CONTROL OF THREE STORED-PRODUCT INSECT SPECIES IN WHEAT USING SUPERHEATED STEAM AND HOT AIR

by

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A Thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfilment of the requirements of the degree of

MASTER OF SCIENCE

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ABSTRACT

Various heating methods have been studied to control stored-product insect pests. The present study compared the effect of superheated steam (SS) and hot air on the germination of wheat and mortality of three important species with adult insects outside kernels; *Tribolium castaneum* (Coleoptera: Tenebrionidae), *Cryptolestes ferrugineus* (Coleoptera: Laemophloeidae), and *Sitophilus oryzae* (Coleoptera: Curculionidae), and mortality of adults and immature stages of *Sitophilus oryzae* inside kernels. Thirty adults of each species or 30 infested wheat kernels mixed with sound wheat kernels at 12.5, 14.5 and 16.5% moisture content were subjected to 105 ± 0.3°C hot air or SS both at velocity of 0.7 m/s with different treatment times (1 to 90 s in hot air and 1 to 3 s in SS). The mortality of adults placed outside kernels was evaluated at 0, 24, and 72 h. Lethal time values were estimated by using probit analysis. In both processing media, insect survival and seed germination decreased with increased treatment time and there were no significant differences among survival of adults outside of kernels evaluated at various times. The mortality for insects outside and inside of kernels was higher at lower initial moisture content of wheat kernels in hot air, whereas initial moisture content of wheat did not influence mortality in SS. Adults of *S. oryzae* outside kernels had higher mortalities than adults inside kernels in both media. In hot air, all the adults of the three species outside kernels had 100% mortality when the treatment times were 60 s for 12.5 and 14.5 % initial wheat moisture content, and 75 s for 16.5%; whereas for SS treatment, the time to reach 100% mortality was 1 s at any moisture content. The adults and immature stages of *S. oryzae* inside kernels required 90 s to reach 100% mortality in hot air, while 3 s was needed in SS at any moisture content. Overall, in hot air, *T. castaneum* and *S. oryzae* adults outside kernels had similar heat intolerance, while the adults of *C. ferrugineus* were more heat tolerant than the other two species. However, there was no significant difference in heat tolerance of three species

in SS. Mortality among adults and immature stages of *Sitophilus oryzae* had lack of clear cut differences in hot air treatment, however pupae were found to be most heat tolerance. In SS, similar heat intolerant of different stages of insects was observed. The treatment times to reach 100% mortality of insects caused a drop in seed germination of 20% in SS and 81% in hot air. Therefore, SS at 105℃ could be used to control insects, as hot air was impracticable. Saturated steam will also have similar results of SS at 105°C because of condensation.

Keywords: stored wheat, insect pest, hot air, SS, mortality, grain quality.

ACKNOWLEDGEMENTS

First of all, I would like to express my deep gratitude and respect to my supervisor, Dr. Fuji Jian, for his guidance, motivation, and support throughout the period of this study. I would like to sincerely thank my co-supervisor, Dr. Stefan Cenkowski, for letting me use the facilities of his lab, providing valuable suggestions and precious guidance of the thesis.

I wish to express my gratitude towards Dr. Paul Fields and Dr. Noel White for their friendly help and willingness to share their knowledge whenever I had problems during my project work and for serving on my advisory committee.

I thank Natural Sciences and Engineering Research Council of Canada for their financial support towards this study.

I gratefully acknowledge the efforts of Mr. Dale Bourns, Mr. Marcel Lehmann. Their help in fabricating the door of the superheated steam system is greatly appreciated. I thank Ms. Kim Stadnyk, Mr. Colin Demianyk, Mr. Matt McDonald and Ms. Minami Maeda for their technical assistance.

I deeply acknowledge and thank my friends Rani Puthukulangara Ramachandran, Lina Diaz Contreras, Jingyun Liu, Narendran Ramasamy Boopathy, Krishna Phani Kaja, Md Abdullah Al Mamun, Lavanya Ganesan, Sandeep Thakur and other friends for their help and support.

I would like to thank my father, mother, brothers and grandmother who provided me moral support, confidence, and inspired me to succeed in my life. Finally, my extreme gratitude goes to my husband, Divagar Vakeesan, who provided the much-needed emotional support during the tough times.

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ANOVA	Analysis of variance,
LT_{50}	Lethal time to kill 50% of the test insect population,
LT_{95}	Lethal time to kill 95% of the test insect population,
LT_{100}	Lethal time to kill 100% of the test insect population,
m.c.	Seed moisture content (%, wet mass basis),
r.h.	Relative humidity (%),
SAS	Statistics analysis system,
w.b.	Wet basis

1. INTRODUCTION

Wheat remains the largest cereal crop in Canada at about 9.1 million hectares of planting area with 29.9 millions of tonnes of annual production in 2017 (CIGI, 2017). Wheat can be infested by stored-product insect pests during storage and transportation. In Canada, infestation of insect pests reduces the quality and quantity of the stored products which can result in millions of dollars of economic losses every year (Karunakaran et al., 2003; Singh et al., 2009). In Western Canada, the abundant insect species associated with stored products reported are *Cryptolestes ferrugineus (Stephens)* and *Tribolium castaneum (Herbst).* These two species eat grain from outside of kernels. *Sitophilus oryzae (L)* is another important insect pest that eats and develops inside wheat kernels (Arthur and Flinn, 2000; Fields et al., 1993; Madrid et al., 1990).

Heat treatment is one of the alternatives to chemical control and can eliminate or control stored-product insects (Fields, 1992; Hansen et al., 2011). Heating methods do not leave chemical residues in products like contact insecticides. Heat treatment methods include: solar heating, water based and atmospheric heating, steam treatment, fire treatment, forced hot air heating, electric field treatment, and high temperature-controlled atmosphere (Hansen et al., 2011). Extensive studies have been conducted on the combinations of temperature and treatment duration to control various stored-product insect pests (Fields 1992; Jian et al., 2002; Yu et al., 2011). Most researchers used temperatures from 40 to 60℃ (Hansen et al., 1997; Beckett and Morton, 2003; Mahroof et al., 2003a; Boina and Subramanyam, 2004; Yu et al., 2011; Jian et al., 2013). However, there are no studies examining the heat tolerance of insect pests at and above 100℃ of hot air or steam (Lange et al., 2012; Subramanyam et al., 2011; Tsuchiya and Kosaka, 1943; Tsuchiya, 1943).

Many authors reported that most heat treatments are more expensive than the chemical methods and quality of the commodity can be adversely affected by the heat (Subramanyam et al., 2011).

However, using steam to control insects can be completed in a short time period with minimal energy usage in heat insensitive materials (Hansen et al., 2011). Steam is used in sterilizing soil, controlling pest insects and mold in woollen products, lumber, and in food drying (Hansen et al., 2011). However, there are no studies conducted to control pest insects by using steam above 100℃ (referred to as superheated steam) in stored grain bulks.

Objectives

The objective of this research was to evaluate the effects of the superheated steam (SS) and hot air on controlling stored-product pest insects.

Specific objectives

i. To determine the mortality of adults of *S. oryzae, T. castaneum,* and *C. ferrugineus* outside wheat kernels of three different moisture contents (m.c.) (12.5, 14.5 and 16.5 %, wet basis) treated by SS and hot air at 105℃ with different treatment times.
ii. To determine mortality of larvae, pupae and adult stages of *S. oryzae* inside wheat kernels exposed to different heating media variables mentioned above.
iii. To compare the susceptibility of adults of *S. oryzae* both inside and outside of the wheat kernels exposed to hot air or SS of at 105℃ and different variables mentioned above.
iv. To determine the seed germination of wheat of different initial moisture content as mentioned above and subjected to 105℃ SS or hot air.

2. LITERATURE REVIEW

2.1 Wheat in Canada

Wheat is one of the most important world cereal crops (Arlene-Christina et al., 2014). Wheat remains the largest seeded crop in Canada at about 9.4 million hectares. Canada produced 31.7 million tonnes of wheat in 2016 (CIGI, 2016). United States, Canada and the European Union (EU) are major producers and exporters (Arlene-Christina et al., 2014; Yang et al., 2003). Canada ranks second in wheat exports next to US, even it is in sixth place in production, and third in the world-wide grain trade. The exporting countries have been facing for many years the imperfect competition and discrimination in price on the international wheat market (Yang et al., 2003). Therefore, it is essential to store grains of high quality to compete with other countries on the international market.

2.2 Stored-wheat pest insects

Harvested grain is stored for future consumption or exported to distant markets, especially for high profits (Hansen et al., 2011). Insect infestation in stored grains occur when the conditions are favourable for growth and development of the insects. Presence of insect pests in grains is unacceptable in both domestic and export markets and this is enforced by the Canadian Grain Commission, because it causes economic damage to the grains during storage and transportation due to significant qualitative and quantitative losses in grains (Dowell et al., 1998). In Canada, there is a zero tolerance for live grain feeding insects in grains. For instance, if a live insect is found in the transported grain, this grain will be considered infested and be fumigated (Canada Grain Act, 1975).

Pest insects consume large quantities of grain and also adversely affect grain quality because metabolic and body parts of the insects contaminate the stored grain and lead to mould growth. Furthermore, baking quality and taste are also affected by undesirable changes in chemical characteristic of wheat flour such as fat acidity, non-protein nitrogen content, and protein and pH reduction (Smith Jr et al., 1971; Venkat Rao et al., 1960).

In the world, 10-30% of annual loss due to insect damage occurs in produced grains during storage (Jayas et al., 1994). In Canada, infestation of insect pests reduces the quality and quantity of the stored food products which results in economic losses every year (Karunakaran et al., 2003; Singh et al., 2009).

The kernel germs affected by insects are unfit for seeding due to loss in germination. In addition, hot spots can develop, and microflora can grow in grain bulk due to the heat and moisture produced by insects during their metabolic activities from respiration. Temperature can increase up to about 75℃ in a hotspot in a stored grain bin and it may lead to self-ignition (Mills, 1989). In Canada, a hot spot in stored grain is often associated with infestation by the rusty grain beetle (Sinha and Wallace, 1966).

2.3 Biology of stored-grain insect pests

In stored-grain, more than 100 species of insect pests have been recorded world-wide (Madrid et al., 1990). In Western Canada, the abundant insect species associated with stored products reported were *T. castaneum* and *C. ferrugineus*. In addition, *S. oryzae* is also another important insect pest that has larval development inside the wheat kernel (Arthur and Flinn, 2000; Madrid et al., 1990). The weevils and borers are considered primary feeders, because their immature stages grow and develop inside the kernels, and feed on the endosperm portion. Insects such as *S. oryzae*,

Sitophilus granarius (L.) and *Rhyzopertha domonica (F.)* are considered primary feeders as well, while *C. ferrugineus* and *T. castaneum* are secondary feeders because of feeding on the germ, on damaged and on broken grains.

2.3.1 *Tribolium castaneum*

Tribolium castaneum is commonly called the red flour beetle. It is a secondary grain feeder and feeds on grain germ, grain flour, grain products, broken grain and dust (Lhaloui et al., 1988). It is found across Canada, especially in long term stored grain in bins (Agriculture Canada, 1981). Female insects lay eggs in the bulk of grain. *Tribolium castaneum* spends all its life stages outside the grain kernels. Each female insect is capable of laying 300 to 400 eggs. The eggs develop into larvae at 20℃ to 40℃ and they do not hatch if the temperature is below 17.5℃ (Fields and White, 1997). Larvae of *T. castaneum* develops to pupae and finally they emerge from kernels as adults. The life cycle of *T. castaneum* at optimum conditions, 30℃ to 37.5℃ and 70 to 90% relative humidity (r.h.) is described in Table 2.1.

Table 2.1 Life cycle of *Tribolium castaneum* at 30 to 37.5℃ and 70 to 90% r.h.

Insect stage	Time period (d)	Description
Egg	2.6 to 3.6	White and oblong; has viscous surface
1st instar		
2nd instar	12 to 15.3	Whitish yellow with an elongate cylindrical body and short yellow hairs
3rd instar		
4th instar		
pupa	3.9 to 5.5	White in colour, pupae on the surface of food substrates
Adult	198	Elongate body with a reddish brown to blackish colour

Modified from Sinha and Watters (1985), and Howe (1956)

2.3.2 *Cryptolestes ferrugineus*

Cryptolestes ferrugineus is commonly called the rusty grain beetle. It is one of the most common secondary grain feeder and serious pests in grain bulks in Canada (Arlene-Christina et al., 2014). Its development is optimum in the range of 32-35 ℃ and 70-90% relative humidity (Smith, 1965). Each female insect has the ability to lay 200 to 500 eggs. They lay eggs on the grain and in kernel fissures. Larvae develop from eggs and they enter germ portion of the kernel through the hole presents at the point where the kernel seed was attached to the floret. Larva consumes the germ inside a kernel until it develops into a pupa. However, they can't penetrate the sound kernel (Ashby, 1961). Developed adults of *C. ferrugineus* make a large hole in the germ portion to feed on and to exit the kernel. Rusty grain beetles have the ability to survive at cold temperature of -15 ℃ with low relative humidity for 2 weeks (Sinha and Watters, 1985). The life cycle of the rusty grain beetle at favourable conditions (32℃ and 60-90% r.h) is shown in Table 2.2.

Table 2.2 Life cycle of *C. ferrugineus* at 32℃ and 60 to 90% r.h.

Insect stage	Time period (d)	Description
Egg	3.6 to 3.9	Long and elongated; white and transparent
1st instar	3.3 to 5.1	
2nd instar	2.4 to 3.6	Slender and flat body; white to straw
3rd instar	2.7 to 4.0	colour
4th instar	6.4 to 7.5	
pupa	4.0 to 4.5	White and translucent body enclosed in silken cocoon; becomes dark as it develops
Adult	93 to 134	Flat and rectangular body with reddish brown colour

Modified from Sinha and Watters (1985).

2.3.3 *Sitophilus oryzae*

The common name of *Sitophilus oryzae* is the rice weevil. It is a primary pest and one of the most voracious feeders of whole grain. The conditions for the optimum development of *S. oryzae* are 28℃ and 70% r.h (Sinha and Watters, 1985). In kernels, females of *S. oryzae* make a hole with their mouth parts and then it lays an egg inside the kernel and plugs the hole with gelatinous secretion. Eggs develop into larvae and feed inside the grain kernel. Larvae of *S. oryzae* change into the pupa stage after 8 to 14 days. A young adult leaves the kernel through the hole. The life cycle of *S. oryzae* at 25℃ and 70% r.h. is described in Table 2.3.

Table 2.3 Life cycle description of *Sitophilus oryzae* at 25℃ and 70% r.h.

Insect stage	Time period (days)	Description
Egg	4.0 to 6.5	White and opaque; ovoid to pear-shaped
1st instar	3.0 to 6.0	
2nd instar	4.0 to 9.0	White and legless; grub-like
3rd instar	4.0 to 6.0	
4th instar	4.0 to 7.0	
pupa	8.3 to 14.0	White; contains legs, wings and snout pressed against the body
Adult	240	Reddish brown colour with long narrow body and snout on the head

Modified from (Sharifi and Mills, 1971; Sinha and Watters, 1985)

2.4 Favourable environmental factors for insects

Stored-product insects have the ability to tolerate a wide range of environmental factors (Jayas et al., 1994), and are able to survive when conditions are unfavourable, whereas, they multiply rapidly in favourable conditions. The temperature range for survival of stored grain insect species lies between 8 and 41℃ (Jayas et al., 1994). Optimum conditions for insects' development and multiplication are 25 to 35℃ and 45-70% relative humidity (Fields, 1992; Jayas et al., 1994), while under 18.3°C or above 35°C their growth and development decreases, and oviposition ceases (Arthur and Flinn, 2000; Fields, 1992).

2.5 Control of stored-grain pests

Storage practices have been followed in grain storage to control insect pest infestation for centuries (Jayas et al., 1994). There are a number of methods used to control pests, such as; chemical, biological and physical methods. A unique type of control method is applied under different situations according to cost, complexity and availability (Fields and White, 1997; Hansen et al., 2011).

