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Original article (Orijinal araştırma)

Residual efficacy of methoxyfenozide applied on different grain commodities for the control of three stored-product insect pests

Depolanan ürün zararlısı üç böcek türünün mücadelesinde farklı tahıl ürünlerine uygulanan methoxyfenozidin kalıntı etkinliği

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Abstract

The residual efficacy of methoxyfenozide was assessed by exposing last instar larvae of *Oryzaephilus surinamensis* (Linnaeus, 1758) (Coleoptera: Silvanidae), *Tribolium castaneum* Herbst, 1797 (Coleoptera: Tenebrionidae) and *Trogoderma granarium* Everts, 1898 (Coleoptera: Dermestidae) to the treated grain commodities (maize, oat, rice and wheat) at concentrations of 1, 2 and 4 mg kg^{-1} of active ingredient under laboratory conditions. This trial was performed at the Department of Entomology, University of Agriculture, Faisalabad, Pakistan during the year 2018. Six bioassays were conducted by releasing the insects on treated commodities after different post treatment periods (0, 2, 4, 8, 12 and 16 weeks). At 4 mg kg^{-1}, the adult emergence from larvae exposed to treated commodities did not exceed 15% at week 0 and it was less than 36% at week 12 in all the tested insect species on all the tested commodities. The methoxyfenozide was generally more effective on oats followed by wheat, maize and rice in the *O. surinamensis* and *T. castaneum* while against *T. granarium* it was more effective in wheat followed by oats, maize and rice. Results show that methoxyfenozide possess great potential for residual control of *O. surinamensis, T. castaneum* and *T. granarium*, and can be used for replacement of conventional neurotoxic insecticides.

Keywords: Ecdysone agonist, grain commodities, insect growth regulator, residual efficacy, stored grain insects

Öz

Laboratuvar koşullarında 1, 2 ve 4 mg kg^{-1} aktif madde konsantrasyonlarında uygulama yapılmış (buğday, mısır, çeltik ve yulaf) ürünlerde, *Oryzaephilus surinamensis* (Linnaeus, 1758) (Coleoptera: Silvanidae), *Tribolium castaneum* Herbst, 1797 (Coleoptera: Tenebrionidae) ve *Trogoderma granarium* Everts, 1898 (Coleoptera: Dermestidae)'un son dönem larvaları üzerinde metoksifenozidin kalıntı etkinliği değerlendirilmiştir. Bu deneme, Ziraat Üniversitesi, Entomoloji Bölümü (Faisalabad, Pakistan)'nde 2018 yılında gerçekleştirilmiştir. Uygulama yapılmış ürünlere zararlı böcekler bırakıldıktan farklı süreler (0, 2, 4, 8, 12 ve 16 hafta) sonrasında, altı biyolojik analiz yapılmıştır. Uygulama yapılmış ürünlerdeki larvaların ergin olma oranı, 4 mg kg^{-1}'de 0. haftada %15'i geçmezken, test edilen tüm ürünlerde ve tüm böcek türlerinde 12. haftada %36'dan daha az olarak saptanmıştır. Metoksifenozid, genellikle yulaf üzerinde sırasıyla buğday, mısır ve pirince göre *T. granarium*'a göre *O. surinamensis* ve *T. castaneum* açısından daha fazla etkiliyken; *T. granarium*'a karşı ise yulaf, mısır ve pirince göre buğday üzerinde daha etkili olmuştur. Sonuçlar, *O. surinamensis*, *T. castaneum* ve *T. granarium* açısından metoksifenozidin kalıntı kontrolü için büyük potansiyele sahip olduğunu ve geleneksel sinir sistemi insektisitlerinin yerini alabileceğini göstermektedir.

Anahtar sözcükler: Ecdysone agonisti, tahıl ürünleri, böcek büyüme düzenleyicisi, kalıntı etkinliği, depolanmış tahıl böcekleri

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Introduction

Insect pests of stored commodities are not only the pests of bulk grains but also of many value-added food products in mills, processing plants and facilities where these products are stored (Gorham, 1991). These insects cause considerable postharvest losses; annually about 9% in developed countries whereas 20% or more in developing countries (Phillips & Throne, 2010). These insects are also responsible for contamination of food products with arthropod fragments and other related contaminants which may be allergic and even carcinogenic (Hubert et al., 2018).

Widely used control methods for stored product insects comprise the application of pyrethroid insecticides (Ghimire et al., 2016; Arthur et al., 2018), use of diatomaceous earth (Korunic, 1998; Kavallieratos et al., 2015, 2018) and phosphine fumigation (Carpaneto et al., 2016). However, the synthetic neurotoxic insecticides possess certain limitations for their usage, like the possible presence of insecticide residues in food (Phillips & Throne, 2010), development of insecticide resistance by the target pest species (Zettler & Cuperus, 1990; Boyer et al., 2012), health hazards (Arthur, 1996), increase in the management expenditures (Hagstrum & Subramanyam, 2006) and unfriendly for non-target organisms (Fields, 1992; Hagstrum & Subramanyam, 2006). To overcome these problems, safe alternate approaches are required for the management of insect pests of stored products. Insect growth regulators (IGRs) are the chemicals that can provide various benefits as alternatives to conventional neurotoxin products (Oberlander et al*.,* 1997; Mondal & Parween, 2000). Generally, these compounds lack harmful effects on the humans or environment and are compatible with other pest management approaches (Staal, 1975). These products possess great potential for acceptance in the food industry (Phillips & Throne, 2010). The IGRs control the pest species through inhibiting adult emergence, and are comparatively friendly for the non-target organisms than most of the conventional neurotoxic grain protectants (Oberlander et al*.,* 1997; Oberlander & Silhacek, 2000).

