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Lethal effects and mechanism of infrared radiation on *Sitophilus zeamais* and *Tribolium castaneum* in rough rice

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ABSTRACT

The objective of this study was to study the lethal effects of IR on *Sitophilus zeamais* and *Tribolium castaneum* in rough rice and its mechanism based on the differences of IR absorption of infrared radiation (IR) absorption characteristics between insects and rough rice. The eggs, larvae, pupae and adults insects (*Sitophilus zeamais* and *Tribolium castaneum*) and the No.5 *Huaiyin* japonica rough rice were used for this study. The IR absorption characteristics of adult *Sitophilus zeamais*, *Tribolium castaneum*, and the rough rice with moisture content of 21.1 ± 0.5% dry base were determined by ATR-FTIR spectra. For IR treatments, rough rice samples mixed with *Sitophilus zeamais* and *Tribolium castaneum* were heated by a laboratorial ceramic IR drying device. The tempering and non-tempering treatments were followed with IR heating for comparison study. The mortality of insects, moisture removal and milling quality of rough rice were further determined. To achieve the temperature distribution of the insects and rough rice after IR heating, insects were concentrated in a circle area surrounded by rough rice for determining with infrared thermal imager. Compared with rough rice, the adult *Sitophilus zeamais* and *Tribolium castaneum* achieved higher absorption of infrared radiation within the wavenumber of 1800 to 1308 cm^{-1}. According to the Wien displacement law, the practical IR heating temperature beyond 300 °C could improve the heating pertinence for insects, and the corresponding IR intensity was beyond 2780 W/m^2. The heated temperatures of adults were higher than that of rough rice based on the thermal images. The results of disinfestation experiments showed that the high insect mortality, heating rate and corresponding high moisture removal could be achieved by IR heating. Tempering process could improve the moisture removal and milling quality of rough rice. When rice samples were heated to 60.2 ± 0.5 °C under the IR intensity of 2780 W/m^2 for 110 s, the *Sitophilus zeamais* and *Tribolium castaneum* were 100% killed. After tempering and natural cooling, good rice milling quality was well maintained and 3.97 percentage points of rice moisture was removed. Therefore, the simultaneous disinfestation and drying for rough rice can be achieved by IR heating followed by tempering and natural cooling.

1. Introduction

Rough rice is a major source of food for both human and animals as one of the three main grain varieties. During storage, infestations of stored grain product pests may occur if the internal and external condition is suitable (Ferreira-Castro, Potenza, Rocha, & Correa, 2012; Lee, Choi, Lee, & Park, 2001). It was estimated that 9–20% of annual production of grain (Mishra, Tripathi, & Tripathi, 2013; Neethirajan, Karunakaran, Jayas, & White, 2007) and 27% of the milled rice was lost due to the infestation of pests (Alfonso-Rubí, Ortego, Castañera, Carbonero, & Díaz, 2003). Various methods of pests control have been implemented to protect the rough rice, in which the chemical fumigation is the most widely used method for disinfestation (Ogendo et al., 2010). However, the disinfestation effect of chemical fumigate on insects is getting weakened because of the resistance of insects. Besides, the chemical method may affect the environment and grains, which could potentially affect the health of human beings (Vadivambal, Deji, Jayas, & White, 2010). Therefore, it is urgent to research and develop an alternative environmentally friendly disinfestation technology beyond the chemical fumigation method.

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Alternative physical heating methods that may replace the chemical fumigation method were investigated, including microwave, radio frequency and infrared heating (Pan et al., 2008; Wang, Tiwari, Jiao, Johnson, & Tang, 2010; Yadav, Anand, Sharma, & Gupta, 2014). The high energy consumption and cost requirements of the microwave and radio frequency methods, limited the application in small and medium enterprises (Duangkhamchan et al., 2017). With the development of catalytic infrared radiation (IR) heating technology, the costs of IR heating could be reduced and acceptable for grain industry. IR is an efficient and safe physical process method, with wavelengths range from 0.75 μm to 100 μm. IR can be directly transferred to the material without medium, and converted into heat after the absorption of the electromagnetic wave. IR heating has been tested as an effective drying (Ding et al., 2016; Laohavanich & Wongpichet, 2009; Pan et al., 2011), disinfestation of stored grains (Tilton, Vardell, & Jones, 1983). Pan et al. (2008) concluded that rough rice heated to 60 °C followed by tempering and slow cooling can achieve simultaneous drying and disinfestation with high rice milling quality. Khamis et al. (2010) treated *Rhyzopertha dominica*, *Sitophilus oryzae (S. oryzae),* and *Tribolium castaneum (T. castaneum)* by the flameless catalytic infrared, and proved that there was significant correlation between mortality and temperatures of the 3 pests according to logistic regression statistics. Duangkhamchan et al. (2017) proposed that the insect mortality could achieve 100% after exposure to IR radiation for 2 min under 50 °C to 60 °C and IR heating temperature and exposure time could significantly affect the quality of heated rice. However, the effects of different IR intensity on the mortality of insects and its theoretical mechanism of insect lethality are unclear. Therefore, the objectives of this research was to investigate the effect of IR on rice disinfestation and quality, and analyze the differences of IR absorption characteristics between insects and rough rice to reveal the relevant mechanism.