The chemical methods are the most commonly used among all the three methods world-wide (Sinha and Watters, 1985). Insecticides and pesticides are used in chemical applications. Insecticides comprise two types, namely fumigants and contact insecticides. Although the chemical application is one of the successful treatments against stored-grain insect pests, residues in commodities are a problem for human consumption. Pesticides are dangerous to humans. Hence, certified and licensed applicators can only use pesticides because most of the pesticides are fumigants and are highly toxic. Plant essential oils and its constituents are used as natural pesticides in controlling insects associated with stored products in both commercial and household use (Tripathi et al., 2009). Tripathy et al. (2009) tested natural pesticides on beetle species such as *R. dominica, T. castaneum, Sitophilus zeamais Mots.* and *S. oryzae* and controlled them successfully. However, susceptibility depends on the essential oil or the compound used, type of insect species and stage of insects (Rajendran and Sriranjini, 2008). For instance, adults of *S. oryzae* are more tolerant compared with *T. castaneum* when a fumigant di-n-propyl disulphide present in neem seed is applied (Koul, 2004). Insects are killed when they get in contact insecticides or respire gas molecules. Malathion, pirimiphos-methyl and chlorpyrifos-methyl are contact insecticide used on stored grain (Jayas et al., 1994; Sinha and Watters, 1985). Methyl bromide, carbon dioxide and phosphine are commonly used fumigants (Sinha and Watters, 1985). Methyl bromide was used for

controlling insect pest in stored-products and buildings, and also in soil against nematodes, insects, pathogens, and weeds (Fields and White, 2002). It acts very rapidly against insects, mites, microflora, and nematodes and has a broad spectrum of activity. Therefore, methyl bromide was used by most of the pesticide applicators. However, it adversely affects the atmospheric ozone layer and in 1992 Montreal Protocol considered methyl bromide as an ozone-depleting substance (Fields and White, 2002). Therefore, it has been banned worldwide after 1992, under the international agreement of the Montreal Protocol. Thereafter, many alternative methods and other fumigants were practiced in controlling pests (Fields and White, 2002).

In a biological method of control, living beneficial organisms are used to control pest as a natural enemy. This method is not dangerous for human health. However, the biological control agents are species specific and they act very slowly. Customers of the stored grain also do not want to see any insects in their food regardless of whether they are considered pests or beneficial organisms. Therefore, the biological method is not commonly used to control stored product pests (Subramanyam et al., 2000).

Physical methods used to control insects comprise of physical removal, mechanical impacts, traps, manipulation of environmental conditions (Hansen et al., 2011; Sinha and Watters, 1985). Insects in stored products can eventually die when the environmental conditions are less than ideal conditions such as elevated temperature and low relative humidity. Physical methods do not leave any residuals on commodities and in the environment after the treatment and also, they have lower risk unlike other management methods such as chemical application (Fields and White, 2002; Hansen et al., 2011).

2.6 Heat treatment for insect control

Heat treatment plays a major role in the elimination of pest insects in grain-processing facilities. Various heating methods have been used around the world to control pest insects as an alternative to chemical control (Fields, 1992; Hansen et al., 2011). Subramanyam et al. (2011) reported that after phasing out of methyl bromide the interest in thermal treatments have been renewed.

2.6.1 Response of insects to several factors in heat treatment

Factors that affect insect mortality at high temperatures are: exposure temperature (Beckett and Morton, 2003; Boina and Subramanyam, 2004; Hansen et al., 1997; Jian et al., 2013; Mahroof et al., 2003a; Yu et al., 2011), species (Boina and Subramanyam, 2004; Jian et al., 2013; Mahroof et al., 2003a), exposure duration (Jian et al., 2002; Mahroof et al., 2003a; Yu et al., 2011), life stage (Boina and Subramanyam, 2004; Mahroof et al., 2003b; Tsuchiya and Kosaka, 1943; Yu et al., 2011), acclimation, and relative humidity (Fields, 1992).

Generally, mortality of insects at high temperatures increases with increasing treatment temperature and exposure time (Jian et al., 2002). The relationships between temperature-time and mortality have been reported for some economically important insect pests (Subramanyam et al., 2011). In 1992, Fields (1992) summarized thermal responses of insect pests associated with stored-products for a wide range of temperatures. In addition, Fields (1992) summarized that most insect species cannot survive if they are exposed for more than 30 s at 60°C, 1 min at 55°C, 5 min at 50°C, 12 h at 45°C and 24 h at 40°C (Fields, 1992).

Mahroof et al. (2003) have shown that 1.8 h is required to kill 99% of egg, old-larvae, pupae and adults of *T. castaneum*, whereas young larvae require 7.2 h at 50 to 60 °C (Mahroof et al., 2003b). Jian et al. (2013) found that young larvae and adults of *T.castaneum* achieved 100% mortality at 135 and 55 min in temperature of 50℃, respectively (Jian et al., 2013). Biona et al.

(2004) also reported that, at 50℃, old larvae of *Tribolium confusum* required 90 min to achieve 99% mortality, whereas eggs, young larvae, pupae, and adults required 41-72 min (Boina and Subramanyam, 2004).

Jian et al. (2002) determined lethal time (LT) to achieve 100% mortality of *C. ferrugineus* at temperatures ranging from 42.5- 50℃. They reported that the mortality was 100% at 45 ℃ in 78 h, at 47 ℃ in 18 h, at 49 ℃ in 4.5 h, and at 50 ℃ in 3 h (Jian et al., 2002). Dermott and Evans (1978) reported that 2.75, 3.82 and 6.58 min were required for complete disinfestation of immature stages of *S. oryzae* at 80, 70 and 60 ℃.

Insect survival to heat treatment varies from species to species. Many authors summarized the order of heat-tolerance for different insect species adults at higher temperatures, *Lasioderma serricorne* (F.), *Cystiscus pusillus* (*Schon.*) and *R. dominica* being the most heat tolerant, *S. oryzae, T. castaneum, S. granarius* and *Gibbium psylloides* (Czenpinski) being moderately tolerant and, *Tribolium confusum* and *0ryzaephilus surinamensis* (*L.*) being least heat tolerant (Fields, 1992; Fields and White, 2002; Kirkpatrick and Tilton, 1972; Oosthuizen, 1935).

At elevated temperatures, different life stages of an insect have different susceptibilities to heat treatment. Oosthuizen (1935) summarized rank based on heat tolerance from lowest to highest at; adults < larvae < eggs < pupae of *T. confusum.* Mahroof et al. (2003 a) conducted heat treatment at a feed mill and tested mortality for eggs, young larvae, old larvae, pupae, and adults of *T. castaneum* (Mahroof et al., 2003b). They observed few adults and pupae survived compared with the other stages. However, in studies conducted by Mahroof et al. (2003a) they reported young larvae were more heat tolerant compared with other stages at 42 to 60℃. Whereas, Boina and Subramanyam (2004) reported that old larvae were the most heat tolerant stage among all the life stages of *T. confusum* at 50 to 60 ℃ (Boina and Subramanyam, 2004).

Insects showed lower heat tolerance with lower grain moisture content or relative humidity (Fields, 1992; Oosthuizen, 1935; Tilton et al., 1983). Evans (1981) evaluated mortality of immature *R. dominica* in 1 kg wheat with two different moisture contents and reported that in fluidized-bed treatments tested at 70 and 80 ℃ the time required to kill 99.9% insects was shorter in dry grains compared with wet grains (Tilton et al., 1983).

2.6.2 Methods of heat treatment

To eliminate or control stored-product insects, heat can be applied separately or in combination of its various forms, such as; solar heating, dry heat, high temperature-controlled atmosphere, forced hot air, high temperature short time treatment, hot water immersion, vapour heat and steam (Hansen et al., 2011).

Solar heating is become a popular inexpensive treatment in sterilizing soil. The United Nations recommended soil solarisation as an alternative method to methyl bromide fumigation (Anonymous, 2003).

Dry heat utilizes hot air and it has no moisture component. Dry heat has been used in controlling pests associated with stored product of grains, nuts, and dried fruits (Hansen et al., 2011). Thermal treatments against the Angoumois Grain Moth, *Sitotroga cerealella* (*olivier*) in stored grains were used in France as early as 1792 (Fields and White, 2002). Hiding pests can be controlled by heating the facility (Hansen et al., 2011). Lintner (1885) determined that grain in USA treated at 49–55℃ for a few hours eliminated the immature stages of the *T. castaneum*. Husain and Bhasin (1921) proposed that superheating wheat up to 100℃ for 30 s can be used to control the khapra beetle, *Trogoderma granarium* Everts (Coleoptera: Dermestidae) (Husain and Bhasin, 1921). Back and Cotton (1924) reported adults of *S. oryzae*, and *Sitophilus granarius* were controlled when they

were exposed at 54.5 ℃ for 30 min (Back and Cotton, 1924). Indian meal moth, *Plodia interpunctella* (Hubner) (Lepidoptera: Pyralidae) in stored peanuts was controlled by heating a room to 47℃ for 30 min (Popenoe, 1911). Heat treatment is also used to control wood pest (Lewis and Haverty, 1996). Heat treatment at 56℃ for 30 min to control insects in imported wood packaging has been approved by many industrialised countries such as Japan, China, Europe, Australia, New Zealand, North America, and most of South America (Anonymous, 2005). Now, this is the standard commercial thermal treatment for the international trade (Fenton and Waite, 1932).

In a high-temperature controlled atmosphere method, oxygen is replaced by a high concentration of nitrogen or carbon dioxide. This increases the demand for oxygen in respiration of pests due to the lack of oxygen, and results in increased mortality in adults of the lesser grain borer, rice weevil, red flour beetle, and the saw-toothed grain beetle (Storey, 1975).

Hot air is used extensively for controlling a wide range of insects. Hansen et al. (1997) reported that banana moth, *Opogona sacchari* (Bojer) (Lepidoptera: Tineidae) was controlled completely on the ornamental *Dracaena fragans* (L.) Ker-Gawl, without damaging propagation or foliage at 44℃ for 30 min. However, unacceptable commodity change was observed in rambutan when it was heated to a seed surface temperature of 47.2℃ for 1 h and held at that temperature for another 20 min to control fruit flies (Follett and Sanxter, 2000). Usually, hot air treatment takes longer in controlling insects in comparison to steaming.

High Temperature and Short Time (HTST) treatment is used in food industries (Tang et al., 2000a). As HTST minimizes thermal degradation, foods and beverages are sanitized and pasteurised for killing pathogenic microbes with better quality retention compare to hot air heating and hot water treatment (Tang et al., 2000a). A similar concept is used for controlling pest insects

as well as minimising detrimental thermal effects on commodities. Tang et al. (2000) examined the effect of different HTST on thermal lethality of fifth instar codling moth and reported shorter time (0.5 min) was used to kill 100% insects at higher temperature (54℃), and lethal time decreases with increasing treatment temperature.

Hot water immersion is the simplest and commonly used technology in controlling pests (Hansen et al., 2011; Tang et al., 2000a), where high energy transfer takes place (Hansen et al., 2011). Earlier studies reported that hot water controls tarsonemid mites in horticultural commodities (Cohen, 1967) and fungal infections of pea seeds when 10 min immersion at 45–47 ℃ is used (Gadd, 1950). Crocker and Morgan (1983) found seed germination of acorns was reduced due to hot water treatment at 60 ℃ in controlling weevils (Crocker and Morgan, 1983) and later, they recommended optimum conditions of the suitable hot water treatment at 49 ℃ for 15 min (Morgan and Crocker, 1986). In 1995, studies conducted at the Potato Research Centre (Fredericton, NB) found that the muscles of legs in adults Colorado potato beetle is inactivated by dipping the beetles in hot water with the temperature from 68 to 75 ℃ for 0.2 to 0.4 s (Pelletier et al., 1995).

Vapor heat (heated, water-saturated air) uses moisture in saturated air for transferring heat energy with air movement. Latta (1932) mentioned that the vapour heat was first used to kill the eggs or larvae of Mexican fruit fly, *Anastrepha ludens Loew* by Crawford in 1913, without affecting the fruit quality (Latta, 1932). However, it was not followed up in commercial applications. Mackie tested (1931) vapor heat treatment in California on different types of fruits and vegetables to control Mediterranean fruit fly (Mackie, 1931). Hansen et al. (2011) summarized that the same method was used for controlling fruit fly. All life stages of the mealy bug were controlled completely using vapor heat at 49℃ for 10 min (Follett, 2004). Now, the vapor heat

method is used to control pests in such fruits and vegetables as: tomato, bell pepper, pineapple and papaya (USDA, 2005).

2.7 Steam

2.7.1 Properties of Steam

Saturated steam is the vapor that is produced when water reaches its boiling point at any specific pressure. Superheated steam is generated when saturated steam is heated above its boiling point. At this point, SS can transfer its sensible heat (which is added to steam) to a processed product, increasing its temperature. The heat energy evaporates moisture from the product reducing its moisture after the temperature of product surface reaches the steam saturation temperature. There are several phases in SS drying of biological materials: condensation period, restoration period, drying and hygroscopic period (Iyota et al., 2001). In the initial steps of SS processing, some condensation on the product is observed as long as the surface temperature stays below the saturation point. The condensation phase does not last more than several seconds. Bonaui et al. (1996) reported that there was a rise in a product's moisture content at the beginning of processing. During steam processing, there is no distinctive mass transfer bounding layer and water is transferred based on heat transfer and not based on mass gradient. Also, SS has superior heat-transfer properties (heat transfer rate) compared with hot air at similar temperature (Shibata, 2005).

2.7.2 Steam applications in the food industry

Tang and Cenkowski (2000) reported that SS drying is an alternative drying method for material that are insensitive to temperature at 100℃ and above. Superheated steam has been utilized as a drying medium for drying products such as wood pulp and paper (Douglas, 1994; McCall and

Douglas, 2006), coal (Potter and Beeby, 1994), sludge (Franics and Di Bella, 1996). Chen et al. (1992) suggested that SS drying of silk cocoons at 45 ℃ improved silk quality (Shi-Ruo et al., 1992).

In the food industry, equipment and metal cans are pre-sterilized using SS in low acid foods (pH>4.5) production such as fish, meats, and vegetables (Brown, 1994). Previous studies have suggested that SS can be utilized for drying various food products, such as spent grain (Johnson et al., 2013; Zielinska and Cenkowski, 2012), soybean (Prachayawarakorn et al., 2006), oat groats (Head et al., 2010), shrimp (Prachayawarakorn et al., 2002), pork (Uengkimbuan et al., 2006), sugar beet pulp (Tang et al., 2000b), Asian noodles (Markowski et al., 2003) and potato (Tang and Cenkowski, 2000). Cenkowski et al. (2007) proved that SS can be used to reduce contaminations in foods. In addition, some authors revealed that SS can be utilized to deodorize, blanch, and pasteurize foods (Pronyk et al., 2004; Van Deventer and Heijmans, 2001).

Rahman and Labuza (1999) reported that air impingement can be used for baking and cooking of products such as pizza, potato chips, cookies, and flat breads (Rahman and Labuza, 1999).

2.7.3 Steam treatments on pest control

In 1893, W.H. Rudd of Greenwood, Illinois, USA used steam for soil sterilization for the very first time (Beachley, 1937). Sterilized soil and seed beds of tomato, potato and tobacco controlled pathogens, nematodes, and wireworms with steam was reported by many authors (Beinhart, 1918; May, 1898; Russell and Petherbridge, 1912; Scherffius, 1911; Winston, 1913). May (1898) and Scherffius (1911) examined and recommended soil steaming for elimination of nematodes. Russell and Petherbridge (1912) studied steam sterilization against pests and found effective results between 82℃ and 100℃. Hunt et al. (1925) revealed that the heat penetration can be doubled by

doubling the steam pressure (Hunt et al., 1925). A mathematical model developed by Van Koot and Wiertz (1947) was used to simulate and explains the steam treatment in controlling soil organisms (van Koot and Wiertz, 1947).

Steam treatment on Mediterranean flour moth was investigated by Chittenden (1897) in flour mill machinery and recommended that steam at 52–60℃ for a few hours could be used to control other insects in grain. Howard and Marlatt (1902) suggested that steam can be used to control carpet beetle, *Anthrenus scrophulariae* (L.) (Coleoptera: Dermestidae), on woollen products. Five different species of mold fungi on cotton were controlled by using five-cycle vacuum/steam treatment (Chen and White, 2008; Howard and Marlatt, 1902). Saturated steam is used for eliminating microorganisms from the surface of commodities which can be contaminated with microbes in processing, storage, or transport such as spices or pharmaceuticals (Devahastin et al., 2004; Dowell et al., 1998).

