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Insect pests in stored wheat cause significant losses and play an important role in the dispersal of viable fungal spores of various species including aflatoxin producing Aspergillus spp. The problems of insecticide resistance in stored insects and environmental hazards associated with fumigants and conventional grain protectants underscore the need to explore reduced risk insecticides to control stored insects and the ultimate effect on fungal infection inhibition. The purpose of this study was to investigate the insecticidal potential of four biorational insecticides: spinosad, thiamethoxam, imidacloprid and indoxacarb on wheat against Rhyzopertha dominica and Sitophilus oryzae and the subsequent effect of insects’ mortality on Aspergillus flavus and A. parasiticus infection in grains. Spinosad and thiamethoxam were the most effective insecticides against R. dominica compared to S. oryzae followed by imidacloprid. Spinosad applied at 0.25, 0.5 and 1ppm and thiamethoxam at 2 and 4ppm concentrations resulted in complete mortality of R. dominica and >90% infection inhibition of A. flavus and A. parasiticus. However, indoxacarb was more toxic against S. oryzae compared to R. dominica. The mortality of R. dominica was directly related to the percent infection inhibition of A. flavus and A. parasiticus in all the treatments. Whereas, mortality of S. oryzae was only related to the percent infection inhibition of A. parasiticus in all the treatments. The results show that although both spinosad and thiamethoxam can provide protection against R. dominica and fungal infections in stored grains, more potent reduced risk insecticides and/or their combinations would be needed than either of these to provide broad spectrum protection of stored grains. In conclusion, the results of the present study provide baseline data for the management of aflatoxigenic fungi by controlling stored insects using biorational insecticides.
Could biorational insecticides be used in the management of aflatoxigenic *Aspergillus* spp. and their insect vectors in stored wheat?

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Abstract

Insect pests in stored wheat cause significant losses and play an important role in the dispersal of viable fungal spores of various species including aflatoxin producing *Aspergillus* spp. The problems of insecticide resistance in stored insects and environmental hazards associated with fumigants and conventional grain protectants underscore the need to explore reduced risk insecticides to control stored insects and the ultimate effect on fungal infection inhibition. The purpose of this study was to investigate the insecticidal potential of four biorational insecticides: spinosad, thiamethoxam, imidacloprid and indoxacarb on wheat against *Rhyzopertha dominica* and *Sitophilus oryzae* and the subsequent effect of insects’ mortality on *Aspergillus flavus* and *A. parasiticus* infection in grains. Spinosad and thiamethoxam were the most effective insecticides against *R. dominica* compared to *S. oryzae* followed by imidacloprid. Spinosad applied at 0.25, 0.5 and 1ppm and thiamethoxam at 2 and 4ppm concentrations resulted in complete mortality of *R. dominica* and >90% infection inhibition of *A. flavus* and *A. parasiticus*. However, indoxacarb was more toxic against *S. oryzae* compared to *R. dominica*. The mortality of *R. dominica* was directly related to the percent infection inhibition of *A. flavus* and *A. parasiticus* in all the treatments. Whereas, mortality of *S. oryzae* was only related to the percent infection inhibition of *A. parasiticus* in all the treatments. The results show that although both spinosad and thiamethoxam can provide protection against *R. dominica* and fungal infections in stored grains, more potent reduced risk insecticides and/or their combinations would be needed than either of these to provide broad spectrum protection of stored grains. In conclusion, the results of the present study provide baseline data for the management of aflatoxigenic fungi by controlling stored insects using biorational insecticides.
Aflatoxins are the group of structurally diverse mycotoxins that are mainly produced by *Aspergillus flavus* and *A. parasiticus*, both belonging to section *Flavi* [1,2]. These mycotoxins are recognized as immunosuppressive, carcinogenic, hepatotoxic, mutagenic and teratogenic [3], since they lead to serious human and animal health hazards, including acute and chronic liver diseases, tumor induction, reproductive disorders, genotoxicity and nephrotoxicity [4-6]. These mycotoxins are known to contaminate more than 25% of the world stored grain cereal commodities of which more than 300 fungal metabolites are reported to cause human and animal toxicity [7].

