bottom side of the vacuum packaged bag, which caused more RF energy coupled to the cold spot area[32].

Table 2 lists T and λ values of the mung beans in Packaging D after different RF treatments. Because of heat loss to ambient air, the T of the top layer was lower than that of the middle and bottom layers, showing the same phenomenon in Packagings A, B, and C. The λ value in Packaging D was lower after RF assisted 54°C hot air heating and 6 min holding due to the heat conduction that happened between the higher and lower temperature spots during holding. The heating uniformity index of mung beans in Packaging D was nearly the same as in Packaging A. The temperature distributions of mung beans under different packaging conditions after RF treatment and holding are shown in Figure 4. The temperature distribution in Packagings B and C was more uniform than that in Packaging A and D due to the heating uniformity being improved after the aluminum foil sheet was added at the top or bottom side of the bags. Also, the temperature distributions indicated general edge and corner RF overheating.

Table 1 Comparisons of T and λ in mung beans among 3 packaging conditions after RF treatment

Item	Layers	RF+Hot air			RF+Hot air+Holding		
		Packaging A	Packaging B	Packaging C	Packaging A	Packaging B	Packaging C
T/°C	Top	53.1±0.1^b	54.4±0.9^a	52.2±0.7^c	52.0±0.2^b	54.0±0.4^a	52.4±0.2^b
	Bottom	58.1±0.2^a	58.6±1.0^a	58.2±0.7^a	56.8±1.0^a	55.3±0.8^{ab}	55.0±0.6^b
λ	Top	0.078±0.004^a	0.078±0.009^a	0.080±0.004^a	0.065±0.001^a	0.046±0.000^b	0.069±0.017^a
	Bottom	0.138±0.015^a	0.110±0.011^b	0.060±0.006^c	0.112±0.001^a	0.103±0.001^b	0.057±0.003^c

Note: The data followed by different lowercase letters at the same row are significantly different at p=0.05 from different packaging conditions. T is the temperature of mung beans (mean±SD over 3 replicates), °C; λ is the heating uniformity index (mean±SD over 3 replicates); RF: Radio frequency. The same as below.

Table 2 Comparisons of T and λ in three layers of Packaging D after RF treatment

Item	Layers	RF+Hot air	RF+Hot air+Holding
T/°C	Top	51.5±0.8^a	51.0±1.1^a
	Middle	54.8±1.3^a	55.6±1.0^a
	Bottom	55.5±0.8^a	56.1±0.7^a
λ	Top	0.092±0.001^a	0.097±0.014^a
	Middle	0.116±0.004^a	0.076±0.017^b
	Bottom	0.144±0.057^a	0.091±0.033^a

3.3 Pest mortality in different packaging conditions after RF treatments

Table 3 shows the mortality of adult *Rhizopathy dominica* in different packaging conditions after hot air assisted RF heating and holding. For the control group, the low mortality of *Rhizopathy dominica* (<1.7%) indicated that the influence of rearing, handling and evaluation processes could be ignored. The mortality of *Rhizopathy dominica* in mung beans for Packagings B and D reached 100% due to the lowest sample temperature above 54°C[7]. Although the insect mortality for the bottom layer in Packaging A was 100% due to the average temperature higher than 54°C, the mortality of *Rhizopathy dominica* was between 96.7% and 100% for the top layer since the average temperature of mung beans was lower than 54°C with non-uniform temperature distributions. The mortality of *Rhizopathy dominica* in Packaging C was the lowest because the aluminum foil sheet added at the top side of the vacuum-packaged bag in Packaging C reduced the absorbed RF energy in the samples. Therefore, Packagings A, B, and D could be used for RF disinfestation due to the complete control of adult *Rhizopathy dominica.*