Pelletier et al. (1998) conducted a field test for controlling Colorado potato beetles by using steam and air mixture at 79.3 °C for 0.72 to 1.4 s. They concluded that only 56% of beetles were injured when the plant damage was at the threshold level (30%) (Pelletier et al., 1998).

2.7.4 Advantages and disadvantages of superheated steam application

In SS applications, numerous advantages have been proven. Overall, processing with SS can save 50–80% energy with no pollution to the environment compared to hot air and other heating methods (Pronyk et al., 2004; Tang and Cenkowski, 2000). Yamsaengsung and Buaphud (2006) found that SS drying of rubberwood reduced the cost and the drying time significantly to less than 2 days without causing any defects, while the conventional hot air drying process takes 7-8 days (Iyota et al., 2001; Yamsaengsung and Buaphud, 2006).

The notable advantage of SS drying in the food industry is minimizing quality reduction such as enzymatic browning, off-flavor development, and lipid oxidation. This is because of the absence of oxygen. Fire and explosion also can be prevented due to the absence of oxygen. Moreover, SS process requires less processing time and labour due to the higher heat transfer coefficients.

Using SS treatment is not widely accepted by the industry due to the requirement of complex equipment (Kumar and Mujumdar, 1990). Heat-sensitive products, like foods and bio products are highly degraded by the applied high temperatures. It leads to melting, glass transition, browning reaction, discoloration and enzyme destruction (Devahastin et al., 2004; Mujumdar, 2000; Pimpaporn et al., 2007; Tang et al., 2000a). Therefore, steam treatment must be precise. In addition, SS process produces condensation on a products' surface initially, followed by the condensate adsorption into the product, leading to the increase of products' moisture content (Ramachandran et al., 2017).

2.8 Heat treatment in facilities and commodities

Heat treatment in grain storage facility are totally different from heat treatment for a commodity, such as grains, flowers, fruits or nuts. In facility heat treatments, a long duration treatment is essential to eliminate all stages of pest insects, especially for heating the wall and equipment. A typical heat treatment takes about 24 to 36 hours for a facility. While for the commodities, it takes only a minute at 60 to 85℃ of heat treatments. Typical heating rates should be about 1 to 15℃ per hour for commodities and 3 to 5℃ per hour for facilities. However, both should be allowed to cool down to ambient temperature (Subramanyam et al., 2011).

Heat applications must be precise, because higher temperature adversely affects quality of commodities such as an increase in the transpiration rate, dehydration, cellular leakage, disruption

in synthesis of protein and nucleic acid, inhibition of pigment synthesis, discoloration of the surface, and advanced senescence that lead to the reduction of the market value of the product. Therefore, insect pests must be more sensitive to heat compared to the commodity when controlling insect pests in stored grains (Hansen et al., 2011).

2.9 Knowledge gaps identified in current research

Many studies conducted in the past agreed that steam and hot air can be used to control pests. However, the previous studies related to steam treatment indicated that pests only in facilities and heat insensitive materials like soil, seed bed, wood, cotton and woolen products were controlled successfully, whereas, Pelletier et al. (1998) found damage in plants when they conducted studies in the field. Hansen et al. (1992) reported that using vapor as the heat source to control pests caused damage in heat sensitive materials, especially flowers and foliage (Hansen et al., 1992), whereas many researchers obtained complete control by using vapor heat in fruits and vegetables without causing any material damage (Fields, 1992). However, none of these studies were reported for grain.

Gaps have also been identified with regards to the temperature in hot air treatment. Disinfestation of grains by using hot air at below 60℃ has been investigated by many authors (Beckett and Morton, 2003; Boina and Subramanyam, 2004; Hansen et al., 1997; Jian et al., 2013; Mahroof et al., 2003a; Yu et al., 2011). In addition, there are studies that reported on disinfestation of wheat at above 60℃ (Dermott and Evans, 1978). There are no studies conducted to check insect mortality at above 100℃.

Moreover, there were no studies conducted comparing the difference between the effect of hot air and SS on insect mortality and commodity quality. Hence, research is needed to determine

whether the hot air and SS at above 100 ℃ can be used to control insect pests in grain without affecting grain quality.

3. MATERIALS AND METHODS

3.1 Wheat and insects

The No. 1 grade wheat (cv. Carberry) with 0% dockage and no visual defects (referred as uninfested kernel) with 12.5, 14.5 and 16.5 % m.c. (w.b.) was used in this study. Wheat kernel moisture content was determined according to the standard method by drying 10 g wheat samples at 130℃ for 19 h (ASABE, 2009). After grain moisture was conditioned to desired levels, the wheat was stored inside sealed plastic bags at 5 ± 1℃ until used for the experiments.

All of the insect rearing was carried out at 30 ± 1℃ and 70 ± 5% r.h. in the dark. The culture media for *T. castaneum*, *C. ferrugineus*, and *S. oryzae* was white wheat flour with 5% brewer's yeast, whole wheat (16% m.c.) with 5% cracked and 5% wheat germ (by weight), and whole wheat kernels (14% m.c.), respectively. Insect cultures had been maintained in the laboratory at the Department of Biosystems Engineering, University of Manitoba, Canada for 2 to 4 y.

To get the same age of adults, approximately 1000 adults were introduced into a jar with about 2 kg of culture media. The adults were sieved out after 48 h. The culture media with the eggs were incubated for 33, 27 and 31 d for *T. castaneum*, *C. ferrugineus*, and *S. oryzae*, respectively, and the emerged adults were sieved out and used for the treatment tests within 48 h.

To produce the same age of *S. oryzae* larvae, pupae and adults inside the wheat kernels, the culture media with the eggs were incubated for 12 d, 23 d and 28 d, respectively. Infested wheat kernels were randomly taken out from the culture media and the infestation status was visually examined by using a soft X-ray imaging system (Model: MX-20, Faxitron Bioptics, LLC) (Karunakaran et al., 2003). Dark feeding cavity (tunnel) in the grain surrounding life stages of *S. oryzae*, dark spot in the head capsule of larvae, articulate margins of pupae and snout in the head of adults were the important features for differentiating stages of *S. oryzae* (Fig. 3.1) (Karunakaran

et al., 2003; Milner et al., 1950). The confirmed infested kernels were stained using red food color (Club House, McCormick, London, Canada).

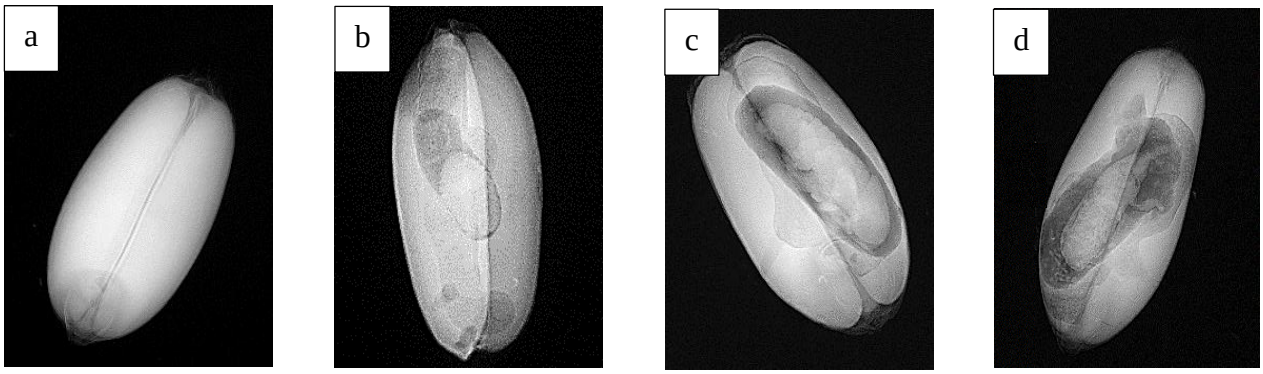

Fig. 3.1 Soft X–ray image of Uninfested kernel, (a) and infested wheat kernel with larva (b), pupa (c) and adult (d) of *Sitophilus oryzae*.

3.2. Metal containers used for both hot air and superheated steam treatment

Metal mesh containers with 540 and 550 mm inner and outer diameters and 410 mm high were used to hold the wheat kernels and insects (Fig. 3.2). The bottom of the container was metal mesh with 250 µm opening which allowed hot air or SS to pass through the mesh and kernels during the heat treatment. The metal container had a 565 mm long handle. At the hand-held side of the handle, there was a 128 x 128 mm^2 metal plate for the hot air treatment (Fig. 3.2) and a metal cap with square cross section (64.5 × 64.5 mm^2) for the SS treatment (Fig. 3.4). After the metal container was inserted into the chambers of the oven or SS system, the metal plate or metal cap covered an opening in the oven or the SS processing chamber, respectively to prevent heat loss.

3.3 Hot air treatment conditions

The heat treatment was conducted inside a programmable oven (model T2C-A-WF4, Tenney, New Columbia, USA) at 105 ± 0.3℃ and the air velocity inside the chamber was 0.7 m/s. Prior to treatment, the temperature inside the oven was checked by using a thermocouple. The air velocity was measured by using a hand-held meter (Turbo meter, David instruments 271 C, Hayward, California, USA) through the opening in the chamber with 890 mm in diameter at side wall of the oven (Fig. 3.2). The opening was also used to insert the metal container which held the infested grain and insects.

3.4 Hot air treatment procedure

After the oven reached the desired equilibrium temperature, 30 adults of each species or 30 infested wheat kernels mixed with 4.5 ± 0.2 g or 4.0 ± 0.2 g uninfested wheat kernels were placed in a single layer in the metal mesh container. During testing, the metal mesh container with the adults or infested kernels mixed with the uninfested kernels were quickly inserted into the middle of the oven through the opening on the side of the oven (Fig. 3.2). The exposure durations were 1, 3, 5, 10, 15, 30, 45, 60, 75 and 90 s. The inserting time or retrieving time of the container took less than 1 s.

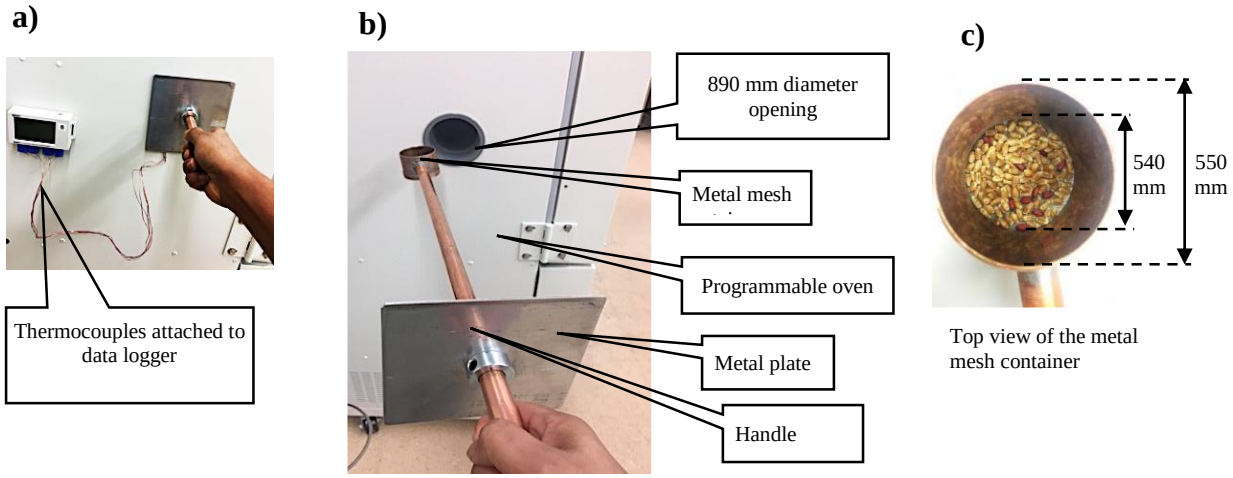

Fig. 3.2 The metal mesh container used to hold the insects, infested and uninfested wheat kernels during the hot air treatment. a) data logger, b) metal mesh container, c) wheat kernels inside the container

3.5 Superheated steam processing system

The SS processing system used in the experiment was designed and fabricated in the Department of Biosystems Engineering at the University of Manitoba, Canada (Fig. 3.3). The SS system has been fully described by Pronyk et al. (2004), Cenkowski et al. (2007) and Zielinska et al. (2009).

The SS system consisted of a water tank (1) supplying water to an electric boiler; an electric boiler (2) (model ES18, Sussman-Automatic Corp., Long Island City, NY), USA) which generated saturated steam at about 10 bars; a pressure reducing valve (5) to reduce pressure of saturated steam and create SS, steam conveying pipelines (10) to transfer the steam, an electric super heater (3) (Sussman Electric Boilers, Long Island City, NY, USA) to heat the steam above 100℃, an external control panel to adjust temperature of the super heater, a SS chamber (4) to process

sample, and a data acquisition system (Agilent Technology Canada Inc.,Agilent 34970A, Mississauga , ON, Canada) to adjust record and control the processing conditions. In addition, electric heating tape with 144 W (Omega Engineering Inc., HTWAT051-004, Laval, QC, Canada) was wrapped around pipelines to maintain stable steam temperature by reducing heat loss and steam condensation in the system. Different valves were used throughout the system to control steam velocity and steam flow path.

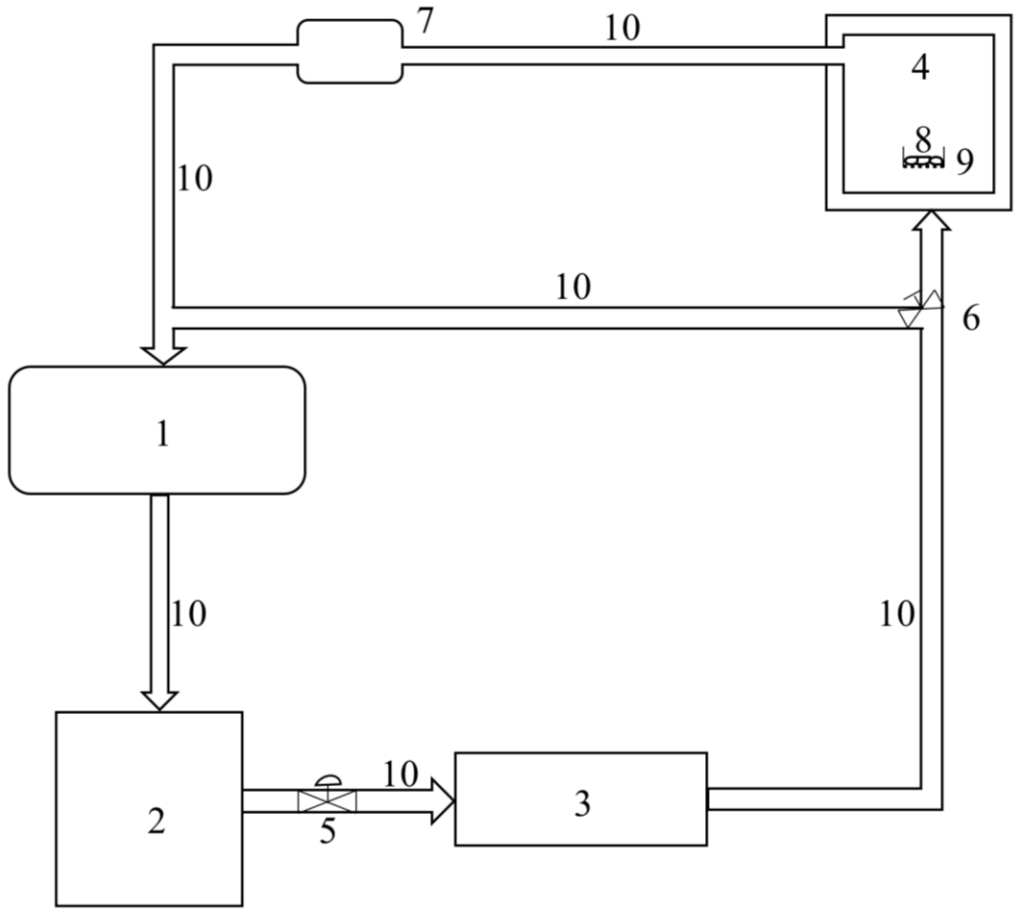

Fig. 3.3 Schematic diagram of the superheated steam processing system: (1) water tank; (2) electric boiler; (3) superheater; (4) superheated steam processing chamber; (5) pressure reducing valve; (6) three-way solenoid valve; (7) condensation unit; (8) Sample; (9) metal mesh container; (10) steam conveying pipeline

The SS chamber (4) itself had a rectangular cavity space. Electric strip heaters were used to prevent condensation on SS chamber walls by heating chamber surface. For maintaining adiabatic conditions in the chamber, the temperature of the chamber walls was kept the same as the temperature of the SS (Zielinska et al., 2009). K-type 30-gauge thermocouples located along height of the chamber connected to the data acquisition system were used to monitor the temperature inside the SS chamber (Zielinska et al., 2009)

Figure 3.4 shows the SS chamber with modified front door. A square pipe with 57.32 ×57.32 mm^2 cross section area and 223 mm long was mounted through the front door of the SS chamber. The thickness of the pipe wall was 3.36 mm. This pipe was used to insert the metal container into the middle of the SS chamber of the system which produced the SS at a desired temperature (Fig. 3.4). The lengths of both the pipe and the handle of the metal container were properly scaled, so that the metal container with the sample was located at the center of the SS chamber when inserted during the treatment period.