Stored grain contamination with insect pests and fungi is a serious problem resulting in more than 20% losses in overall production by decreasing seed germination and downgrading of grains [8]. Contamination of stored grains with fungal spores is mainly a source of mycotoxins which usually results from stored insect pest’s infestation [9]. Insects disseminate the fungal spores all over the grain bulk by their constant movement, which are carried on their body and/or deposited in insect frass [10]. These insects break seed coat as a natural barrier to fungus and provide entry point for fungal infection [11]. Therefore strategies to control insects are needed. The most serious insect pests of stored grains that cause >20% postharvest losses in developing countries are: rice weevil (*Sitophilus oryzae*), red flour beetle (*Tribolium castaneum*), lesser grain borer (*Rhyzopertha dominica*), rusty grain beetle (*Cryptolestes ferrugineus*) and khapra beetle (*Trogoderma granarium*) [8,12].

Control of these insects is of prime importance as they have the ability to carry and transmit spores of *Aspergillus* spp. internally [13]. Current control measures for these insects rely on the
extensive use of fumigants and conventional insecticides that have resulted in increased insect resistance [14], primary pest resurgence [15], secondary pest outbreak [16], and their use as grain protectant is being reconsidered for their effect on health and environmental safety [17]. Therefore, there is a need to explore reduced risk or biorational insecticides with minimal environmental effect and mammalian toxicity for judicious insect pest management.

Biorational insecticides are usually target specific new insecticides with low mammalian toxicity. Some of the biorational insecticides like spinosad, thiamethoxam have been proved as potential grain protectants against stored insect pests in different parts of the world [17, 18]. However, such studies are rare at Pakistan level. Therefore, in the present study, our aims were to evaluate the toxicity of spinosad, thiamethoxam, imidacloprid and indoxacarb against two major pests of stored wheat *R. dominica* and *S. oryzae*, and the subsequent effect of insects’ mortality on *A. flavus* and *A. parasiticus* infection in wheat grains. The results would be helpful in the management of insects and aflatoxigenic fungi in stored commodities.
Materials and Methods

Commodities, formulations and fungal cultures

Untreated, clean and infestation free wheat grains (var Seher-06) with 11.1% moisture contents were used in the present study. The insecticide formulations were spinosad (Tracer® 24% active ingredients [IA], Arysta Life Sciences, Pakistan), thiamethoxam (Actara® 25% [AI], Syngenta, Pakistan), imidacloprid (Confidor® 20% [AI], Bayer Crop Sciences, Pakistan) and indoxacarb (Steward 15%, DuPont, Pakistan). Aspergillus flavus and A. parasiticus cultures were obtained from First Fungus Culture Bank, Pakistan (FFCB).

Insects

Healthy cultures of Rhyzopertha dominica and S. oryzae adults were collected from grain market, Lahore (31.5497° N, 74.3436° E), and reared on whole wheat in the laboratory at 26±1 °C and 70±5%. The insects were reared for five generations before starting experiments. Adults of both species used in bioassays were mixed sex and 2-3-weeks-old [19].

Bioassays

Insecticidal bioassays were done by following the methodology of Athanassiou et al. [19] with some modifications. Briefly, insecticides were applied as a solution diluted with distilled water. Individual replicate lots of 200 g of wheat grains were placed in 0.5 litre glass jars for insecticide treatments: 0 (control; the grains treated with distilled water), 0.25, 0.5 and 1 mg/kg for spinosad; 0 (control; the grains treated with distilled water), 1, 2 and 4 mg/kg for thiamethoxam; 0 (control; the grains treated with distilled water), 1, 2 and 4 mg/kg for imidacloprid; 0 (control; the grains treated with distilled water), 1, 2 and 4 mg/kg for indoxacarb. To achieve above concentrations, 2 mL solution of each treatment was prepared and applied to the 200 g grains. In order to maximize insecticide distribution, the jar was shaken manually for 5 minutes [19,21].
The jars were left in the laboratory for 24 h at 25 °C and complete darkness to dry. After 24 h, the jars with insecticide treated wheat grains were inoculated with 0.5 ml spore suspension (10^4 spores/ml) of *A. flavus* (Arena “A”) or *A. parasiticus* (Arena “B”) separately. Twenty adults of *R. dominica* or *S. oryzae* were introduced in each jar, and the insects were disinfected with 0.5% sodium hypochlorite for 2 min and washed with sterile distilled water before entering into the jars [20]. To check the direct effect of insecticides on fungal infection inhibition, the same procedure was repeated but without introducing insects in the treated jars. The treated jars were closed with muslin cloth and maintained in the laboratory at 26±1 °C and 70±5%. After 14 days, the jars were opened for mortality counts and percent infection inhibition of *A. flavus* or *A. parasiticus*.