Mainly, the IGRs include the compounds that interfere by three different modes of action: cuticle formation; growth and development of immature insects or stimulation of metamorphosis (Oberlander et al., 1997; Oberlander & Silhacek, 2000) and are termed as chitin synthesis inhibitors, juvenile hormone agonists and ecdysteroid agonists, respectively (Oberlander et al., 1997; Mondal & Parween, 2000). Among these, the ecdysteroid agonists causes the premature synthesis of the insect's cuticle and feeding inhibition (Schneiderman, 1972; Fox, 1990; Wing & Aller, 1990). These compounds have the ability to penetrate the insect's cuticle (Schneiderman, 1972) and have chemosterilant activity in females (Heller et al*.,* 1992) through stomach and contact (Fox, 1990). Several studies have been conducted for evaluating the potential of other insect growth regulators (juvenile hormone analogues and chitin synthesis inhibitors) against different stored-grain insect pests (Elek, 1998a, b; Parween et al., 2001; Abo-Elghar et al., 2004; Arthur et al., 2009, 2018; Sagheer et al., 2011, 2012; Yasir et al., 2012, 2019; Trostanetsky et al., 2015; Ali et al., 2016, 2017, 2018; Malik et al., 2017; Arthur & Hartzer, 2018).

However, very few studies have evaluated the potential of ecdysteroid agonists against stored-grain insect pests (Oberlander et al*.,* 1998; Kostyukovsky et al., 2000; Kavallieratos et al., 2012; Ali et al., 2016, 2017). Methoxyfenozide, an ecdysteroid agonist, is the member of the diacylhydrazine class (Carlson et al., 2001), novel and potent molt-accelerating compound that targets Lepidoptera (Enríquez et al., 2010), but is harmless to beneficial insects. This compound mimics the natural insect molting hormone by binding competitively to ecdysteroid receptors in insect cells, thus to prematurely inducing larval molt (Chen et al., 2019). It is registered for use on several agricultural and horticultural plants including cotton in the United States (Alavo et al., 2011). It is important to assess the long-term residual efficacy of methoxyfenozide against stored-grain insect pests which have not been tested in these studies. Therefore, the current study was planned to evaluate the residual efficacy of methoxyfenozide (ecdysteroid agonist) against three stored-grain insects *Oryzaephilus surinamensis* (Linnaeus, 1758) (Coleoptera: Silvanidae), *Tribolium castaneum* Herbst, 1797 (Coleoptera: Tenebrionidae) and *Trogoderma granarium* Everts, 1898 (Coleoptera: Dermestidae).

Materials and Methods

The current studies were conducted at the Grain Research, Training and Storage Management Cell, Department of Entomology, University of Agriculture, Faisalabad, Pakistan during 2018.

Test insects and insecticide

The heterogeneous culture of *O. surinamensis, T. castaneum* and *T. granarium* was collected from household granaries, grain markets and stores of Punjab Food Department located at Faisalabad, Pakistan. The collected insect species were reared in sterilized glass jars placed in incubator (SANYO, MIR-254) at 30±2ºC and 65±5% RH to achieve uniform-aged first generation. The culture medium was cracked wheat grains, sterilized wheat flour and whole wheat grains for rearing of *O. surinamensis, T. castaneum* and *T. granarium*, respectively. The methoxyfenozide 240 SC (Runner®) was obtained from Arysta Life Sciences, Pakistan.

Grain commodity and treatment

Untreated, clean and infestation free four different grain commodities maize, oats, rice and wheat were obtained from the local market and used in these tests. The moisture content of these grain commodities was determined by a Dickey-John moisture meter (Dickey-John multigrain CAC-II, Dickey-John Co., Auburn, IL, USA) and it was recorded 12.4, 10.4, 12.1 and 11.2% for maize, oats, rice and wheat, respectively. For evaluating methoxyfenozide at concentration of 1, 2 and 4 mg kg^{-1} of active ingredient, the serial solution of 4 mg kg^{-1} was prepared in acetone and further concentrations were prepared from this stock solution. Commodities treatment with different concentrations of methoxyfenozide was performed by following the method of Vayias et al. (2010) with little modifications. Briefly, a lot of 4 kg grains from each commodity were prepared and treated with the desired concentrations. Separate 4 kg grain lot from each commodity was treated with acetone only to act as a control treatment. Treatment with different tested concentrations was carried out in a tray containing thin layer spread into it. All the treated grain lots were kept at 25±2ºC, 65±5% RH and continuous darkness to dry for 24 h. Then, the grain lots were placed in sealed 5 L plastic containers and stored at the above conditions for the total period of 16 weeks. For bioassays, the grains samples were obtained at the day of storage (24 h after treatment) and after the period of 2, 4, 8, 12 and 16 weeks.