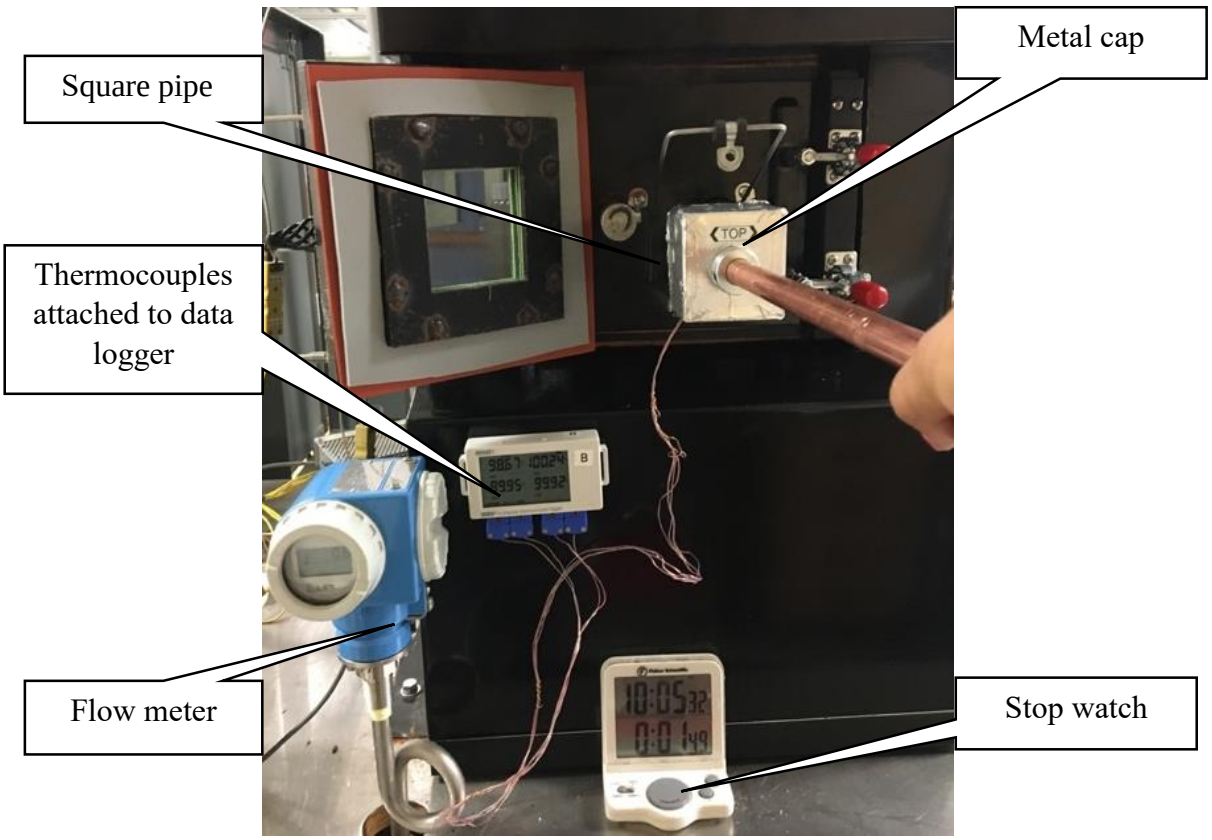

Fig. 3.4 Processing chamber used for superheated steam treatment at 105℃.

3.6 Superheated steam treatment conditions

The SS with temperature of 105 ± 0.3 ℃ and 0.7 ± 0.05 m/s velocity inside the SS chamber was used during this study. A data acquisition system (Agilent Technology Canada Inc., Agilent 34970A, Mississauga, ON, Canada) was used to continuously monitor every second the SS temperature inside the SS chamber. Velocity of the SS was calculated by using the measured volumetric flow rate and cross-sectional area of the entrance port for steam. This calculated velocity was verified by using the method developed by Irvine and Liley (1984). Irvine and Liley (1984) tabularized the relationship between the amount of condensate exiting the SS dryer in 3 min and the velocity at the outlet of the entrance part under processing temperatures and pressures.

During pre-test, condensate in 3 min was collected and the table developed by Irvine and Liley (1984) was used. Then, the required SS velocity was manually adjusted using the steam flow rate control valve and maintained at 0.7 $\pm$ 0.05 m/s. Treatment time was from 1 to 5 s. A preliminary test was conducted to determine the temperatures inside the wheat kernels. It was found that the maximum 5 s was required because the temperature inside the infested wheat kernel reached 70°C in less than 5 s.

3.7 Superheated steam treatment procedure

The treatment procedure with SS was similar to the hot air treatment. The SS at 0.7 m/s and 105 °C was allowed to enter into the SS chamber continuously. After the SS system reached the desired temperature, the metal mesh container containing 30 adults of each species or 30 infested wheat kernels mixed with 4.5, or 4.0 g uninfested kernels was inserted into the SS chamber through the square pipe (Fig. 3.4). The stop watch was started the moment the sample reached the center of the SS. The treatment time was 1, 3, and 5 s. After the sample was retrieved from the SS chamber, it was immediately transferred into a tray and cooled at room temperature (22 ± 1℃). Each treatment was repeated five times.

3.8 Measurement of temperature inside and between kernels

Data loggers (Onset HOBO 4-channel thermocouple loggers, UX120-014M, Bourne, MA, USA) were used to measure temperatures inside uninfested and infested kernels, and between the wheat kernels in both media (Fig. 3.2 & 3.4). Four thermocouples were used to monitor temperature between the kernels. To measure temperature inside infested kernels, each of four thermocouples was inserted into each hole bored by an insect of four infested kernels. To measure the temperatures inside the uninfested wheat kernels, each of four thermocouples was inserted into

one kernel through a pre-drilled 0.5 mm diameter hole along the major axis of the wheat kernel. The depth of the individual holes was about half length of the kernel along the major axis direction. After the thermocouple was inserted into the kernel, glue (Permatex, High-Temp Gasket Maker, USA) was applied to seal the hole. The measurement time was 5 and 90 s for the SS and hot air treatment, respectively. Three replicates were conducted in each medium.

3.9 Determination of moisture content change

Uninfested kernels with three various initial moisture contents were used to determine the change in seed moisture content in both media treatments. Initially, moisture content and mass of the uninfested kernels was measured prior to the treatment. The mass of the treated uninfested kernels was measured again 15 min after the treatment. The kernel moisture content after the treatment (final m.c.) was calculated by using the initial kernel moisture content and the gained or lost mass.

3.10 Evaluation of insect mortality

Mortality of insects outside the wheat kernels was assessed after the sample reached room temperature at about 15 min after the heat treatment. The adults were considered alive if they showed any movement under a microscope when gently touched with a small brush (Arlene-Christina et al., 2014). Then, the treated adults were transferred into a 100 mL jar with about 50 g culture media, and their mortalities were assessed again after 24 and 72 h. Each experiment was repeated five times for each treatment.

To evaluate the mortality of insects inside wheat kernels, the treated infested kernels were transferred into a jar with 100 g culture medium. The jar with larvae, pupae and adults was kept at

the rearing conditions for 18, 7 and 1 d, respectively. After this incubation period, the emerged adults were counted, and the infested kernels were dissected under a microscope (Evans, 1981; Mahroof et al., 2003a). The death of the insects was verified by touching insects with a brush (Arlene-Christina et al., 2014). There were five replicates conducted for each treatment.

Control mortality was determined by placing the adults or infested kernels mixed with 4.5 $\pm$ 0.2 or 4.0 $\pm$ 0.2 g uninfested wheat kernels respectively in the metal mesh container and the container was placed in the oven or SS chamber at room temperature for 90 and 5 s, respectively.

3.11 Seed germination

Germination of seeds were determined by using the standard procedure of the International Seed Testing Association (ISTA, 1999). The uninfested kernels, which were treated in both media, were randomly selected for the germination test. In a 90-mm diameter Petridish, Whatman no. 3 filter paper was moistened with 7 mL of distilled water and twenty-five kernels were placed on the filter paper. The Petridishes were covered with lids and kept inside a polyethylene bag at room conditions. Germination was assessed after one week (Lehner et al., 2008; Manickavasagan et al., 2007). The germination of the untreated wheat kernels was used as a control. There were three replicates done.

3.12 Statistical analysis

The control mortality of all the insects inside and outside kernels was less than 0.67%. Therefore, the determined insect mortality was directly used to conduct the data analysis.

Initially, three-way ANOVA test was conducted to determine the effect of mortality evaluation time on adults insect mortality (SAS studio, Java Version: 1.7.0_151). There was no significant

difference in mortalities evaluated at 0, 24, and 72 h after heat treatment ($p \geq 0.95$, $F = 0.054$). Therefore, the mortality evaluated at 15 minutes after the heat treatment was used for further data analysis.

A three-factorial analysis of variance (ANOVA) was performed on the mortality of adults of various species outside kernels, treatment time, and moisture content. Mortality of three life stages at different treatment times and moisture content were subjected to another three factorial ANOVA. Two-factorial ANOVA were performed on the seed germination of various moisture contents and treatment time for both medium, separately. The mean differences of mortality or seed germination were compared by Tukey's multiple range tests using the GLM procedure ($\alpha = 0.05$) in both media. Lethal time ($LT_{50,}$ LT_{95} and LT_{99}) values were estimated by using probit analysis (Polo Plus, version: 2.0, LeOra software, Berkeley, Canada), followed by Tukey's test ($\alpha = 0.05$). Lethal time values were pooled among tested moisture content of wheat, when the LT values overlapped.

4. RESULTS AND DISCUSSION

4.1 Temperature of the treated kernels

During the hot air treatment, the temperature inside the uninfested and infested kernels reached 74.4 ± 2.3 ℃ and 87.6 ± 3.0 ℃ in 90 s, respectively, while the temperature of the processing medium at the surface of kernels was 102.6 ± 0.6 ℃ (Fig. 4.1 (a)).

In SS treatment, temperature inside uninfested and infested kernels reached 44.5 ± 5.6℃ and 74 ± 4.9℃, respectively in 4 s when the kernels were treated for 3 s. The temperature inside kernels was kept increasing for another second (Fig. 4.1 (b)). This might be due to the response time (lag time) related to conductivity of the thermocouples. Whereas, temperature of the medium at the surface of the kernels was 96.7 ± 0.3℃ at 3 s (Fig. 4.1(b)).

For both treatments, temperature outside the kernels almost reached the medium temperature, while the temperature inside kernels was lower than the medium temperature. Therefore, insects outside kernels experienced higher temperature than insects inside the kernels. Large variations of the temperatures inside kernels were observed (Fig. 4.1) because of the variations in the shape and size of wheat kernels and the location of the thermocouples. As well as, the temperature inside the uninfested kernels was lower than the temperature inside the infested kernels. This is because of the higher heat transfer rate into the infested kernels which was damaged by the insects compared with uninfested kernels.

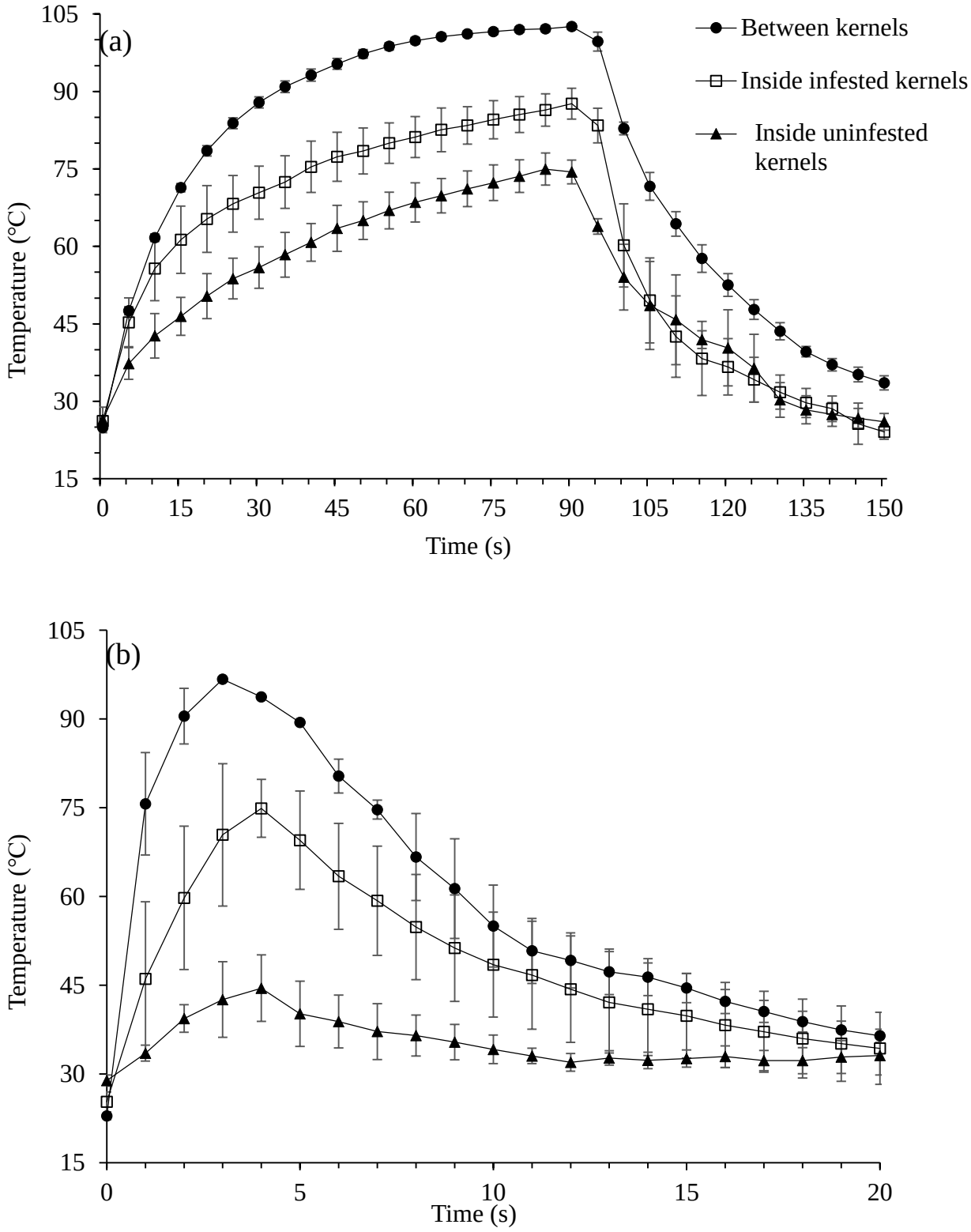

Fig. 4.1 Temperatures inside uninfested and infested kernels, and between wheat kernels treated at 105°C in hot air for 90 s (a) and superheated steam for 3 s (b).

4.2 Moisture content changes

In hot air treatment, initial moisture content of wheat kernels had significant effect on moisture content change at and above 15 s and is shown in Table 4.1. Moisture content of uninfested kernels decreased as treatment time was increased. The moisture content loss of hot air treated kernels was $\leq 0.06\%$ when the treatment time was ≤ 10 s.

In SS treatment, the initial moisture content of wheat had no influences on moisture content changes ($p=0.9975$). Moisture content of uninfested kernels increased as treatment time increased. Even SS was set to 105℃ there was surface condensation taking place for the sample after several seconds.