3.4 Cooling rate comparisons of mung beans among different packagings

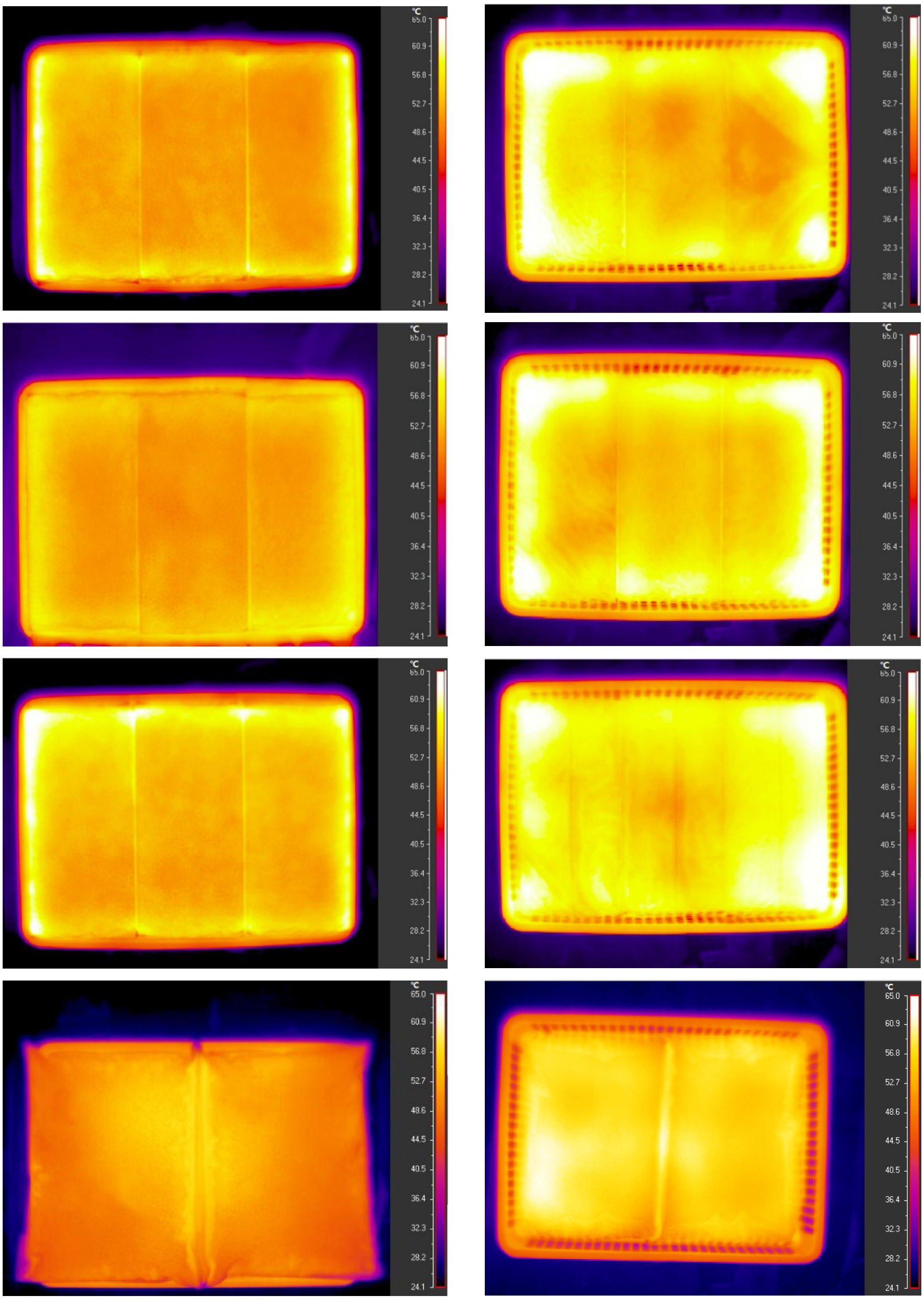
Figure 5 shows the cooling profiles of mung beans under different packaging conditions. The cooling rates were different among different packaging conditions, indicating that the cooling rate was affected by different packaging conditions[34]. The fastest cooling rate was observed in Packaging C, followed by Packaging B, Packaging A, and Packaging D. This is probably caused by the fast heat loss from the aluminum foil sheet with higher thermal conductivity added at the top side of Packaging C to the ambient air. To achieve 100% mortality of adult *Rhizopathy dominica* and fewer negative impacts on the product quality after RF treatment, the vacuum-packaged bags with added aluminum foil sheet at the bottom side in Packaging B were selected and placed upward for cooling.

Packaging A

Packaging B

Packaging C

Packaging D



a. Top b. Bottom

Figure 4 Typical thermal images of mung beans under different packaging conditions after RF treatment and holding

Table 3 Mortality of adult *Rhizopathy dominica* in different packaging conditions after RF treatment

Replicates	Packaging Conditions	Layers	Mortality/%
Rep 1	Packaging A	Top	96.7
		Bottom	100
	Packaging B	Top	100
		Bottom	100
	Packaging C	Top	73.3
		Bottom	90.0
	Packaging D	Top	100
		Middle	100
		Bottom	100
	Control		1.7
Rep 2	Packaging A	Top	100
		Bottom	100
	Packaging B	Top	100
		Bottom	100
	Packaging C	Top	76.7
		Bottom	96.7
	Packaging D	Top	100
		Middle	100
		Bottom	100
	Control		0.0
Rep 3	Packaging A	Top	96.7
		Bottom	100
	Packaging B	Top	100
		Bottom	100
	Packaging C	Top	70.0
		Bottom	93.3
	Packaging D	Top	100
		Middle	100
		Bottom	100
	Control		0