2. Materials and methods

2.1. Preparation of insect and rough rice samples

As one of the main cultivated japonica rice in Jiangsu province, freshly harvested No.5 Huaiyin japonica rough rice was selected for this study, which was obtained from Shibuqiao Grain Reserve Depot, Nanjing, Jiangsu province. The moisture content (MC) of rough rice was 21.1 ± 0.5% in dry basis (d.b.). All MC was determined by the standard air oven method at 130 °C for 24 h (ASAE, 1995) in an electric dry oven (Model 101-3AS, Sujin Instrument Factory, Shang Hai, China) and was expressed as percentage in dry mass basis with triplicates.

Two major stored-grain insects *T. castaneum* and *S. zeamais* (Solà, Riudavets, & Agusti, 2018) obtained from Chengdu Grain Storage Research Institute (Chengdu, Sichuan province), were used for this study. The *T. castaneum* samples were grown in laboratory on wheat meal and yeast extract (Oxoid Lid, Wade Road, Basingstoke, Hants, UK) in an incubator at a temperature of 28.0 ± 2.0 °C and a relative humidity (RH) of 64.0 ± 3.0% (Kirkpatrick, 1975). The *S. zeamais* samples were maintained on organic whole wheat (Beidahuang Qinmin Organic Foods CO., LTD) in an incubator at a temperature of 30.0 ± 2.0 °C and 70.0 ± 2.0% RH (Vadivambal et al., 2010).

Unsexed *T. castaneum and S. zeamais* adults were kept in jars with uninfected rough rice. After 3 d of infestation, the adults were removed and the contents were left for preparation of the different life stage insects. For *S. zeamais,* the eggs, larvae and pupae samples could be respectively separated from the rice after 0, 14 and 24 d of infestation following the method described by Singh, Jayas, Paliwal, and White (2009). The adults emerged from kernels after 29 d of infestation and could be directly selected out. In the case of *T. castaneum*, the emergence of four stages was similar to that of *S. zeamais*. However, the procedures for extracting eggs, larvae, pupae and adults were similar to the sifting methods described by Mahroof, Subramanyam, Throne, and Menon (2003). For IR treatment, 50 individuals of all stages were mixed with 100 g uninfested rough rice immediately and placed under IR emitter for heating. The mixed samples without IR treating were set to be the control samples.

2.2. Determination of infrared absorption characteristics of insects and rough rice

IR heating would result in the vibration and the rotation of atoms and molecules in the infested rough rice, and lead to the sample temperature rising. In order to understand the IR absorption characteristics of insect and rough rice, the spectral information of alive adults and rough rice were collected by attenuated total reflectance-Fourier transform infrared spectroscopy (ATR-FTIR, Tensor 27, Bruker Corporation, Germany). A single adult or rough rice was placed at the center of the ATR ZnSe crystal (Pike, USA) using a pair of forceps. The background spectrum of the air was scanned before testing the sample. The spectral region of samples ranged from 4000 cm^{-1} to 600 cm^{-1} by ATR-FTIR appliance, the numbers of scan were 64, and the resolution was 4 cm^{-1}. All reported data were means of triplicates. The ATR-FTIR spectra of tested samples were calculated to evaluate the optimum radiation temperature during IR heating following Wien displacement law with equation (1).

$$T = 2898/\lambda_{max} \tag{1}$$

where T is blackbody temperature, K. λ_{max} is the peak wavelength of blackbody radiation energy, μm.

2.3. Infrared heating treatment

A laboratory-scale ceramic infrared drying device provided by Maybo Innovation (MB-EHR12/10KW, Zhen Jiang) was used to treat the rough rice and the insect samples. The infrared drying device consists of an IR emitter, a circulating fan, a sample holder and a control panel. The IR emitter was the source of IR radiation (HFS, Elstein-Werk, Germany), and it had a maximum surface temperature of 630 °C and corresponding peak wavelength of 3.2 μm assuming a blackbody. The temperature of IR emitter could be continuously adjusted during the range from 20 °C to 630 °C based on the experiment requirements. The sample holder was a steel reticulation of dimension 50 cm × 35 cm.

Before the IR treatments for rice and insects samples, the IR emitter was adjusted to the preset temperature for warming up the device. After 20 min of preheating, the temperature of IR device became stable. Then, the mixture of rough rice and insect samples were placed in single layer on tray with a loading rate of 2.08 kg/m^3 at a 20 cm distance under IR emitter. The mixture samples were separately heated to 50 °C, 55 °C, 60 °C and 65 °C under different IR emitter temperatures (200 °C, 300 °C, 400 °C, and 500 °C), which corresponding to the IR radiation intensity of 2125 W/m^2, 2780 W/m^2, 3358 W/m^2 and 3974 W/m^2. The temperature of IR emitter was controlled using the control panel. The radiation intensity of heated rice was measured with Ophir thermal excimer absorber head (FL205A, Ophir, Washington, USA) under the different temperature of IR emitter. The temperature of heated rice was measured by using a type-K thermocouple and RDXL4SD thermometer (time constant of 0.15 s, OMEGA Engineering Inc. Stamford, USA). Four thermocouples were equidistantly fixed and placed inside the rice