Moisture content gain was 1.0 ± 0.3, 2.1 ± 0.3 and $3.1 \pm 0.5\%$ at 1, 3 and 5 s treatment time, respectively. This gain in moisture was a result of vapor condensation on the surface of the kernels. Earlier study also reported that the moisture content of product increased in the first phase of SS drying (Bonaui et al., 1996). In addition, Tang et al. (2005) observed that the steam condensation caused a small moisture gain on the surface of the tested sample at the beginning of drying process (Tang et al., 2005).

Table 4.1 Final moisture content (%) of wheat kernels of different initial moisture contents after keeping them in a hot air oven at 105℃ from 15 to 90 s of treatment time.

Treatment time (s)	Initial moisture content of wheat (%)		
	12.5	14.5	16.5
15	12.4 ± 0.0	14.4 ± 0.0	16.4 ± 0.0
30	12.4 ± 0.0	14.4 ± 0.0	16.3 ± 0.1
45	12.3 ± 0.0	14.3 ± 0.0	16.2 ± 0.0
60	12.3 ± 0.0	14.1 ± 0.0	16.0 ± 0.0
75	12.2 ± 0.1	14.1 ± 0.0	15.8 ± 0.1
90	12.1 ± 0.0	13.8 ± 0.1	15.2 ± 0.1

4.3 Mortality of adults outside kernels

4.3.1 Hot air treatment

In hot air treatment, there was a three-way interaction between treatment times, moisture content of wheat kernels and insect species ($p<0.0001$). Mortality increased with increasing treatment time as reported in other studies (Boina and Subramanyam, 2004; Fields, 1992; Mahroof et al., 2003a). Mortality of the three tested species in all initial moisture contents of grain was $\leq 1.9 \pm 1.6\%$ when treatment time was at and below 5 s. The adults of three species present outside kernels had 100% mortality (complete mortality) when treatment time was 60 s at 12.5 and 14.5 % m.c, whereas it required 75 s to kill all adults at 16.5 % m.c. (Fig. 4.2). Fields (1992) also reported that insects can be killed within 1 min at temperature above 62℃.

Effect of moisture content on mortality of adults was significant at 15, 30 and 45 s treatment times ($p<0.0001$), while moisture content had no significant influences on mortality when the

treatment times were ≤ 10 s or ≥ 60 s (Fig. 4.2). Overall, higher mortality was obtained for tested species at 12.5% m.c. compared with 14.5 and 16.5 % m.c. when the treatment times were 15, 30 and 45 s (Fig. 4.2). Whereas, similar mortality was obtained for tested species at 14.5 and 16.5 % m.c. in all the treatment times (p=0.1534). *Cryptolestes ferrugineus* adults showed less heat tolerance when it was mixed with lower moisture content wheat, whereas other species did not exhibit clear difference in heat tolerance with moisture content changes (Fig. 4.2). For instance, adults of *C. ferrugineus* had 96.3% mortality for 12.5%, 60.0 for 14.5% and 64.3 for 16.5% m.c. Previous studies also revealed that the mortality increased as the moisture content was decreased (Fields, 1992; Kirkpatrick et al., 1972; Tilton et al., 1983).

Adults of *C. ferrugineus* were the most heat tolerant species when present outside 14.5 and 16.5 % m.c. wheat kernels at 30 and 45 s (Fig. 4.2), whereas adults of *T. castaneum* and *S. oryzae* were equally sensitive to heat treatment at all wheat moisture contents (p = 0.963). Kirkpatrick and Tilton (1972) also observed that the adults of *T. castaneum* and *S. oryzae* had similar heat tolerance (Kirkpatrick et al., 1972). There was no clear significant difference in mortality among the adults of three species at 12.5 % m.c. in all the treatment times.

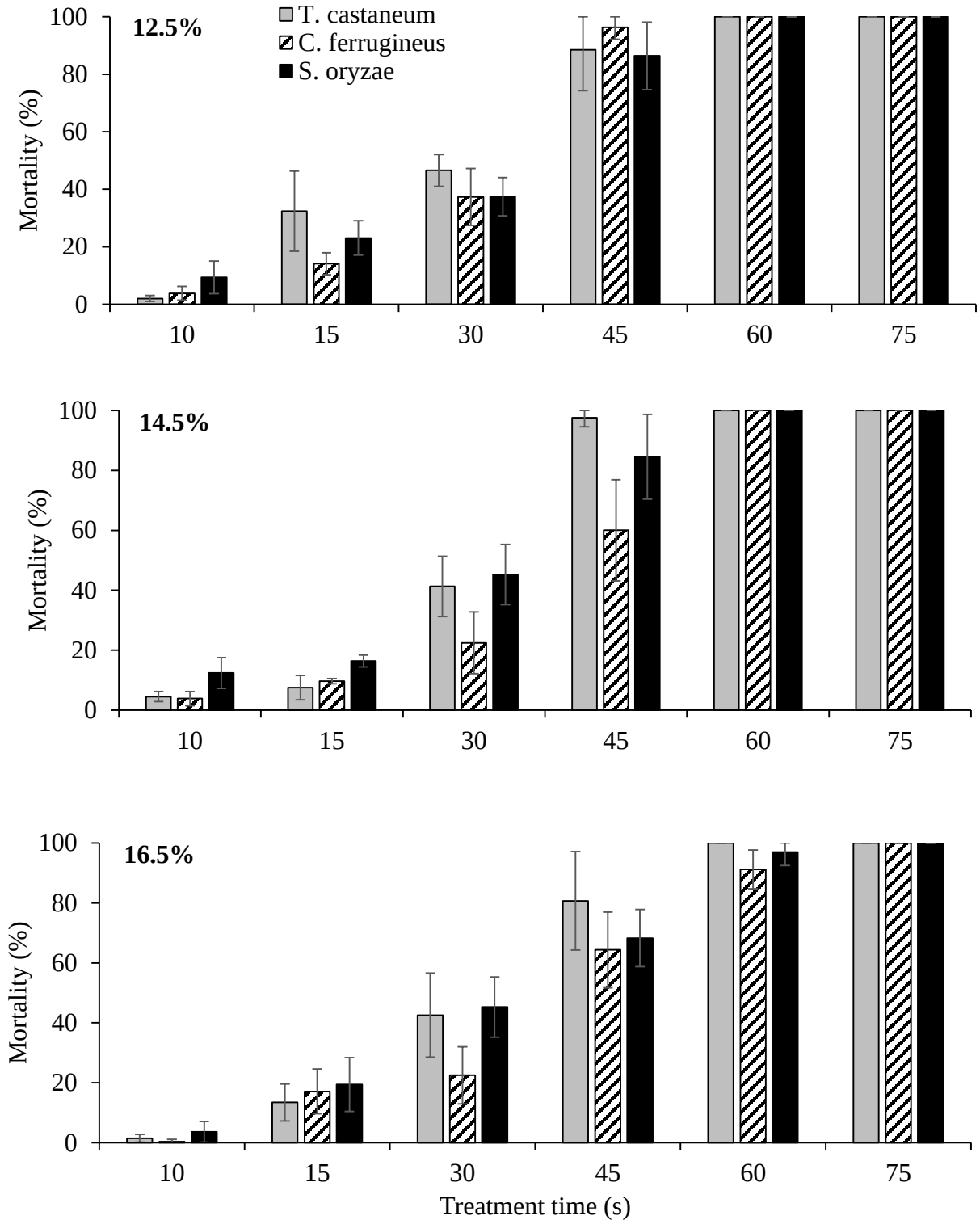

Fig. 4.2. Mortality of adults present on the outside of wheat kernels of 12.5, 14.5 and 16.5% initial moisture contents, held in the oven at 105°C for up to 75 s.

Lethal time values overlapped among various moisture content levels for the adults, therefore the data were pooled. Pooled LT values for adults of *T. castaneum, C. ferrugineus* and *S. oryzae* outside kernels with 12.5 to 16.5 % m.c. wheat treated in hot air are shown in Table 4.2. *Cryptolestes ferrugineus* adults required significantly longer duration to reach 50 % mortality than adults of *T. castaneum* and *S. oryzae*. The estimated LT values also exhibited that adults of *T. castaneum* and *S. oryzae* had similar heat tolerance (Table 4.2). However, there were no significant differences between the lethal times estimated to reach 99 % mortality among the insects tested. LT_{99} values for adults of *T. castaneum, C. ferrugineus* and *S. oryzae* were 79.8, 100.5 and 105.4 s, respectively (Table 4.2).

Table 4.2 Lethal time of adults present outside wheat kernels of initial moisture content of 12.5 to 16.5 % held in the hot air oven at 105°C.

Insects	Lethal time values (s) (95% CL)			Slope ± SEM	X^2
	LT_{50}	LT_{95}	LT_{99}		
T. castaneum	26.3 (25.0- 27.7)	57.7 (53.4- 63.0)	79.8 (72.3 - 89.6)	4.83 ± 0.12	491.04
C. ferrugineus	30.9 (28.6- 33.2)	71.1 (63.8 - 81.3)	100.5 (87.2 - 120.3)	4.54 ± 0.12	972.61
S. oryzae	25.4 (23.7 - 27.1)	69.5 (62.6 - 78.4)	105.4 (92.1 - 123.8)	3.76 ± 0.09	575.55

SEM= standard error mean, X^2=Chi square value

4.3.2 Superheated steam treatment

Adults of three species present outside kernels had 100% mortality when they were treated with SS for 1 s (Fig. 4.3), whereas mortality of adults was ≤ 3.5% when they exposed to hot air for 5 s. Estimated treatment time using the SS based on the law of energy conservation was also around 1 s. This is due to the superior heat transfer properties of SS (Shibata and Mujumdar, 1994). Superheated steam has higher energy than hot air in the similar conditions and SS can transfer heat energy more quickly to grains and insects than hot air. Therefore, insects experienced higher temperatures in a shorter time during SS treatment and resulted in higher mortality than hot air treatment. Treatment time for achieving 100% mortality was reduced by 98.3 % when insects were treated with SS instead of hot air.

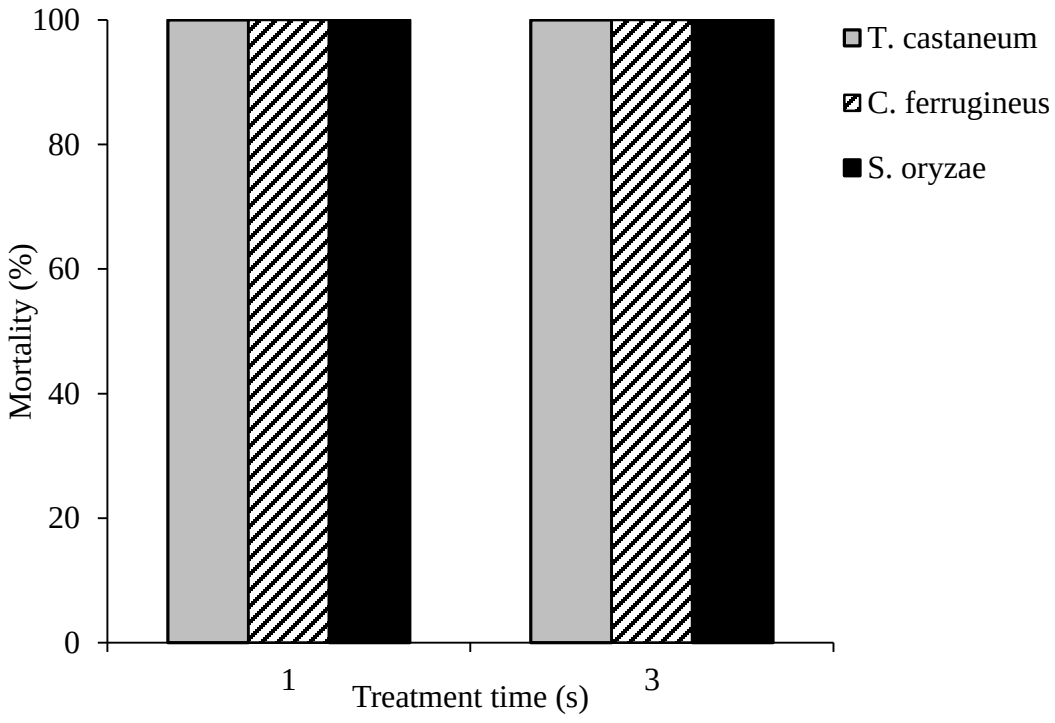

Fig. 4.3. Mortality of adults present outside wheat kernels of 12.5 to 16.5 % initial moisture contents, held in superheated steam at 105°C for 1 to 3 s.

4.4 Mortality of *Sitophilus oryzae* inside kernels

4.4.1 Hot air treatment

The treatment time, moisture content of wheat, and life stages showed three-way interaction effect on mortality ($p<0.0001$). The mortality of each life stage significantly increased with increasing the treatment time in all initial moisture content levels of wheat ($p<0.0001$), however no mortality difference was obtained when treatment time was ≤ 5 s ($p=0.938$).

Mortality of adults and immature stages of *S. oryzae* was higher at lower initial moisture content (Fig. 4.4). The same trend was observed for insects present outside wheat kernels. For instance, adults of *S. oryzae* required 30.7 and 40.3 s to reach 50 % mortality in wheat of 12.5 and 16.5 % m.c., respectively. This is in agreement with other studies. Dermott and Evans (1978) concluded that LT values of the insects with 14% initial moisture content wheat was considerably longer than the wheat of 11.3 % when they were exposed to 70 and 80℃, and they reported that LT_{50} for immature *R. dominica* were 3.72 and 4.88 min when the insects were mixed with wheat of 11.3 and 14.0 % initial m.c and placed in air temperature of 70℃. It appeared that the insects on a lower moisture content wheat were killed faster than those on a higher moisture content. The reason was that the specific heat of water (4200 kJ/kg) was very much higher than dried grain (1100 to 1400 kJ/kg) and moist kernels had higher water content than dried kernels, therefore, the dried kernels (12.5%) had a higher heating rate than that of wet kernels (14.5 and 16.5%) and it led to higher mortality. This was consistent to the result reported by Evan et al. in 1981. (Evans, 1981; Tilton et al., 1983).

Figure 4.4 shows a lack of clear-cut difference in heat tolerance among adults and immature stages of *S. oryzae*. Overall, mortality among adults and pupae of *S. oryzae* inside kernel was significantly different when they were exposed to hot air for 45, 60 and 75 s ($\alpha = 0.05$) and there

was no significant difference when the treatment times were ≤ 30 s and >75 s (Fig. 4.4). Generally, mortality of pupae was lower than that of adults at treatment times at and below 75 s at any moisture content of wheat, whereas there was no significant difference between mortality of adults and larvae, and larvae and pupae (Fig. 4.4). Therefore, pupae of *S. oryzae* should be the target stage during heat treatment. Oosthuizen (1935) ranked life stages of *Tribolium confusum* based on their heat tolerance at 44 ℃ as: pupae> egg> larvae> adults (Oosthuizen, 1935). Beckett and Morton (2003) concluded that the later developing stages were more susceptible to denaturation or coagulation of protein, inactivation of enzymes, and metabolic reactions. During heat treatment, higher moisture content inside younger stage of insects than that in the old stage might also delay the temperature increase of the insect bodies. Mahroof et al. (2003b) also reported that young larvae had highest thermo-tolerance than old larvae, pupae, and adults of *T. castaneum*.

The mortality of *S. oryzae* adults placed outside wheat kernels had about two times the mortality of the *S. oryzae* adults inside kernels when hot air treatment times were 10, 15 and 30 s. Generally, adults placed outside wheat kernels resulted in higher mortality than adults present inside kernels of all the initial moisture content tested (Fig. 4.2 and 4.4). Dermott and Evans (1978) and Fleurat-Lessard (1985) also reported that insects inside seeds have lower mortality than insects outside the kernels (Dermott and Evans, 1978; Lessard, 1985). This low mortality was caused by the lower temperatures experienced by insects present inside wheat kernels than insects which are often present outside kernels (Fig. 4.1).