Bioassays

Three samples of 50 g each were acquired from each lot and placed in glass jars. Thirty last instar larvae (3 weeks old) of each of the tested insect species were placed into each glass jar and the jars were kept in incubator (SANYO, MIR-254) at 28±2ºC, 65±5% RH and continuous darkness. The emergence of adults from larvae exposed to treated commodities were recorded after period of 30 days. Separate trials were conducted at the 2, 4, 8, 12 and 16 weeks post treatment, as described above. The entire experiment was repeated four times by using new treated lots every time.

Statistical analysis

All the treatments were performed under completely randomized design and replicated four times. The collected data was statistically analyzed by using the R-software (version 3.5.2) (R Core Team, 2013) and the means of the treatments were compared by using Tukey-Kramer HSD test at 0.05 (Sokal & Rohlf, 1995).

Results and Discussion

Efficacy on *Oryzaephilus surinamensis*

The ANOVA for *O. surinamensis* shows that all the main effects and their interactions were significant (Table 1). From week 0-16, the effect of concentration on adult emergence from exposed larvae was significant on specific commodity (Table 2). However, the effect of commodity on adult emergence was only significant from week 8-16 at 4 mg kg^{-1} concentration (Table 2). At week 0, the adult emergence from larvae exposed to 4 mg kg^{-1} did not exceeded 14.1% on all the tested commodities compared to control where the emergence was above 97.5% (Table 2). Similarly, at week 12, among the tested commodities, the adult emergence was minimum (29.1%) in oats and not exceeded 37.5% in other commodities at 4 mg kg^{-1} (Table 2). However, at week 16, the emergence of adults reached to 78.3-91.7% at concentration of 4 mg kg^{-1} (Table 2).

Table 1. ANOVA for main effects and interactions for adult emergence of *Oryzaephilus surinamensis*, *Tribolium castaneum* and *Trogoderma granarium* (error df = 288)

Source	df	*O. surinamensis*		*T. castaneum*		*T. granarium*	
		F	P	F	P	F	P
Week	5	4016	< 0.01	2073	< 0.01	3246	< 0.01
Concentration	3	18661	< 0.01	9514	< 0.01	14743	< 0.01
Commodity	3	44.0	< 0.01	9.81	< 0.01	20.8	< 0.01
Week × Concentration	15	544	< 0.01	267	< 0.01	425	< 0.01
Week × Commodity	15	4.15	< 0.01	2.28	< 0.01	2.13	< 0.01
Concentration × Commodity	9	7.21	< 0.01	5.02	< 0.01	6.75	< 0.01
Week × Concentration × Commodity	45	1.51	0.025	0.88	0.689	1.27	0.127

Efficacy on *Tribolium castaneum*

The ANOVA for *T. castaneum* shows that all the main effects and their interactions were significant except the interaction week by concentration by commodity (Table 1). From week 0-16, the effect of concentration on adult emergence from exposed larvae was significant on specific commodity (Table 3). However, the effect of commodity on adult emergence was only significant from week 8-16 at 4 mg kg^{-1} concentration (Table 3). At week 0, the adult emergence from larvae exposed to 4 mg kg^{-1} did not exceeded 13.3% on all the tested commodities compared to control where the emergence was above 98.3% (Table 3). Similarly, at week 12, among the tested commodities, the adult emergence was minimum (28.3%) in oats and not exceeded 35.8% in other commodities at 4 mg kg^{-1} (Table 3). However, at week 16, the emergence of adults increased to 77.5-88.3% at concentration of 4 mg kg^{-1} (Table 3).

Efficacy on *Trogoderma granarium*

The ANOVA for *T. granarium* shows that all the main effects and their interactions were significant except the interaction week by concentration by commodity (Table 1). From week 0-16, the effect of concentration on adult emergence from exposed larvae was significant on specific commodity (Table 4). However, the effect of commodity on adult emergence was only significant from week 8-16 at 4 mg kg^{-1} concentration (Table 4). At week 0, the adult emergence from larvae exposed to 4 mg kg^{-1} did not exceeded 15% on all the tested commodities compared to control where the emergence was above 98.3% (Table 4). Similarly, at week 12, among the tested commodities, the adult emergence was minimum (32.5%) in wheat and not exceeded 38.3% in other commodities at 4 mg kg^{-1} (Table 4). However, at week 16, the emergence of adults increased to 80.0-90.8% at concentration of 4 mg kg^{-1} (Table 4).

Table 2. Percentage emergence of *Oryzaephilus surinamensis* normal adult (mean±SE) from last instar larvae exposed at different post-treatment periods on treated grain commodities with different concentrations of methoxyfenozide at 28±2ºC