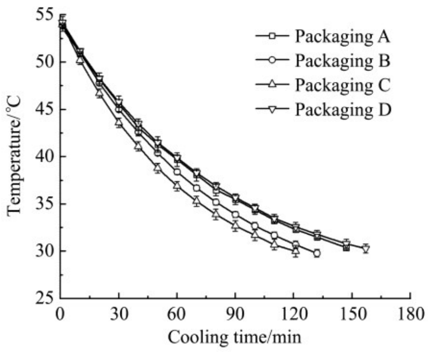


Figure 5 Cooling profiles of the central sample in different packaging conditions when subjected to ambient forced air cooling

3.5 Quality assessment

Table 4 lists the physical quality indexes (moisture content, water activity, and color), biological index (germination rate), and chemical compositions (protein and starch contents) of control and RF-treated mung beans in Packagings A, B, and D. The water activity of mung beans in Packagings A, B and D slightly increased after RF treatments, probably because some bound water changed into free water. The moisture, protein, germination rate, starch content, and color value of mung beans in Packagings A, B, and D after RF treatments had no significant difference from those of control samples (p>0.05). However, the protein or starch content and germination rate of mung beans in Packaging D decreased significantly after RF treatment. The color value of a^* had a little change after RF treatment in Packaging D. Generally, RF treatments had little effect on the quality of mung beans in Packagings A and B, which was similar to the results of Wang et al.[23]

Table 4 Mung beans' quality assessment in Packaging A, B, and D before and after RF treatments

Quality	Treatment			
	Control	Packaging A	Packaging B	Packaging D
Moisture/% w.b.	$9.14±0.07^a$	$9.21±0.13^a$	$9.18±0.17^a$	$9.31±0.19^a$
Aw	$0.43±0.00^b$	$0.46±0.01^a$	$0.45±0.00^a$	$0.46±0.00^a$
Protein/g·100 g^{-1}	$21.99±0.07^a$	$22.14±0.10^a$	$22.12±0.08^a$	$21.59±0.01^b$
Starch/g·100 g^{-1}	$51.82±0.04^a$	$51.67±0.04^a$	$51.88±0.14^a$	$51.08±0.08^b$
Germination rate/%	$1.00±0.00^a$	$1.00±0.00^a$	$0.99±0.02^{ab}$	$0.97±0.02^b$
L^*	$53.09±0.33^a$	$52.56±0.17^b$	$53.04±0.09^a$	$52.27±0.22^b$
a^*	$-1.86±0.06^a$	$-2.00±0.05^b$	$-2.02±0.07^b$	$-1.91±0.12^{ab}$
b^*	$23.03±0.36^b$	$23.50±0.11^b$	$23.36±0.38^b$	$24.04±0.11^a$

Note: Mung beans' quality assessment after RF treatment represented as means±SD over three replicates. Aw means the water activity of mung beans.

3.6 Energy efficiency in different packaging conditions with the given RF treatment

According to Equation (3), the energy efficiency of the RF system with an electrode gap of 13.5 cm for mung beans in Packagings A, B, C, and D was 54.8%, 56.0%, 53.6%, and 54.8%, respectively. The energy efficiency in Packaging B was the highest since an aluminum foil sheet was added at the bottom side, which enhanced RF energy absorbed in the samples. However, the energy efficiency in Packaging C was the lowest because the aluminum foil sheet added at the top side of the vacuum packaged bag reflected the partial RF electromagnetic wave, causing reduced RF energy absorption. The RF energy efficiency of mung beans was lower than that reported in rough and brown rice ranging from 57.9% to 64.2%[13] due to different RF systems.

4 Conclusions

The T and λ values of mung beans in Packagings A, B, C, and D were compared under RF treatment with an electrode gap of 13.5 cm. Based on the lower λ value, the RF heating uniformity of mung beans in Packagings B and C was better than that in Packagings A and D. The mortality of *Rhizopathy dominica* in RF-treated mung beans was 100% for Packagings B and D. The vacuum-packaged bags with added aluminum foil sheets at the bottom side in Packaging B were placed upward for cooling. The quality between RF-treated mung beans and controls in Packagings A and B was nearly the same. The energy efficiency of RF-treated Packaging B was the highest. The effective RF treatment protocol was finally developed using Packaging B, 54°C hot air assisted RF treatment under an electrode gap of 13.5 cm for 5 min, holding for 6 min, and bags placed upward for cooling.

This study provided useful information for guiding the mung bean industry to develop the non-chemical disinfestation process.

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