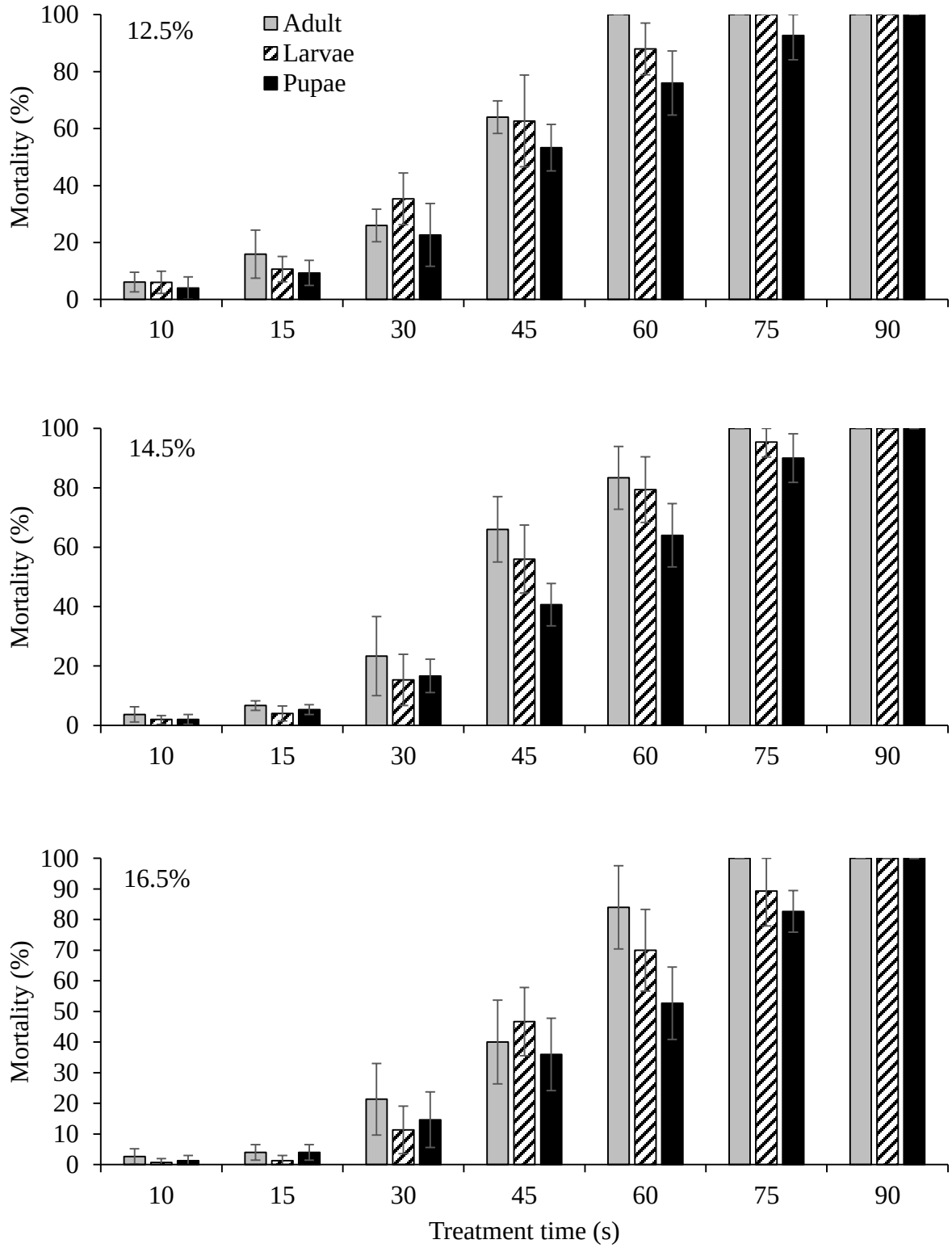

Fig. 4.4 Mortality of adults and immature stages of *Sitophilus oryzae* thriving inside wheat kernels of 12.5, 14.5 and 16.5% initial moisture content and held in the oven at 105°C for up to 90 s.

The lethal time values of 50, 95 and 99 values for adults and immature stages of *S. oryzae* are shown in Table 4.3. As the initial moisture content of wheat increased, higher LT_{50} values were obtained in all the three stages (Table 4.3). Whereas, the LT_{95} and LT_{99} values did not exhibit a clear difference at the different moisture contents, LT_{50} values for adults in each m.c were significantly lower than for pupae, whereas LT_{50} values were not different between adults and larvae, and pupae and larvae. There were no significant differences between LT_{95} and LT_{99} values for adults and immature stages of *S. oryzae* at all the initial moisture contents of wheat. Lethal time to achieve 99% mortality in adults and immature stages of *S. oryzae* at all the wheat moisture contents was greater than100 s.

Table 4.3 Lethal times for adults and immature stages of *Sitophilus oryzae* thriving inside wheat kernels of 12.5 to 16.5 % initial moisture content and exposed to 105℃ hot air.

Insect stage	Wheat moisture content (%)	Lethal time values (s) (95% CL)			Slope ± SEM	X^2
		LT_{50}	LT_{95}	LT_{99}		
Adults	12.5	30.7 ^{aA} (27.4 - 34.2)	78.0 ^{aA} (65.8 - 98.1)	114.7 ^{aA} (92.1 – 155.9)	4.06±0.21	150.42
	14.5	35.5 ^{abA} (32.8 - 38.4)	83.1 ^{aAB} (73.3 – 97.6)	118.1 ^{aA} (100.2 – 146.70)	4.46±0.25	88.24
	16.5	40.3 ^{bA} (36.1 - 44.8)	90.1 ^{aAB} (76.0- 115.7)	125.6 ^{aAB} (100.6- 176.4)	4.71±0.28	174.02
Larvae	12.5	32.6 ^{aAB} (29.7- 35.3)	77.7 ^{aA} (69.2 – 90.2)	111.4 ^{aA} (95.3 – 136.9)	4.36±0.25	457.36
	14.5	42.9 ^{abB} (40.0- 45.5)	76.0 ^{aA} (69.8 – 85.5)	96.3 ^{aA} (85.6- 114.2)	6.63±0.50	86.92
	16.5	47.2 ^{bA} (44.7- 49.7)	83.8 ^{aA} (77.5- 92.7)	106.4 ^{aA} (95.7- 122.3)	6.60±0.42	77.99
Pupae	12.5	37.8 ^{aB} (34.6- 41.0)	97.8 ^{aA} (85.8- 115.5)	145.2 ^{aA} (122.1- 181.6)	3.98±0.20	105.25
	14.5	44.2 ^{abB} (40.8- 47.6)	104.4 ^{aB} (92.0- 122.9)	149.0 ^{aA} (126.1- 186.1)	4.41 ±0.24	104.94
	16.5	48.7 ^{bA} (44.6 – 53.0)	114.5 ^{aB} (98.5 – 141.1)	163.2 ^{aB} (133.6 – 216.7)	4.43±0.25	139.19

^{a,b,c} The same letter in a column indicates no significant difference among different moisture contents. ^{A,B,C} The same letter in a column among different stages at the same moisture content indicates no significant difference at $\alpha = 0.05$ level (SEM= standard error mean, X^2=Chi square value).

4.4.2 Superheated steam treatment

Mortality among the adults and immature stages of *S. oryzae* inside kernels did not show a significant difference ($p=0.0568$). Initial moisture content of wheat also did not influence insects' mortality ($p=0.0847$). Mortality was significantly higher at 3 s treatment time than at 1 s ($p<0.0001$). All adults and immature stages of *S. oryzae* had 100% mortality at 3 s, whereas adults, larvae and pupae reached 88.0 ± 6.9, 90.0 ± 9.9 and 81.3 ± 11.7 % mortality, respectively when exposure time was 1 s (Fig. 4.5). This is because of the higher specific heat of SS, and this high specific heat resulted in the faster heating rate and higher temperature in comparison to the hot air treatment.

The mortality of adults and immature stages of *S. oryzae* present inside the wheat kernels had larger standard errors in both media compared with insects outside kernels (Fig. 4.4 and 4.5). This larger standard error might be due to the differences in kernel size and the location of the insects inside kernels. If the insect was located at a place close to the kernel surface, the insect would be exposed to a higher temperature than that at the core location. This was evident from the high standard error observed in temperatures inside kernels (Fig. 4.1). Insects were probably located at different locations (Karunakaran et al., 2003) (Fig. 3.1), and this would explain the larger variation of the mortality.

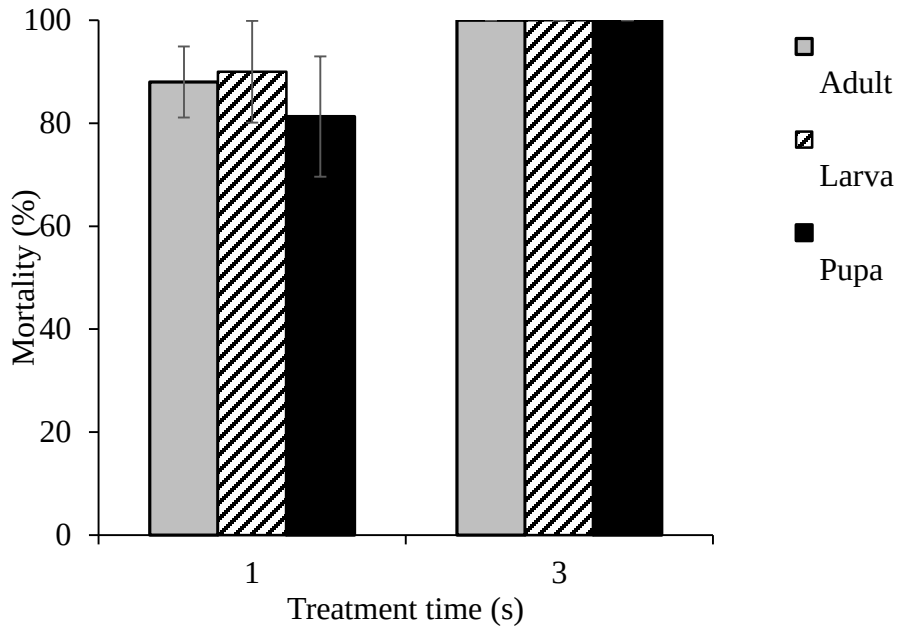

Fig. 4.5 Mortality of adults and immature stages of *Sitophilus oryzae* thriving inside wheat kernels of 12.5 to 16.5 % initial moisture contents treated with superheated steam at 105°C for 1 to 3 s.

4.5 Seed germination

4.5.1 Hot air treatment

The initial germination of the uninfested kernels was around 95.1 ± 4.0% at all wheat moisture contents. There was no significant difference in germination between control and hot air treated kernels with 12.5 and 14.5 - 16.5 % m.c. at ≤ 5 and ≤ 15 s treatment time, respectively (α =0.05). In other exposure durations, wheat germination decreased with increasing treatment time (Fig. 4.6). Wheat of 12.5 % m.c. had lower germination than the wheat with 14.5 and 16.5 % m.c. at ≥ 10 and ≤ 75 s (Fig. 4.6).

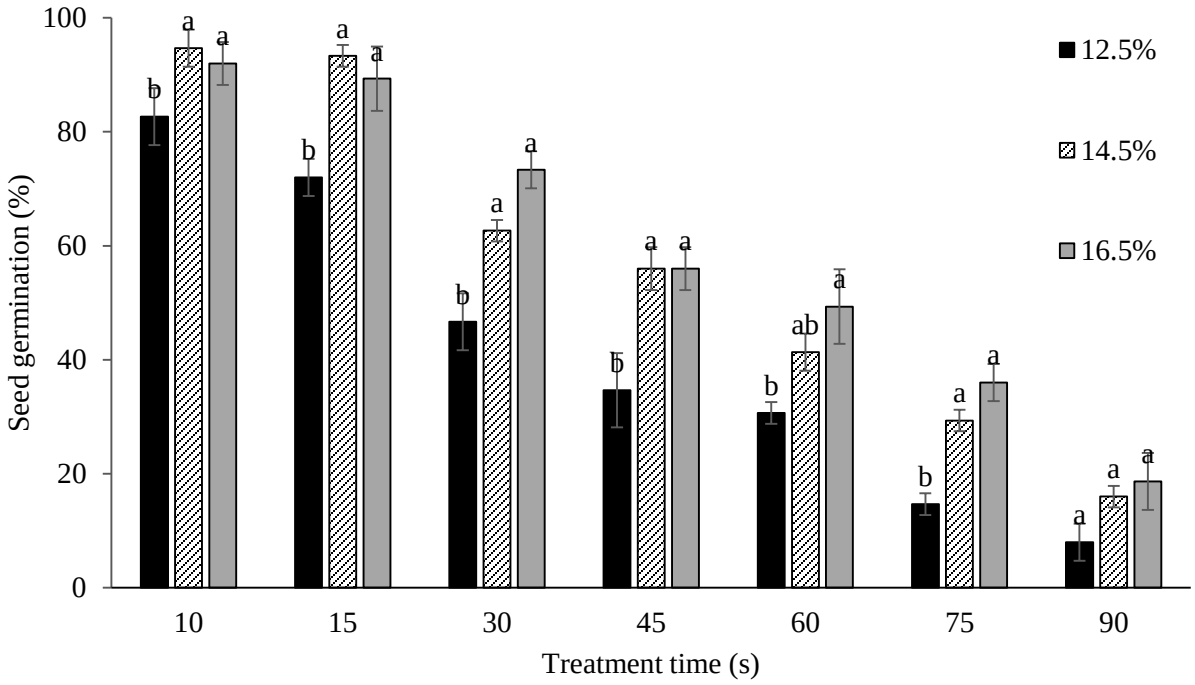

Fig. 4.6 Germination of uninfested kernels treated in hot air at 105℃ for up to 90 s.

In hot air treatment, probit analysis estimated that uninfested kernels with 12.5 and 14.5 – 16.5 % m.c. lost about 50% of germination when exposed at 105℃ for 29 and 51 s, respectively, and lost all the germination at > 313 s (Table. 4.4). Therefore, hot air treatment at 105℃ is not applicable due to a high loss in germination percentage which occurred when the complete insect mortality was achieved. Many authors reported that the quality of product eventually reduces by heat treatments at elevated temperature. Dermott and Evans (1978) reported quality of flour was affected when it was heated at 100°C for 5 min.

Table 4.4 Lethal time values (s) for seed germination of uninfested wheat kernels treated in hot air and superheated steam at 105°C.

Medium	Wheat moisture content (%)	Lethal time values (s) (95% CL)			Slope ± SEM	X^2
		LT_{50}	LT_{95}	LT_{99}		
Hot air	12.5	29.0 (24.9 - 33.3)	173.2 (131.0 - 258.1)	363.0 (245.8 - 639.2)	2.12 ± 0.21	26.41
	14.5 - 16.5	51.7 (47.7 - 55.9)	184.8 (152.3 - 240.8)	313.3 (240.4 - 451.8)	2.97 ± 0.24	67.84
Superheated steam	12.5 - 16.5	6.6 (5.5 - 8.7)	81.7 (44.2 - 214.1)	231.2 (103.7 - 817.1)	1.51 ± 0.17	53.26

SEM= standard error mean, X^2=Chi square value

4.5.2 Superheated steam treatment

The results indicated that seed germination decreased as treatment time increased. The wheat kernels lost germination quickly in the SS compared with hot air treated kernels (Table 4.5). This is also due to the sudden higher temperature increase experienced by kernels exposed to the SS in comparison to hot air.

According to the lethal time values, SS treated kernels of the initial of 12.5 to 16.5% moisture content lost about 50 % of germination at about 7 s of processing time and lost complete germination when exposed for about 231 s (Table 4.4). The germination corresponding to 100%

mortality of all the tested insect stages at 3 s was 74.9 ± 7.6 % seed germination. Therefore, SS could be used for controlling stored insect pests.

Table 4.5 Germination (mean ± SEM) of uninfested kernels treated with superheated steam at 105°C for 5 s.