Week	Concentration (mg kg^{-1})	Commodity			
		Maize	Oats	Rice	Wheat
0	0	98.3±0.10 Aa*	99.2±0.08 Aa	97.5±0.08 Aa	97.5±0.08 Aa
	1	51.7±0.10 Ab	51.7±0.10Ab	52.5±0.08 Ab	53.3±0.14 Ab
	2	28.3±0.10 Ac	28.3±0.10 Ac	30.8±0.08 Ac	27.5±0.08 Ac
	4	12.5±0.08 Ad	13.3±0.14 Ad	14.2±0.08 Ad	11.7±0.10 Ad
2	0	98.3±0.10 Aa	98.3±0.10 Aa	99.2±0.08 Aa	99.2±0.08 Aa
	1	53.3±0.14 Ab	52.5±0.08 Ab	53.3±0.14 Ab	53.3±0.14 Ab
	2	30.8±0.08 Ac	30.8±0.08 Ac	31.7±0.10 Ac	30.0±0.14 Ac
	4	13.3±0.00 Ad	14.2±0.25 Ad	15.8±0.08 Ad	14.2±0.08 Ad
4	0	98.3±0.10 Aa	98.3±0.17 Aa	100.0±0.00 Aa	97.5±0.08 Aa
	1	56.7±0.14 Ab	53.3±0.14 Ab	57.5±0.08 Ab	54.2±0.08 Ab
	2	34.2±0.08 Ac	31.7±0.10 Ac	34.2±0.08 Ac	32.5±0.08 Ac
	4	17.5±0.16 Ad	15.0±0.10 Ad	17.5±0.08 Ad	15.8±0.08 Ad
8	0	98.3±0.10 Aa	99.2±0.08 Aa	98.3±0.10 Aa	98.3±0.10 Aa
	1	62.5±0.08 Ab	57.5±0.08 Bb	60.8±0.08 ABb	60.0±0.14 ABb
	2	40.8±0.08 ABc	37.5±0.08 Bc	41.7±0.10 Ac	38.3±0.14 ABc
	4	25.0±0.10 ABd	20.0±0.14 Cd	27.5±0.08 Ad	22.5±0.08 BCd
12	0	99.2±0.08 Aa	99.2±0.08 Aa	98.3±0.10 Aa	100.0±0.00 Aa
	1	66.7±0.14 Ab	61.7±0.10 Bb	67.5±0.08 Ab	64.2±0.08 ABb
	2	48.3±0.10 Ac	40.8±0.08 Bc	50.8±0.08 Ac	44.2±0.08 Bc
	4	36.7±0.14 Ad	29.1±0.10 Bd	37.5±0.16 Ad	32.5±0.08 ABd
16	0	99.2±0.08 Aa	98.3±0.10 Aa	97.5±0.16 Aa	99.2±0.08 Aa
	1	93.3±0.14 Ab	90.8±0.08 Ab	94.2±0.08 Aab	92.5±0.16 Ab
	2	91.7±0.10 Ab	87.5±0.21 Ab	93.3±0.14 Aab	89.2±0.08 Ab
	4	89.2±0.08 Ab	78.3±0.10 Cc	91.7±0.10 Ab	84.2±0.08 Bc

* Significant difference between treatments (columns) denoted by different lower-case letters, significant difference between commodities (rows) denoted by different upper-case letters.

Among the tested stored grain insect species, *T. granarium* was the least susceptible to methoxyfenozide irrespective of the type of grain commodity, concentration and the post-treatment period. While, *T. castaneum* was definitely the most susceptible among the tested insect species. A similar trend between stored-grain insect species has already been reported by Arthur et al. (2009) by exposing the larvae of *O. surinamensis* and *T. castaneum* to pyriproxyfen and hydroprene treated surfaces, and found that *O. surinamensis* was least susceptible compared to *T. castaneum.* Similarly, in another study Arthur & Hartzer (2018) found *Trogoderma variabile* Ballion, 1878 more tolerant than *T. castaneum* due to the combination treatment of novaluron and pyriproxyfen. Similar results were also found in other studies

(Scheff et al., 2016, 2017), in which *T. castaneum* and *T. variabile* larvae were exposed to methoprene-treated packaging materials; *T. variabile* was found to be the more tolerant species. This wavering susceptibility can be related to specific IGRs, or most probably it may be due to the morphological characters of the larvae of *Trogoderma* spp. that possess bristles and hairs on the body that might be responsible for the less exposure of the insecticide from the treated grain commodities.

Table 3. Percentage emergence of *Tribolium castaneum* normal adult (mean ± se) from last instar larvae exposed at different post-treatment periods on treated grain commodities with different concentrations of methoxyfenozide at 28±2ºC