Percent infection inhibition was determined by following the methodology of Krishnamurthy et al. [21]. Briefly, 60 treated and insect infested wheat grains were withdrawn from the individual replicate and placed on three layers of sterilized moistened blotter discs in sterilized petri plates (90 mm diameter) at the rate of 20 grains per layer. The plates were incubated for 7 days in the laboratory at 26±1 °C. After incubation, the plates were examined under the stereobinocular microscope for the presence *A. flavus* or *A. parasiticus* and the number of fungal colonies and healthy seeds (i.e., without colony) were counted. Infection inhibition percentage was calculated as follows:

\[ \text{Percent infection inhibition} = \left( \frac{\text{number of healthy (uninfected) seeds}}{\text{total number of seeds}} \right) \times 100 \]

The entire procedure was replicated five times by preparing new lots of treated wheat for each replicate, and exposing, counting, and recording data for adult mortality and fungal infection as described above.

**Data analysis**
Percent mortality and infection inhibition percentage data were analyzed separately for each insect and fungal species using a one-way analysis of variance (ANOVA) with Statistix 8.1 software [22]. Means were compared by Tukey’s Honestly Significant Difference (HSD) test, at 0.05 probability.
Results

Mortality

In case of spinosad, mortality for *R. dominica* was higher than for *S. oryzae*. *Rhyzopertha dominica* showed 100% mortality at the spinosad concentrations of 0.25-1 mg/kg, in both the arena (F=6273; df=3, 16; p<0.01, for arena A, and F=2401; df=3, 16; p<0.01, for arena B). Whereas, *S. oryzae* showed the highest mortality at the concentration 1ppm followed by 0.5 and 0.25ppm (F=235; df=3, 16; p<0.01, for arena A, and F=218; df=3, 16; p<0.01, for arena B) (Fig. 1.).

*Rhyzopertha dominica* showed complete mortality on wheat treated with thiamethoxam at concentrations 2 and 4ppm (F=858; df=3, 16; p<0.01, for arena A, and F=262; df=3, 16; p<0.01, for arena B). Whereas, *S. oryzae* showed complete mortality only at 4 ppm, in both arena (F=1421; df=3, 16; p<0.01, for arena A, and F=498; df=3, 16; p<0.01, for arena B) (Fig. 2).

In case of imidacloprid, mortality for *R. dominica* was higher than for *S. oryzae*. *R. dominica* showed 92 and 94% mortality in arena A and B respectively, at the highest concentration 4ppm (F=234; df=3, 16; p<0.01, arena A, and F=192; df=3, 16; p<0.01, for arena B) (Fig. 3). Whereas, *S. oryzae* showed 33 and 39% mortality in arena A and B respectively, at the highest concentration 4ppm (F=43.6; df=3, 16; p<0.01, for arena A, and F=50.8; df=3, 16; p<0.01, for arena B).

For indoxacarb, in contrast, mortality for *R. dominica* was lower than for *S. oryzae*. *R. dominica* showed 94 and 92.3% mortality in arena A and B, respectively at the concentration 4ppm (F=140; df=3, 16; p<0.01, for arena A, and F=150; df=3, 16; p<0.01, for arena B). However, *S.
oryzae showed complete mortality at 2 and 4ppm (F=403; df=3, 16; p<0.01, for arena A, and F=661; df=3, 16; p<0.01, for arena B)

**Fungal infection inhibition**

Mortality of *R. dominica* seems to influence directly the percent infection inhibition of *A. flavus* and *A. parasiticus* in all the treatments. In the controls, where the survival percentage was high, less infection inhibition of both fungi was observed. In case of spinosad, where mortality of *R. dominica* was 100% at the tested concentrations, more than 93% infection inhibition of *A. flavus* and *A. parasiticus* was observed. Whereas, in controls where the survival percentage of *R. dominica* was high (>90%), significantly more incidence of both fungi was observed. The same trend was observed with rest of the insecticides tested (Fig. 1-4). Similarly, percent mortality of *S. oryzae* seems to influence only the infection inhibition of *A. parasiticus* (Fig. 1-4). Moreover, highly significant positive correlations (p<0.01) were observed between mortality of *R. dominica* and infection inhibition of *A. flavus* or *A. parasiticus*, and mortality of *S. oryzae* and infection inhibition of *A. parasiticus* (p<0.01; Table 1). However, in the present study there was statistically no effect of insecticides on fungal infection inhibition when the insecticides were tested without introducing insects in the treated jars (data not shown here).
Discussion

The results of the present study revealed varying level of toxicities of insecticide against *R. dominica* and *S. oryzae*. The results also suggest that control of these insects may help limit the infection of aflatoxigenic fungi in stored wheat.