Treatment time (s)	Seed germination (%)
0	95.3 ± 4.1
1	82.0 ± 5.8
3	74.9 ± 7.6
5	48.9 ± 5.9

SEM=standard error mean

5. CONCLUSIONS

1. *Sitophilus oryzae* adults outside kernels had higher mortality than the ones inside kernels in both heating media. In the hot air treatment, *S. oryzae* adults placed outside wheat kernels had about two times the mortality of the *S. oryzae* adults inside kernels when treatment times were 10, 15 and 30 s.
2. Overall, mortality of insects was lower in moister wheat kernels in hot air, while moisture content did not influence survival of insects in SS treatment.
3. In hot air treatment, adults of *T. castaneum*, *C. ferrugineus* and *S. oryzae* outside kernels had 100% of mortality at 60 s treatment time for wheat with initial moisture contents of 12.5 and 14.5 % or 75 s treatment time for wheat of 16.5 % m.c., whereas the adults of three species had 100% mortality at 1 s in SS at all initial moisture contents.
4. Overall, adults of *C. ferrugineus* were more heat tolerant than the other tested insects, and the adults of *S. oryzae* and *T. castaneum* had equal heat tolerance in hot air. There was no difference in mortality among the species exposed to SS.
5. In hot air treatment, mortality of *S. oryzae* pupae was lower than larvae and adults when treatment time was > 30 s, whereas there was no difference in SS.
6. Adults and immature stages of *S. oryzae* present inside kernels had 100 % mortality at 90 s with hot air treatment and 3 s in SS treatment.
7. Wheat germination was reduced by 81% in hot air treatment and 20% in SS treatment at 105°C, when all the insects reached 100% mortality inside kernels with 12.5 – 16.5 % m.c.

6. RECOMMENDATIONS FOR FUTURE RESEARCH

1. Quality analysis (proximate analysis, baking properties and other end uses) for flour made from SS treated kernels should be under taken.
2. Possible ways to minimize wheat quality damage during SS treatment need to be developed.
3. Wheat should be disinfested by using steam at saturated conditions of different conditions (velocity and flow rate) at the commercial level.
4. Further research needs to be done to compare cost analysis with other pest control methods.
5. Heat tolerance of other heat tolerant insect species and their life stages should be tested.

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Appendix A

Temperature data of the treated kernels

Table Appendix-A1 Temperatures between kernels treated at 105℃ in hot air for 90 s

Treatment time (s)	Temperature (℃)						
	Replication 1	Replication 2	Replication 3	Replication 4	Replication 5	Replication 6	Replication 7
0	25.64	25.35	25.18	26.15	28.37	26.07	26.52
5	54.01	38.39	45.83	45.57	48.12	44.64	40.46
10	68.18	48.99	59.57	56.36	55.09	53.14	48.65
15	73.99	56.19	67.34	60.1	59.97	57.86	53.63
20	77.09	61.77	73.01	63.48	61.83	61.9	57.93
25	77.79	65.24	75.58	65.44	65.32	66.09	62.22
30	78.93	68.08	77.71	67.02	66.93	68.94	65.13
35	80.7	70.84	79.75	69.39	67.96	71.39	67.25
40	83.43	74	82.43	72.42	71.05	74.37	70.18
45	84.75	76.24	84.22	74.23	73.07	76.66	72.24
50	84.83	77.76	85.29	75.42	74.02	78.21	73.85
55	85.42	79.32	86.16	76.6	76.52	80.1	75.98
60	86.75	80.88	87.27	78.14	77.34	80.85	76.9
65	88.88	82.65	88.69	79.77	78.33	81.81	77.88
70	88.35	83.31	89.04	80.52	80.04	83.35	79.33
75	89.77	84.59	90.05	81.62	80.92	84.36	80.44
80	90.18	85.64	90.89	83.21	81.85	85.23	81.65
85	90.67	86.37	91.26	83.65	83.51	86.43	82.99
90	91.82	87.39	92.1	84.94	84.75	87.79	84.64
95	84.8	85.41	88.87	81.9	83.33	82.46	77.06
100	51.2	68.53	68.51	49.01	52.99	65.69	65.42
105	40.14	55.41	57.97	37.99	42.42	55.59	57.22
110	33.72	46.16	47.93	30.68	37.3	49.87	52.11
115	30.53	42.63	41.42	27.19	33.7	45.79	46.69
120	31.01	39.88	39.3	27.85	33.47	42.19	43.06
125	29.87	37.23	36.53	27.21	31.21	38.09	39.21
130	28.59	34.44	34.03	26.32	29.37	34.63	35
135	27.19	31.71	31.31	25.23	27.26	32.3	32.82
140	26.01	28.89	29.34	24.73	27.52	31.79	31.63
145	22.33	24.88	25.63	18.62	27.02	30.72	30.44
150	23.61	24.83	24.89	21.54	25.52	24.145	28.376

Table Appendix-A2 Temperatures inside infested kernels treated at 105°C in hot air for 90 s

Treatment time (s)	Temperature (°C)		
	Replication 1	Replication 2	Replication 3
0	29.88	24.22	25.15
5	33.38	40.88	37.68
10	37.63	48.2	42.21
15	42.41	51.29	45.59
20	46.8	56.52	47.85
25	50.53	59.32	51.44
30	53.41	61.56	52.69
35	56.77	64.29	54.09
40	59.47	65.78	57.14
45	62.1	69.53	58.89
50	64.76	69.57	60.63
55	67.01	71.26	62.59
60	69.42	72.64	63.48
65	71.48	72.82	65.19
70	73.26	73.91	66.29
75	74.89	74.64	67.43
80	76.3	75.33	69.15
85	77.95	76.29	70.67
90	77.6	73.32	72.29
95	65.98	62.74	62.86
100	57.15	59.83	45.14
105	50.81	57.66	37.16
110	45.97	56.36	35.09
115	41.98	44.05	39.81
120	38.98	32.08	49.97
125	36.27	28.43	44.51
130	33.92	25.84	31.06
135	32.1	25.69	27.28
140	30.68	25.67	25.98
145	29.41	25.31	25.46
150	28.3	24.97	24.77

Table Appendix-A3 Temperatures inside uninfested kernels treated at 105℃ in hot air for 90 s

Treatment time (s)	Temperature (℃)		
	Replication 1	Replication 2	Replication 3
0	24.7	25.38	24.7
5	46.98	48.61	46.98
10	61.15	62.72	61.15
15	70.78	72.51	70.78
20	77.81	79.92	77.81
25	83.11	85.31	83.11
30	87.13	89.39	87.13
35	90.1	92.49	90.1
40	92.35	94.81	92.35
45	94.6	96.81	94.6
50	96.69	98.47	96.69
55	98.24	99.7	98.24
60	99.38	100.72	99.38
65	100.21	101.48	100.21
70	100.73	101.98	100.73
75	101.18	102.43	101.18
80	101.8	102.74	101.47
85	101.74	103.01	101.69
90	98.57	102.27	98.15
95	81.49	84.43	82.59
100	68.11	74.72	72.04
105	61.46	67.26	64.33
110	54.5	61	57.46
115	50.32	55.51	51.76
120	45.85	50.38	47.11
125	41.88	45.83	42.96
130	38.67	41	39.16
135	35.7	38.63	36.91
140	33.4	36.84	35.36
145	31.81	35.11	33.79
150	30.36	33.71	32.49

Table Appendix-A4 Temperatures between kernels treated at 105°C in superheated steam for 3 s

Treatment time (s)	Replication 1	Replication 2	Replication 3	Replication 4	Replication 5	Replication 6	Replication 7
0	21.85	22.04	24.25	22.61	24.06	22.68	22.75
1	94.56	36.64	89.48	41.12	77.1	94.46	96.34
2	99.53	79.55	99.63	68.3	88.8	98.88	98.67
3	99.68	92.95	99.81	86.63	99.16	99.49	99.28
4	99.07	95.33	68.59	94.3	99.64	99.97	99.27
5	86.38	90.65	54.39	95.46	99.78	99.95	99.41
6	79.06	85.92	51.67	92.07	88.51	83.5	81.72
7	69.45	81.23	42.55	88.62	81.82	81.02	78.13
8	59.97	75.6	37.12	85.87	72.17	76.66	59.34
9	59.27	71.93	38.96	81.07	58.91	69.88	49.27
10	59.47	69.62	39.21	74.26	41.35	57.15	43.94
11	58.39	68.52	37.7	68.5	34.43	47.84	40.27
12	59.16	66.39	39.38	63.83	33.09	44.49	38
13	56.93	63.69	40.69	60.2	32.84	41.77	34.72
14	57.79	61.75	41.43	57.29	32.9	39.86	33.61
15	51.75	59.15	40.78	54.88	33.25	38.49	33.28
16	44.9	55.68	38.71	52.76	33.37	37.4	32.92
17	41.53	52.82	36.87	50.96	33.14	36.5	32.2
18	37.9	49.96	34.71	49.31	32.83	35.66	31.44
19	35.38	47.47	32.82	47.81	32.82	34.75	31.11
20	34.15	45.49	31.56	46.45	32.47	33.87	31.17

Table Appendix-A5 Temperatures inside infested kernels treated at 105℃ in superheated steam for 3 s

Treatment time (s)	Replicatio n 1	Replicatio n 2	Replicatio n 3	Replicatio n 4	Replicatio n 5	Replicatio n 6	Replicatio n 7	Replicatio n 8	Replicatio n 9	Replicatio n 10	Replicatio n 11
0	22.62	25.76	26.69	26.61	23.28	23.01	25.71	26.55	23.74	26.65	27.52
1	52.2	48.69	48.1	52.09	81.43	32.31	38.71	35.8	36.67	35.94	44.69
2	73.77	67.71	68.1	70.33	80.57	46.21	49.07	49.41	46.5	46.91	58.89
3	88.29	80.92	81.75	79.07	84.2	57.63	56.81	62.17	57.13	57.12	69.59
4	78.99	84.77	75.64	76.26	78.41	67.83	67.84	74.11	73.64	69.45	76.92
5	74.75	81.08	80.01	76.68	53.04	63.7	67.83	73.12	63.06	61.01	70.35
6	71.53	74.94	70.08	66.26	42.48	60.27	66.48	69.84	56.35	54.53	64.73
7	69.45	68.84	63.14	61.58	37.48	57.44	66.92	65.74	51.65	49.96	60.02
8	67.54	64.62	55.58	52.08	35.82	53.92	63.37	60.86	47.36	46.12	55.82
9	64.91	61.64	52.43	46.85	32.93	50.87	60.07	56.37	42.84	43.32	51.72
10	62.86	59.31	46.69	43.75	31.57	49.06	57.81	52.64	40.28	40.82	48.53
11	61.27	57.31	48.8	42.25	29.62	47.43	56.3	49.68	36.99	37.79	46.21
12	58.66	55.47	44.23	36.86	30.06	46.22	54.92	46.94	34.51	35.44	44.41
13	55.39	53.87	38.23	33.79	29.58	45.06	52.17	44.48	33.77	33.98	42.85
14	52.61	52.41	38.05	32.24	30.76	43.97	50.09	42.61	33.32	32.96	41.41
15	49.89	50.98	36.66	31.05	32.02	43.01	48.43	40.81	33.02	32.2	40.18
16	47.68	49.68	34	29.26	28.87	42.15	46.75	39.08	32.75	31.44	39.2
17	45.82	48.44	31.73	28.18	29.45	41.32	44.93	37.33	32.42	30.73	38.23
18	44.09	47.28	29.8	26.77	29.05	40.45	43.21	35.6	32.13	30.06	37.39
19	42.5	46.16	28.95	25.91	29.24	39.7	41.76	34.39	31.81	29.46	36.58
20	41.09	45.17	28.41	25.51	28.67	39.02	40.39	33.19	31.47	28.94	35.81

Table Appendix-A6 Temperatures inside uninfested kernels treated at 105℃ in superheated steam for 3 s

Treatment time (s)	Replication 1	Replication 2	Replication 3
0	29.64	27.55	29.45
1	35.27	32.02	33.28
2	42.55	37.05	38.49
3	51.62	38.38	37.74
4	52.43	41.23	39.87
5	47.6	34.42	38.45
6	44.31	33.38	38.87
7	42.18	30.84	38.5
8	39.15	31.62	38.72
9	36.18	31.37	38.61
10	34.59	31	36.86
11	33.52	31.26	34.38
12	32.91	29.88	33.11
13	32.28	31.49	34.37
14	31.89	30.84	34.13
15	31.37	31.79	34.67
16	30.66	32.99	35.14
17	30.08	32.43	34.27
18	29.53	32.32	34.92
19	29.1	33.77	35.71
20	28.6	34.37	36.37

Appendix B

Weight data of the wheat kernels

Table Appendix-B1Weight of uninfested kernels of 12.5% initial m.c. treated at 105℃ in hot air for 90 s

Treatment time (s)	Initial weight (g)	Final weight (g)
1	4.4847	4.4845
	4.4116	4.4116
	4.4491	4.4486
3	4.4762	4.4756
	4.4480	4.4479
	4.4268	4.4267
5	4.4167	4.4162
	4.4224	4.4216
	4.4326	4.4318
10	4.4379	4.4348
	4.4123	4.4102
	4.4529	4.4492
15	4.4885	4.4840
	4.4165	4.4108
	4.4429	4.4382
30	4.4936	4.4874
	4.4443	4.4384
	4.4719	4.4662
45	4.4116	4.4025
	4.4703	4.4614
	4.4237	4.4158
60	4.4421	4.4335
	4.4753	4.4647
	4.4061	4.3954
75	4.4547	4.4348
	4.4945	4.4828
	4.4914	4.4822
90	4.4617	4.4424
	4.4479	4.4303
	4.4055	4.3884

Table Appendix-B2 Weight of uninfested kernels of 14.5% initial m.c. treated at 105°C in hot air for 90 s

Treatment time (s)	Initial weight (g)	Final weight (g)
1	4.4421	4.4418
	4.4803	4.4801
	4.4623	4.4620
3	4.4941	4.4933
	4.4116	4.4098
	4.4609	4.4606
5	4.4635	4.4631
	4.4061	4.4047
	4.4269	4.4253
10	4.4752	4.4716
	4.4873	4.4853
	4.4922	4.4903
15	4.4222	4.4153
	4.4414	4.4356
	4.4498	4.4434
30	4.4429	4.4361
	4.4343	4.4291
	4.4906	4.4808
45	4.4215	4.4087
	4.4704	4.4580
	4.4783	4.4668
60	4.455	4.4372
	4.4701	4.4504
	4.4528	4.4334
75	4.4021	4.3775
	4.4788	4.4571
	4.4093	4.3868
90	4.4191	4.3825
	4.4677	4.4253
	4.4591	4.4278

Table Appendix-B3 Weight of uninfested kernels of 16.5% initial m.c. treated at 105°C in hot air for 90 s

Treatment time (s)	Initial weight (g)	Final weight (g)
1	4.4401	4.4400
	4.4843	4.4842
	4.4893	4.4893
3	4.4542	4.4540
	4.4685	4.4684
	4.4092	4.4091
5	4.4981	4.4965
	4.4821	4.4812
	4.493	4.4925
10	4.4848	4.4834
	4.4173	4.4149
	4.4643	4.4592
15	4.419	4.4110
	4.441	4.4356
	4.4161	4.4119
30	4.4924	4.4864
	4.413	4.3983
	4.4965	4.4878
45	4.4246	4.4080
	4.443	4.4252
	4.4004	4.3815
60	4.4063	4.3793
	4.4074	4.3753
	4.4977	4.4689
75	4.4357	4.4027
	4.4616	4.4222
	4.4977	4.4615
90	4.446	4.3804
	4.4543	4.3898
	4.4443	4.3735

Table Appendix-B4 Weight of uninfested kernels of 12.5% initial m.c. treated at 105℃ in superheated steam for 5 s

Treatment tie (s)	Initial weight (g)	Final weight (g)
1	4.5764	4.6521
1	4.5897	4.6444
1	4.5900	4.6254
3	4.4977	4.6121
3	4.5338	4.6220
3	4.4896	4.6119
5	4.5576	4.7329
5	4.5209	4.7188
5	4.4690	4.6113

Table Appendix-B5 Weight of uninfested kernels of 14.5% initial m.c. treated at 105℃ in superheated steam for 5 s

Treatment time (s)	Initial weight (g)	Final weight (g)
1	4.6853	4.77067
1	4.3976	4.434424
1	4.6765	4.732403
3	4.4896	4.599339
3	4.5513	4.666461
3	4.6231	4.76235
5	4.6811	4.897027
5	4.5514	4.696979
5	4.6143	4.751568

Table Appendix-B6 Weight of uninfested kernels of 16.5% initial m.c. treated at 105°C in superheated steam for 5 s

Treatment time (s)	Initial weight (g)	Final weight (g)
1	4.5764	4.611191
1	4.5897	4.640271
1	4.59	4.667702
3	4.4977	4.590612
3	4.5338	4.653052
3	4.4896	4.633889
5	4.5576	4.701749
5	4.5209	4.737045
5	4.469	4.637275