Week	Concentration (mg kg^{-1})	Commodity			
		Maize	Oats	Rice	Wheat
0	0	99.2±0.08 Aa*	98.3±0.10 Aa	98.3±0.10 Aa	98.3±0.10 Aa
	1	47.5±0.16 Ab	48.3±0.22 Ab	45.8±0.21 Ab	50.8±0.25 Ab
	2	26.7±0.14 Ac	27.5±0.16 Ac	28.3±0.17 Ac	25.0±0.10 Ac
	4	9.2±0.16 Ad	12.5±0.16 Ad	13.3±0.14 Ad	10.0±0.14 Ad
2	0	99.2±0.08 Aa	98.3±0.10 Aa	99.2±0.08 Aa	100.0±0.00 Aa
	1	48.3±0.10 Ab	49.2±0.21 Ab	45.8±0.21 Ab	51.7±0.22 Ab
	2	31.7±0.10 Ac	32.5±0.08 Ac	31.7±0.10 Ac	28.3±0.22 Ac
	4	15.8±0.08 Ad	13.3±0.24 Ad	15.3±0.16 Ad	13.3±0.14 Ad
4	0	99.2±0.08 Aa	97.5±0.16 Aa	98.3±0.17 Aa	98.3±0.10 Aa
	1	50.0±0.14 ABb	50.0±0.14A Bb	47.5±0.08 Bb	53.3±0.14 Ab
	2	32.5±0.08 Ac	32.5±0.08 Ac	33.3±0.14 Ac	30.0±0.14 Ac
	4	16.7±0.14 Ad	14.2±0.16 Ad	16.7±0.14 Ad	14.2±0.16 Ad
8	0	99.2±0.08 Aa	97.5±0.08 Aa	98.3±0.10 Aa	99.2±0.08 Aa
	1	55.8±0.16 Ab	52.5±0.16 Ab	55.8±0.16 Ab	59.2±0.16 Ab
	2	35.8±0.16 Ac	34.2±0.08 Ac	38.3±0.10 Ac	35.0±0.10 Ac
	4	20.0±0.14 Bd	18.3±0.10 Bd	25.0±0.10 Ad	19.2±0.08 Bd
12	0	98.3±0.17 Aa	98.3±0.10 Aa	97.5±0.16 Aa	98.3±0.10 Aa
	1	64.2±0.16 Ab	60.8±0.38 Ab	65.8±0.16 Ab	63.3±0.14 Ab
	2	44.2±0.25 Ac	40.0±0.24 Ac	48.3±0.22 Ac	41.7±0.22 Ac
	4	32.5±0.16 ABd	28.3±0.10 Bd	35.8±0.16 Ad	30.8±0.25 ABd
16	0	99.2±0.08 Aa	98.3±0.10 Aa	98.3±0.10 Aa	98.3±0.17 Aa
	1	94.2±0.16 Aab	90.0±0.14 Ab	95.8±0.08 Aab	91.7±0.17 Ab
	2	90.0±0.14 Abc	88.3±0.22 Ab	91.7±0.10 Abc	89.2±0.10 Abc
	4	85.8±0.16 Ac	77.5±0.16 Bc	88.3±0.22 Ac	85.0±0.10 Ac

* Significant difference between treatments (columns) denoted by different lower-case letters, significant difference between commodities (rows) denoted by different upper-case letters.

Table 4. Percentage emergence of *Trogoderma granarium* normal adult (mean ± se) from last instar larvae exposed at different post-treatment periods on treated grain commodities with different concentrations of methoxyfenozide at 28±2ºC

Week	Concentration (mg kg^{-1})	Commodity			
		Maize	Oats	Rice	Wheat
0	0	98.3±0.10 Aa*	98.3±0.10 Aa	98.3±0.10 Aa	99.2±0.10 Aa
	1	53.3±0.14 Ab	49.2±0.16 Ab	50.0±0.14 Ab	54.2±0.21 Ab
	2	29.2±0.16 Ac	28.3±0.10 Ac	33.3±0.14 Ac	28.3±0.10 Ac
	4	13.3±0.14 Ad	13.3±0.14 Ad	15.0±0.10 Ad	14.2±0.16 Ad
2	0	98.3±0.10 Aa	99.2±0.08 Aa	99.2±0.08 Aa	100.0±0.00 Aa
	1	55.0±0.22 Ab	50.8±0.08 Ab	51.2±0.22 Ab	56.7±0.14 Ab
	2	32.5±0.08 Ac	33.3±0.14 Ac	34.2±0.08 Ac	30.8±0.16 Ac
	4	15.8±0.08 Ad	15.0±0.22 Ad	16.7±0.14 Ad	15.8±0.16 Ad
4	0	99.2±0.08 Aa	97.5±0.16 Aa	97.5±0.16 Aa	99.2±0.08 Aa
	1	57.5±0.08 Ab	55.8±0.08 Ab	59.2±0.08 Ab	58.3±0.10 Ab
	2	35.8±0.16 Ac	34.2±0.08 Ac	35.8±0.08 Ac	35.0±0.10 Ac
	4	18.3±0.17 Ad	15.8±0.08 Ad	18.3±0.10 Ad	17.5±0.08 Ad
8	0	99.2±0.08 Aa	98.3±0.10 Aa	99.2±0.08 Aa	100.0±0.00 Aa
	1	62.5±0.08 Ab	57.5±0.16 Ab	61.7±0.10 Ab	60.0±0.14 Ab
	2	41.7±0.10 ABc	40.8±0.08 ABc	44.2±0.08 Ac	39.2±0.08 Bc
	4	29.2±0.08 ABd	26.7±0.14 Abd	30.0±0.14 Ad	25.0±0.10 Bd
12	0	98.3±0.17 Aa	98.3±0.10 Aa	99.2±0.08 Aa	99.2±0.08 Aa
	1	68.3±0.10 Ab	67.5±0.08 Ab	68.3±0.10 Ab	65.8±0.08 Ab
	2	49.2±0.08 ABc	46.7±0.14 Bc	51.7±0.10 Ac	45.0±0.10 Bc
	4	37.5±0.08 ABd	33.3±0.14 ABd	38.3±0.17 Ad	32.5±0.08 Bd
16	0	99.2±0.08 Aa	98.3±0.10 Aa	99.2±0.08 Aa	100.0±0.00 Aa
	1	95.0±0.10 Ab	92.5±0.08 Ab	94.2±0.08 Ab	93.3±0.14 Ab
	2	91.7±0.10 Abc	90.0±0.14 Ab	93.3±0.00 Ab	90.8±0.08 Ab
	4	89.2±0.08 Ac	81.7±0.10 Bc	90.8±0.16 Ab	80.0±0.14 Bc

* Significant difference between treatments (columns) denoted by different lower-case letters, significant difference between commodities (rows) denoted by different upper-case letters.