Overall, spinosad was the most effective insecticide against *R. dominica* compared to *S. oryzae*. Spinosad applied at 0.25, 0.5 and 1 ppm concentrations resulted in complete mortality of *R. dominica*. In contrast, *S. oryzae* showed 94% mortality at the highest concentration of spinosad tested. Spinosad is a relatively new insecticide of low mammalian toxicity and has a broad spectrum of target species, including stored insect pests [23], and has been registered for use in the United States [19]. The findings on spinosad toxicity against the tested insect species are in agreement with a number of previous reports [19,23-26]. It seems that if *R. dominica* is the sole species in stored commodities, spinosad may be as an effective grain protectant.

In case of thiamethoxam, *R. dominica* showed complete mortality at concentrations 2 and 4 ppm, whereas *S. oryzae* showed complete mortality at only 4 ppm. Thiamethoxam is a neonicotinoid and a relatively new insecticide of low mammalian toxicity and does not produce mutagenic and/or teratogenic effects [18]. It has been extensively used as a seed coat treatment with satisfactory results against a wide range of pests [27]. Thiamethoxam was the first time evaluated as a grain protectant by Arthur et al. [18] and found it effective against *R. dominica* and *S. oryzae*. It was further reported that the mortality of *S. oryzae* and *R. dominica* increased with time and it had reached approximately 100% after 6 d of exposure to thiamethoxam. But in our study, *S. oryzae*, showed less than 100% mortality at 2 ppm after 14 d of exposure. This difference could be due to the different origin of *S. oryzae*. 
Imidacloprid is also a neonicotinoid with low mammalian toxicity and has been used as seed treatment for the management of a number of sucking insect pests [27]. Recently, Daglish et al. [28] investigated the potential of imidacloprid against different beetle pests of stored grains. They reported that the toxicity of imidacloprid was species and dose dependent, and that *R. dominica* was more susceptible to imidacloprid than *S. oryzae*. The results of the present study with respect to imidacloprid also revealed that the mortality for *R. dominica* was higher than for *S. oryzae*. *Rhyzopertha dominica* showed up to 94% mortality at the highest concentration 4 ppm as compared to 39% mortality for *S. oryzae*.

Indoxacarb belongs to an oxadiazine insecticide group and has strong potential against different insect pests [29]. In the present study mortality for *R. dominica* was lower than for *S. oryzae*, which is in agreement with Daglish et al. [28] who evaluated indoxacarb potential as a grain protectant first time.

Concerning the infection inhibition of tested fungi, mortality of *R. dominica* was directly related to the percent infection inhibition of *A. flavus* and *A. parasiticus* in all the treatments. In the controls, where survival percentage was high, less inhibition of both fungi was observed. Moreover, a highly significant positive correlation was observed between mortality of *R. dominica* and infection inhibition of *A. flavus* or *A. parasiticus*, and mortality of *S. oryzae* and infection inhibition of *A. parasiticus*. There was an indirect effect of insecticides on the inhibition of both fungi. Insecticides caused mortality of the insect species which ultimately resulted in infection inhibition of fungi. One most probable reason could be that increased mortality of insects resulted in reduced movement and seed coat damage which ultimately lead to reduced infection of the fungi. After the harvest of crops, temperature and humidity play an important role in the growth of toxigenic fungi and insects in the storage ecosystem [30]. Stored
insect pests in the granary ecosystem move for breeding and feeding purposes from one point another and contribute the dispersal of viable spores of fungi of various species, including A. flavus and A. parasiticus, which are carried on the insect body surface or deposited in their frass [30]. During feeding in stored commodities, insects break the seed coat of grains, which is a natural barrier to fungal growth, and ultimately promote easy spread of fungal spores [11]. Hence, in the present study fungi infection was more in those treatments where the survival rate of insects was high, most probably due to a high rate of feeding and movement activities.