Appendix C

Mortality data of the insects

Table Appendix-C1 Mortality of adults present outside wheat kernels of 12.5 initial m.c., treated at 105℃ in hot air for 75 s

Treatment time (s)	*Tribolium castaneum*		*Cryptolestes ferrugineus*		*Sitophilus oryzae*	
	Total No of insects	No of dead insects	Total No of insects	No of dead insects	Total No of insects	No of dead insects
0	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
1	22	0	32	0	39	0
	35	0	51	0	35	0
	29	0	46	0	34	0
	42	0	28	0	31	0
	38	0	27	0	30	0
3	38	0	41	0	30	0
	35	0	23	0	35	1
	34	0	39	0	43	0
	39	0	47	0	32	0
	42	0	56	0	31	0
5	33	0	25	0	31	1
	35	0	32	1	30	1
	30	0	21	0	33	0
	31	0	20	0	30	0
	34	0	26	0	34	1
10	40	1	32	1	42	2
	38	1	30	0	30	1
	44	1	44	3	47	7
	51	0	29	1	31	2
	36	1	35	2	46	8
15	44	6	40	4	35	11
	43	19	32	5	37	7
	48	21	29	6	52	10
	35	6	36	4	36	6
	30	13	38	5	48	14
30	38	14	40	15	34	14
	39	20	31	9	35	11
	38	17	32	18	40	11
	46	24	42	14	43	19
	46	22	36	11	35	15

Table Appendix-C1 continued

45	55	41	40	38	29	29
	37	37	45	44	39	32
	53	53	45	45	30	30
	50	34	51	51	41	29
	29	29	36	32	53	42
60	32	32	25	25	29	29
	47	47	34	34	43	43
	33	33	62	62	30	30
	28	28	47	47	35	35
	40	40	33	33	27	27
75	38	38	47	47	24	24
	42	42	51	51	35	35
	51	51	24	24	39	39
	48	48	43	43	41	41
	33	33	38	38	36	36

Table Appendix-C2 Mortality of adults present outside wheat kernels of 14.5 initial m.c., treated at 105℃ in hot air for 75 s

Treatment time (s)	*Tribolium castaneum*		*Cryptolestes ferrugineus*		*Sitophilus oryzae*	
	Total No of insects	No of dead insects	Total No of insects	No of dead insects	Total No of insects	No of dead insects
0	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
1	22	0	25	0	39	0
	35	0	27	0	35	0
	29	0	21	0	34	0
	42	0	21	0	31	0
	38	0	25	0	30	0
3	38	0	25	0	30	0
	35	0	21	0	35	1
	34	0	21	0	43	0
	39	0	22	0	32	0
	42	0	26	0	31	0
5	33	0	25	0	31	1
	35	0	32	1	30	1
	30	0	21	0	33	0
	31	0	20	0	30	0
	34	0	26	0	34	1
10	33	1	32	1	39	2
	40	3	30	0	54	8
	31	1	44	3	33	6
	39	2	29	1	49	8
	29	1	35	2	40	3
15	40	2	33	3	41	6
	32	1	40	4	38	6
	35	5	46	5	48	8
	38	2	36	3	35	7
	41	4	41	4	41	6
30	42	24	30	3	30	14
	37	12	44	5	34	16
	32	10	49	18	38	10
	49	18	48	14	30	15
	43	21	36	9	32	18

Table Appendix-C2 continued

45	43	40	56	26	40	35
	39	37	54	44	41	24
	42	42	30	23	44	41
	31	31	53	20	37	37
	29	29	38	22	43	36
60	32	32	42	42	34	34
	47	47	54	54	45	45
	33	33	30	30	49	49
	28	28	35	35	31	31
	40	40	48	48	24	24
75	38	38	36	36	24	24
	42	42	45	45	35	35
	51	51	38	38	39	39
	48	48	44	44	41	41
	33	33	68	68	36	36

Table Appendix-C3 Mortality of adults present outside wheat kernels of 16.5 initial m.c., treated at 105℃ in hot air for 75 s

Treatment time (s)	*Tribolium castaneum*		*Cryptolestes ferrugineus*		*Sitophilus oryzae*	
	Total No of insects	No of dead insects	Total No of insects	No of dead insects	Total No of insects	No of dead insects
0	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
1	43	0	32	0	40	0
	29	0	46	0	30	0
	35	0	23	0	42	0
	37	0	49	0	52	0
	42	0	21	0	40	0
3	54	0	22	0	45	0
	32	0	45	0	42	0
	31	0	48	0	30	0
	31	0	36	0	22	0
	35	0	49	0	36	0
5	42	1	46	0	29	0
	36	0	45	1	41	0
	34	0	29	0	52	0
	29	0	35	0	25	0
	44	0	37	0	28	0
10	62	2	30	0	32	0
	55	0	54	1	44	3
	48	1	42	0	34	1
	57	0	31	0	46	0
	49	1	26	0	36	3
15	45	10	30	1	33	9
	43	2	45	8	30	5
	35	3	34	6	33	8
	55	9	40	10	40	10
	52	8	32	7	44	11
30	37	22	46	6	30	14
	40	12	28	7	34	16
	45	20	35	13	38	10
	36	20	36	4	30	15
	30	7	42	11	32	18

Table Appendix-C3 continued

45	45	27	40	22	43	24
	52	36	39	21	36	22
	35	26	46	25	44	31
	47	47	52	44	37	26
	33	33	42	31	43	36
60	45	45	62	51	52	50
	56	56	32	32	46	46
	52	52	37	34	35	31
	33	33	49	47	32	32
	37	37	35	30	55	55
75	36	36	35	35	32	32
	29	29	48	48	45	45
	35	35	47	47	47	47
	44	44	61	61	36	36
	62	62	38	38	44	44

Table Appendix-C4 Mortality of adults present outside wheat kernels of 12.5 initial m.c., treated at 105°C in superheated steam for 3 s

Treatment time (s)	*Tribolium castaneum*		*Cryptolestes ferrugineus*		*Sitophilus oryzae*	
	Total No of insects	No of dead insects	Total No of insects	No of dead insects	Total No of insects	No of dead insects
0	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
1	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
3	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30

Table Appendix-C5 Mortality of adults present outside wheat kernels of 14.5 initial m.c., treated at 105°C in superheated steam for 3 s

Treatment time (s)	*Tribolium castaneum*		*Cryptolestes ferrugineus*		*Sitophilus oryzae*	
	Total No of insects	No of dead insects	Total No of insects	No of dead insects	Total No of insects	No of dead insects
0	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
1	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
3	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30

Table Appendix-C6 Mortality of adults present outside wheat kernels of 16.5 initial m.c., treated at 105°C in superheated steam for 3 s

Treatment time (s)	*Tribolium castaneum*		*Cryptolestes ferrugineus*		*Sitophilus oryzae*	
	Total No of insects	No of dead insects	Total No of insects	No of dead insects	Total No of insects	No of dead insects
0	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
1	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
3	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30

Table Appendix-C7 Mortality of adults and immature stages of *Sitophilus oryzae* thriving inside wheat kernels of 12.5% initial m.c. treated in hot air at 105℃ for 90 s.

Treatment time (s)	Adults		Larvae		Pupae	
	Total No of insects	No of dead insects	Total No of insects	No of dead insects	Total No of insects	No of dead insects
0	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	1	30	0
	30	0	30	0	30	0
1	20	0	30	0	30	0
	21	0	30	0	30	0
	22	0	30	0	30	0
	20	0	30	0	30	0
	20	0	30	0	30	0
3	20	0	30	0	30	0
	20	0	30	0	30	0
	20	0	30	0	30	0
	20	0	30	0	30	0
	20	0	30	0	30	0
5	30	0	30	0	30	0
	30	1	30	0	30	0
	21	0	30	0	30	0
	20	0	30	0	30	0
	22	0	30	0	30	0
10	25	3	30	2	30	0
	30	1	30	0	30	2
	33	1	30	1	30	3
	25	2	30	3	30	0
	24	1	30	3	30	1
15	30	6	30	4	30	3
	30	6	30	3	30	1
	35	1	30	1	30	5
	30	8	30	5	30	2
	30	3	30	3	30	3
30	30	8	30	10	30	6
	30	7	30	9	30	12
	30	5	30	15	30	4
	30	9	30	12	30	3
	30	10	30	7	30	9

Table Appendix-C7 continued

45	30	20	30	15	30	16
	30	18	30	24	30	13
	30	17	30	17	30	20
	30	19	30	13	30	14
	30	22	30	25	30	17
60	30	30	30	23	30	23
	30	30	30	29	30	29
	30	30	30	24	30	22
	30	30	30	30	30	19
	30	30	30	26	30	21
75	30	30	30	30	30	28
	30	30	30	30	30	28
	30	30	30	30	30	30
	30	30	30	30	30	23
	30	30	30	30	30	30
90	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30

Table Appendix-C8 Mortality of adults and immature stages of *Sitophilus oryzae* thriving inside wheat kernels of 14.5% initial m.c. treated in hot air at 105℃ for 90 s.

Treatment time (s)	Adults		Larvae		Pupae	
	Total No of insects	No of dead insects	Total No of insects	No of dead insects	Total No of insects	No of dead insects
0	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	1	30	0
	30	0	30	0	30	0
1	20	0	30	0	30	0
	21	0	30	0	30	0
	22	0	30	0	30	0
	20	0	30	0	30	0
	20	0	30	0	30	0
3	20	0	30	0	30	0
	20	0	30	0	30	0
	20	0	30	0	30	0
	20	0	30	0	30	0
	20	0	30	0	30	0
5	20	0	30	0	30	0
	30	1	30	0	30	0
	21	0	30	0	30	0
	20	0	30	0	30	0
	22	0	30	0	30	0
10	25	0	30	1	30	1
	30	1	30	1	30	0
	33	1	30	0	30	0
	25	2	30	0	30	1
	24	1	30	1	30	1
15	30	2	30	0	30	2
	26	2	30	1	30	2
	35	3	30	2	30	1
	26	1	30	1	30	1
	30	2	30	2	30	2
30	30	6	30	4	30	5
	30	10	30	7	30	3
	30	4	30	3	30	4
	30	2	30	1	30	8
	30	13	30	8	30	5

Table Appendix-C8 continued

45	30	21	30	22	30	15
	30	24	30	15	30	9
	30	17	30	12	30	12
	30	22	30	19	30	14
	30	15	30	16	30	11
60	30	26	30	30	30	23
	30	19	30	21	30	14
	30	28	30	23	30	19
	30	25	30	21	30	22
	30	27	30	24	30	18
75	30	30	30	26	30	29
	30	30	30	28	30	23
	30	30	30	30	30	30
	30	30	30	30	30	26
	30	30	30	29	30	27
90	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30

Table Appendix-C9 Mortality of adults and immature stages of *Sitophilus oryzae* thriving inside wheat kernels of 16.5% initial m.c. treated in hot air at 105℃ for 90 s.

Treatment time (s)	Adults		Larvae		Pupae	
	Total No of insects	No of dead insects	Total No of insects	No of dead insects	Total No of insects	No of dead insects
0	30	0	30	0	30	0
	30	0	30	1	30	0
	30	1	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
1	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
3	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
5	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
10	30	1	30	1	30	0
	30	0	30	0	30	1
	30	2	30	0	30	1
	30	1	30	0	30	0
	30	0	30	0	30	0
15	30	0	30	1	30	2
	30	1	30	1	30	0
	30	2	30	0	30	1
	30	2	30	0	30	1
	30	1	30	0	30	2
30	30	10	30	1	30	2
	30	4	30	7	30	1
	30	2	30	3	30	8
	30	11	30	5	30	4
	30	5	30	1	30	7

Table Appendix-C9 continued

45	30	19	30	13	30	16
	30	13	30	20	30	6
	30	7	30	11	30	8
	30	9	30	15	30	13
	30	12	30	11	30	11
60	30	22	30	18	30	21
	30	28	30	26	30	17
	30	30	30	22	30	16
	30	19	30	15	30	10
	30	27	30	24	30	15
75	30	30	30	25	30	25
	30	30	30	30	30	21
	30	30	30	28	30	27
	30	30	30	21	30	25
	30	30	30	30	30	26
90	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30
	30	30	30	30	30	30

Table Appendix-C10 Mortality of adults and immature stages of *Sitophilus oryzae* thriving inside wheat kernels of 12.5% initial m.c. treated in superheated steam at 105°C for 3 s.

	Adults		Larvae		Pupae	
Treatment time (s)	Total No of insects	No of dead insects	Total No of insects	No of dead insects	Total No of insects	No of dead insects
0	30	0	30	0	30	0
	30	0	30	1	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
1	30	30	30	25	30	25
	30	27	30	29	30	30
	30	30	30	28	30	26
	30	28	30	28	30	25
	30	30	30	29	30	30
3	30	0	30	30	30	30
	30	0	30	30	30	30
	30	0	30	30	30	30
	30	0	30	30	30	30
	30	0	30	30	30	30

Table Appendix-C11 Mortality of adults and immature stages of *Sitophilus oryzae* thriving inside wheat kernels of 14.5% initial m.c. treated in superheated steam at 105°C for 3 s.

Treatment time (s)	Adults		Larvae		Pupae	
	Total No of insects	No of dead insects	Total No of insects	No of dead insects	Total No of insects	No of dead insects
0	30	0	30	0	30	0
	30	0	30	1	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
1	30	26	30	24	30	22
	30	25	30	30	30	22
	30	30	30	23	30	27
	30	27	30	28	30	30
	30	24	30	30	30	21
3	30	0	30	30	30	30
	30	0	30	30	30	30
	30	0	30	30	30	30
	30	0	30	30	30	30
	30	0	30	30	30	30

Table Appendix-C12 Mortality of adults and immature stages of *Sitophilus oryzae* thriving inside wheat kernels of 16.5% initial m.c. treated in superheated steam at 105°C for 3 s.

Treatment time (s)	Adults		Larvae		Pupae	
	Total No of insects	No of dead insects	Total No of insects	No of dead insects	Total No of insects	No of dead insects
0	30	0	30	0	30	0
	30	0	30	1	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
	30	0	30	0	30	0
1	30	28	30	28	30	24
	30	30	30	26	30	26
	30	26	30	30	30	30
	30	28	30	27	30	24
	30	25	30	29	30	23
3	30	0	30	30	30	30
	30	0	30	30	30	30
	30	0	30	30	30	30
	30	0	30	30	30	30
	30	0	30	30	30	30

Appendix D

Germination data of the wheat kernels

Table Appendix-D1 Germination of uninfested wheat kernels of 12.5, 14.5 and 16.5% initial m.c., treated in hot air at 105℃ for 90 s.

Treatment time (s)	Total No of seeds	No of germinated seeds		
		12.5%	14.5%	16.5%
Control	25	24	24	25
	25	25	25	23
	25	22	23	23
1	25	24	25	25
	25	23	24	25
	25	22	24	22
3	25	22	21	22
	25	20	23	24
	25	24	21	22
5	25	22	24	23
	25	21	23	21
	25	22	25	25
10	25	21	24	22
	25	20	23	24
	25	21	24	23
15	25	19	23	22
	25	18	23	21
	25	17	24	24
30	25	12	16	20
	25	13	17	17
	25	10	14	18
45	25	10	13	13
	25	9	15	14
	25	7	14	15
60	25	8	11	12
	25	9	11	12
	25	6	9	13
75	25	3	9	10
	25	3	7	9
	25	5	6	8
90	25	2	3	7
	25	1	7	4
	25	3	2	3

Table Appendix-D2 Germination of uninfested wheat kernels of 12.5, 14.5 and 16.5% initial m.c., treated in superheated steam at 105℃ for 5 s.

Treatment time (s)	Total No of seeds	No of germinated seeds		
		12.5%	14.5%	16.5%
Control	25	24	24	25
	25	25	25	23
	25	22	23	23
	25	24	24	25
	25	25	25	23
	25	22	23	23
1	25	20	21	20
	25	21	20	19
	25	20	22	23
	25	22	18	22
	25	18	21	18
	25	21	22	21
3	25	19	18	18
	25	17	15	22
	25	17	20	20
	25	21	17	19
	25	18	20	18
	25	20	22	16
5	25	10	15	11
	25	13	13	14
	25	11	12	10
	25	14	13	13
	25	10	14	12
	25	12	12	11