The efficacy of methoxyfenozide was not affected due to the type of commodity for initial bioassays (week 0-4) in all the tested insect species. However, this effect become prominent in later bioassays (week 8-16), particularly at 4 ppm in all species tested. The methoxyfenozide was generally more effective on oats followed by wheat, maize and rice in the *O. surinamensis* and *T. castaneum* while against *T. granarium* it was more effective in wheat followed by oats, maize and rice at bioassays performed after 16 weeks post treatment at the higher concentration. The present results are opposite to those of Athanassiou et al., (2011) who found methoprene more effective on maize as compared to rice and wheat. These results are in contrast to those of Kavallieratos et al. (2009), who reported abamectin more effective in maize than that in wheat against stored-grain insect species tested. Similarly, Vayias et al. (2010) reported that spinosad was more persistent in barley and wheat than that in maize against stored-grain insects tested during storage period of six month. These results are also in accordance with those of Ali et al. (2017) in which *T. castaneum* and *T. granarium* were exposed to methoxyfenozide treated gain commodities and it was found that its efficacy was better on wheat than maize and rice. Therefore, it is proposed that there may be interactions between methoxyfenozie and specific features (morphological or physiological) of the grain, which may be responsible for the process of methoxyfenozide degradation over time.

With respect to residual activity, the residue of methoxyfenozide degraded over time (week 1-16) as the exposed larvae were able to complete their development to the adult stage near the end of the test period (week 16). These results are similar to those of Arthur & Hartzer (2018) by using combination treatment of novaluron and pyriproxyfen against *T. variabile.* These results are consistent with other studies in which larvae of *O. surinamensis* and *T. castaneum* were exposed to the hydroprene and pyriproxyfen treated surfaces at 1, 28 and 56 d post treatment. It was concluded that pyriproxyfen was more persistent in the entire testing period, while hydroprene lost its effectiveness after 28 d (Arthur et al., 2009). The results of methoxfenozide persistence are in contrast to those obtained by Liu et al. (2016) who found that methoprene (a juvenoid IGR) was effective up to 40 weeks at 1 ppm due to its residual activity in treated wheat. Similarly, Arthur (2019) reported that efficacy of the IGR increased with different combinations of deltamethrin and methoprene were applied to grain, all treatments were effective against *T. castaneum* for 15 months on maize.

In conclusion, the methoxyfenozide evaluated in this study provide adequate control of the insect species tested. However, it is advisable to further evaluate this product in combination with other insecticides that are suitable for the complete control of these three pest species.

References

Abo-Elghar, G. E., A. E. El-Sheikh, F. M. El-Sayed, H. M. El-Maghraby & H. M. El-Zun, 2004. Persistence and residual activity of an organophosphate, pirimiphos-methyl, and three IGRs, hexaflumuron, teflubenzuron and pyriproxyfen, against the cowpea weevil, *Callosobruchus maculates* (Coleoptera: Bruchidae). Pest Management Science, 60: 95-102.

Alavo, T. B. C., K. J. C. Tégbéssou & B. B. Yarou, 2011. Potentialities of methoxyfenozide for the integrated management of *Helicoverpa armigera* (Lepidoptera: Noctuidae) on cotton in Benin, West Africa. Archives of Phytopathology and Plant Protection, 44: 813-819.

Ali, Q., M. Hasan, L. J. Mason, M. Sagheer & N. Javed, 2016. Biological activity of insect growth regulators, pyriproxyfen, lufenuron and methoxyfenozide against *Tribolium castaneum* (Herbst). Pakistan Journal of Zoology, 48 (5): 1337-1342.

Ali, Q., M. Hasan, M. Sagheer, S. Saleem, M. Faisal, A. Naeem & J. Iqbal, 2017. Screening of seven insect growth regulators for their anti-insect activity against the larvae of *Trogoderma granarium* (Everts) and *Tribolium castaneum* (Herbst). Pakistan Journal of Agricultural Sciences, 54 (3): 589-595.

Ali, Q., M. Hasan, H. U. Shakir, N. A. Anjum, S. Saleem, M. Y. Iqbal, M. U. Qasim & M. Faisal, 2018. Transgenerational effect of insect growth regulators on the *Trogoderma granarium* (Everts) (Coleoptera: Dermestidae) under different abiotic factors. Pakistan Journal of Agricultural Sciences, 55 (4): 897-903.

Arthur, F. H., 1996. Grain protectants: current status and prospects for the future. Journal of Stored Products Research, 32: 293-302.

Arthur, F. H., 2019. Efficacy of combinations of methoprene and deltamethrin as long-term commodity protectants. Insects, 10 (2): 50.

Arthur, F. H., M. N. Ghimire, S. W. Myers & T. W. Phillips, 2018. Evaluation of pyrethroid insecticides and insect growth regulators applied to different surfaces for control of *Trogoderma granarium* (Coleoptera: Dermestidae) the khapra beetle. Journal of Economic Entomology, 111 (2): 612-619.