Dispersal of fungal spores in storage commodities usually depends on the type of insect species present in those commodities [31]. During storage, the invasion by a variety of insects causes losses to storage grains and act as mechanical vectors of viable fungal spores [20]. If storage grains left untreated, insects within the granary ecosystem can create local conditions of humidity and temperature that favor the rapid growth of fungi, resulting in deterioration of the grain mass and production of mycotoxins [32]. The results of the correlation in the present study are in accordance with those of Lamboni and Hell [31] who reported a significant and positive association between the activity of Sitophilus sp. and A. parasiticus. Similarly, Nesci et al. [30] reported weak involvement of Sitophilus sp. in the distribution of A. flavus spores in stored maize whereas R. dominica was more susceptible to fungal contamination and spread. From the results it is assumed that if the storage commodities left untreated and have viable spores of A. flavus and A. parasiticus, and R. dominica and S. oryzae infestation, there would be more chances of spread of the said fungi.

Since the insecticides tested in the present study are not recommended yet as grain protectants in Pakistan, further studies should be conducted to assess their long term efficacy or persistence against different stored pests across different stored grain commodities. Spinosad and
thiamethoxam proved very effective against *R. dominica* and the subsequent infection inhibition
of both aflatoxin producing fungi than the rest of the insecticide tested. In granary systems where
*R. dominica* is the sole problem, spinosad and thiamethoxam may provide adequate protection.
However, tested insecticides except indoxacarb did not provide adequate control of *S. oryzae*.
Therefore, in storage bins where both insect species coexist, there is a need to evaluate other
insecticides or insecticide combinations which can provide adequate protection against insect
pests and subsequent fungal infection. In conclusion, the results of the present study provide
baseline data for the management of aflatoxigenic fungi by controlling *R. dominica* and *S. oryzae*
using biorational insecticides. Whether this is a practical solution in granary systems for a long
time needs to be further characterizing in future studies.
References

Figure 1. Effect of different concentrations of spinosad on insects’ mortality and fungal infection inhibition. Data bars of specific color with different letters are significantly different; in all cases df=3,16, Tukey’s HSD test at p<0.05.
Figure 2. Effect of different concentrations of thiamethoxam on insects’ mortality and fungal infection inhibition. Data bars of specific color with different letters are significantly different; in all cases df=3, 16, Tukey’s HSD test at p<0.05
**Figure 3.** Effect of different concentrations of imidacloprid on insects’ mortality and fungal infection inhibition. Data bars of specific color with different letters are significantly different; in all cases df=3, 16, Tukey’s HSD test at p<0.05
**Figure 4.** Effect of different concentrations of indoxacarb on insects’ mortality and fungal infection inhibition. Data bars of specific color with different letters are significantly different; in all cases df = 3, 16, Tukey’s HSD test at p<0.05

**Table 1.** Correlation analysis between insects’ mortality and fungal infection inhibition

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<th><em>Aspergillus flavus</em></th>
<th><em>Aspergillus parasiticus</em></th>
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<tbody>
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<td><em>Ryzopertha dominica</em></td>
<td>0.93**</td>
<td>0.87**</td>
</tr>
<tr>
<td><em>Sitophilus oryzae</em></td>
<td>0.18 ns</td>
<td>0.96**</td>
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**Figure 1 (on next page)**

figure of insecticide fungus paper

**Figure 1 (Spinosad).** Effect of different concentrations of spinosad on insects’ mortality and fungal infection inhibition. Data bars of specific color with different letters are significantly different; in all cases df=3,16, Tukey’s HSD test at p<0.05. **Figure 2 (Thiamethoxam).** Effect of different concentrations of thiamethoxam on insects’ mortality and fungal infection inhibition. Data bars of specific color with different letters are significantly different; in all cases df=3, 16, Tukey’s HSD test at p<0.05. **Figure 3 (Imidacloprid).** Effect of different concentrations of imidacloprid on insects’ mortality and fungal infection inhibition. Data bars of specific color with different letters are significantly different; in all cases df=3, 16, Tukey’s HSD test at p<0.05. **Figure 4 (Indoxacarb).** Effect of different concentrations of indoxacarb on insects’ mortality and fungal infection inhibition. Data bars of specific color with different letters are significantly different; in all cases df = 3, 16, Tukey’s HSD test at p<0.05.
Thiamethoxam

A. R. dominica mortality
B. S. oryzae mortality
C. A. flavus inhibition
D. A. parasiticus inhibition

Percentage

Concentration


Thiamethoxam

R. dominica mortality
A. flavus inhibition
S. oryzae mortality
A. parasiticus inhibition

Control