Arthur, F. H. & K. L. Hartzer, 2018. Susceptibility of selected stored product insects to a combination treatment of pyriproxyfen and novaluron. Journal of Pest Science, 91 (2): 699-705.

Arthur, F. H., S. Liu, B. Zhao & T. W. Phillips, 2009. Residual efficacy of pyriproxifen and hydroprene applied to wood, metal and concrete for control of stored-product insects. Pest Management Science, 65: 791-797.

Athanassiou, C. G., F. H. Arthur & J. E. Throne, 2011. Efficacy of layer treatment with methoprene for control of *Rhyzopertha dominica* (Coleoptera: Bostrychidae) on wheat, rice and maize. Pest Management Science, 67: 380-384.

Boyer, S., H. Zhang & G. Lempérière, 2012. A review of control methods and resistance mechanisms in stored-product insects. Bulletin of Entomological Research, 102 (2): 213-229.

Carlson, G. R., T. S. Dhadialla, R. Hunter, R. K. Jansson, C. S. Jany, Z. Lidert & R. A. Slawecki, 2001. The chemical and biological properties of methoxyfenozide, a new insecticidal ecdysteroid agonist. Pest Management Science, 57: 115-119.

Carpaneto, B., R. Bartosik, L. Cardoso & P. Manetti, 2016. Pest control treatments with phosphine and controlled atmospheres in silo bags with different airtightness conditions. Journal of Stored Products Research, 69: 143-151.

Chen J., W. Jiang, H. Hu, X. Ma, Q. Li, X. Song, X. Ren & Y. Ma, 2019. Joint toxicity of methoxyfenozide and lufenuron on larvae of *Spodoptera exigua* Hübner (Lepidoptera: Noctuidae). Journal of Asia-Pacific Entomology, 22: 795-801.

Elek, J. A., 1998a. Treatment of adult Coleoptera with a chitin synthesis inhibitor affects mortality and development time of their progeny. Entomolgia Experimentalis et Applicata, 88: 31-39.

Elek, J. A., 1998b. Interaction of treatment of both adult and immature Coleoptera with a chitin synthesis inhibitor affects mortality and development time of their progeny. Entomolgia Experimentalis et Applicata, 89: 125-136.

Enríquez, C. L. R., S. Pineda, J. I. Figueroa, M. I. Schneider & A. M. Martínez, 2010. Toxicity and sublethal effects of methoxyfenozide on *Spodoptera exigua* (Lepidoptera: Noctuidae). Journal of Economic Entomology, 103: 662-667.

Fields, P. G., 1992. The control of stored-product insects and mites with extreme temperatures. Journal of Stored Products Research, 28: 89-118.

Fox, P., 1990. Insect Growth Regulators. Richmond, PJB Publ. Ltd. UK, 102 pp.

Ghimire, M. N., F. H. Arthur, S. M. Myers & T. W. Phillips, 2016. Residual efficacy of deltamethrin and b-cyfluthrin against *Trogoderma variabile* and *Trogoderma inclusum* (Coleoptera: Dermestidae). Journal of Stored Products Research, 66: 6-11.

Gorham, J. R, ed. 1991. Ecology and Management of Food Industry Pests. Association of Official Analytical Chemists, Arlington, Virginia, USA, 595 pp.

Hagstrum, D.W. & B. Subramanyam, 2006. Fundamentals of Stored-product Entomology. AACC International, St. Paul, Minnesota, USA, 215 pp.

Heller, J. J., H. Mattioda, E. Klein & A. Sagenmuller, 1992. "Field evaluation of RH5992 on lepidopterous pests in Europe, 59-65". Proceedings of the Bright on Crop Protection Conference, Pests and Diseases, (23 to 26 November 1992, Brighton, UK), British Crop Protection Council, Farnham, UK, 1500 pp.

Hubert, J., V. Stejskal, C. Athanassiou & J. E. Throne, 2018. Health hazards associated with arthropod infestation of stored products. Annual Review of Entomology, 63: 553-573.

Kavallieratos, N. G., C. G. Athanassiou, G. G. Peteinatos, M. C. Boukouvala & G. Benelli, 2018. Insecticidal effect and impact of fitness of three diatomaceous earths on different maize hybrids for the eco-friendly control of the invasive stored-product pest *Prostephanus truncatus* (Horn). Environmental Science and Pollution Research, 25: 10407-10417.

Kavallieratos, N. G., C. G. Athanassiou, B. J. Vayias, S. B. Mihail & Z. Tomanovic, 2009. Insecticidal efficacy of abamectin against three stored-product insect pests: influence of dose rate, temperature, commodity, and exposure interval. Journal of Economic Entomology, 102 (3): 1352-1359.

Kavallieratos, N. G., C. G. Athanassiou, B. J. Vayias & Z. Tomanovic, 2012. Efficacy of insect growth regulators as grain protectants against two stored-product pests in wheat and maize. Journal of Food Protection, 75 (5): 942-950.

Kavallieratos, N. G., C. G. Athanassiou, Z. Korunic & N. H. Mikeli, 2015. Evaluation of three novel diatomaceous earths against three stored-grain beetle species on wheat and maize. Crop Protection, 75: 132-138.

Korunic, Z., 1998. Diatomaceous earths, a group of natural insecticides. Journal of Stored Products Research, 34: 87-97.

Kostyukovsky, M., B. Chen, S. Atsmi & E. Shaaya, 2000. Biological activity of two juvenoids and two ecdysteroids against three stored product insects. Insect Biochemistry and Molecular Biology, 30 (8-9): 891-897.

Liu, S. S., F. H. Arthur, D. Van Gundy & T. W. Phillips, 2016. Combination of methoprene and controlled aeration to manage insects in stored wheat. Insects, 7 (2): 25.

Malik, G., A. Qadir, H. A. A. Khan & A. Aslam, 2017. Toxicity of lufenuron and thiamethoxam against five Pakistani strains of *Sitophilus oryzae* on wheat, rice and maize. Pakistan Entomologist, 39 (1): 41-47.

Mondal, K. A. M. S. H. & S. Parween, 2000. Insect growth regulators and their potential in the management of stored-product insect pests. Integrated Pest Management Reviews, 5: 255-295.

Oberlander, H. & D. Silhacek, 2000. "Insect Growth Regulators, 147-163". In: Alternatives to Pesticides in Stored-Product IPM (Eds. B. Subramanyam & D. W. Hagstrum), Kluwer Academic Publishers, New York, USA, 437 pp.

Oberlander, H., D. Silhacek & C. E. Leach, 1998. Interactions of ecdysteroid and juvenoid agonists in *Plodia interpunctella* (Hubner). Archives of Insect Biochemistry and Physiology, 38: 91-99.

Oberlander, H., D. L. Silhacek, E. Shaaya & I. Ishaaya, 1997. Current status and future perspectives of the use of insect growth regulators for the control of stored product pests. Journal of Stored Products Research, 33: 1-6.

Parween, S., S. I. Faruki & M. Begum, 2001. Impairment of reproduction in the red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) due to larval feeding on triflumuron-treated diet. Journal of Applied Entomology, 125: 413-416.

Phillips, T. W. & J. E. Throne, 2010. Biorational approaches to managing stored-product insects. Annual Review of Entomology, 55: 375-397.

R Core Team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Sagheer, M., M. Yasir, M. Hasan & M. Ashfaq, 2012. Impact of triflumuron on reproduction and development of red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae). Pakistan Journal of Agricultural Sciences, 49 (2): 173-178.

Sagheer, M., M. Yasir, B. S. Khan & M. Hasan, 2011. Ovicidal and reproduction inhibition activity of flufenoxuron, an acylurea insect growth regulator, against *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae). Pakistan Entomologist, 33 (2): 131-136.

Scheff, D. S., B. Subramanyam & F. H. Arthur, 2016. Effect of methoprene treated polymer packaging on fecundity, egg hatchability, and egg-to-adult emergence of *Tribolium castaneum* and *Trogoderma variabile*. Journal of Stored Products Research, 69: 227-234.

Scheff, D. S., B. Subramanyam & F. H. Arthur, 2017. Susceptibility of *Tribolium castaneum* and *Trogoderma variabile* larvae and adults exposed to methoprene-treated woven packaging material. Journal of Stored Products Research, 73: 142-150.

Schneiderman, H. A., 1972. "Insect Hormones and Insect Control, 3-29". In: Insect Juvenile Hormones: Chemistry & Action (Eds. J. J. Menn & M. Beroza). Academic Press, London, 358 pp.

Sokal, R. R. & F. J. Rohlf, 1995. Biometry: The Principles and Practice of Statistics in Biological Research. 3rd edition, W.H. Freeman and Co., New York, USA, 880 pp.

Staal, G. B., 1975. Insect growth regulators with juvenile hormone activity. Annual Review of Entomology, 20: 417-460.

Trostanetsky, A., M. Kostyukovsky & E. Quinn, 2015. Transovarial effect of novaluron on *Tribolium castaneum* (Coleoptera: Tenebrionidae) after termination of direct contact. Journal of Insect Science, 15 (1): 125.

Vayias, B. J., C. G. Athanassiou, D. N. Milonas & C. Mavrotas, 2010. Persistence and efficacy of spinosad on wheat, maize and barley grains against four major stored product pests. Crop Protection, 29 (5): 496-505.

Wing, H. D. & H. E. Aller, 1990. "Ecdysteroid Agonists as Novel Insect Regulators, 251-257". In: Pesticides and Alternatives: Innovative Chemical and Biological Approaches to Pest Control (Ed. J. E. Casida). Elsevier, Amsterdam, the Netherlands, 586 pp.

Yasir, M., M. Sagheer, S. K. Abbas, M. Hasan, S. Ahmad & M. Ijaz, 2019. Bioactivity of lufenuron against *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae). Sains Malaysiana, 48 (1): 75-80.

Yasir, M., M. Sagheer, M. Hasan, S. K. Abbas & S. Ahmad, 2012. Bioactivity of a chitin synthesis inhibitor, triflumuron, against red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae). Sarhad Journal of Agriculture, 28 (4): 603-609.

Zettler, J. L. & G. W. Cuperus, 1990. Pesticide resistance in *Tribolium castaneum* (Coleoptera: Tenebrionidae) and *Rhyzopertha dominica* (Coleoptera: Bostrichidae) in wheat. Journal of Economic Entomology, 83: 1677-1681.