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Growth disruptive effects of ferulic acid against *Spodoptera litura* (Fabricius) and its parasitoid *Bracon hebetor* (Say)

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ABSTRACT

We studied the effects of ferulic acid (5, 25, 125, 625, 3125 ppm concentrations) in artificial diet on *Spodoptera litura* (Fabricius) and its parasitoid *Bracon hebetor* (Say) on 6-days old larvae of *S. litura*. Higher concentrations of ferulic acid increased the mortality of *S. litura* larvae, decreased adult emergence and delayed the developmental period. The higher concentration (LC_{50}= 2573.33ppm) of ferulic acid also decreased the growth of *B. hebetor* (Say) larvae. However, the adverse effects were less at lower concentration (LC_{30}=25.92 ppm). The ferulic acid significantly reduced the nutritional indices (RGR, RCR, ECD and ECI) and immune response in *S. litura* larvae. Our findings suggested that lower concentrations of ferulic acid may help in controlling insect-pest population and conserve the parasitoid's fitness.

Keywords: *Bracon hebetor*, Ferulic acid, haemocyte, larval, nutritional indices, Phenols, *Spodoptera litura*, tritrophic.

INTRODUCTION

Insect-pests cause huge losses in crops despite too much use of chemical pesticides (38). Botanical insecticides as an alternative to organic pesticides are being considered for pest management due to their low impact on non-target organisms, minimal residual environmental effects, fast degradation in field conditions and low toxicity for humans (27,39). Thus, recently there is an increased interest in their development especially in the developing countries (India, China and Brazil) and other emerging economies (15). Plants synthesize allelochemicals that are feeding deterrent to insects and thereby regulate the insect population (24,53). Plant phenolics, hydroxybenzoic acids viz., gallic acid, hydroxyl-cinnamic acids found in grape juice are used by plants for pigmentation, growth, reproduction, resistance to pathogens and insect herbivores etc. (23). Plant secondary metabolites such as ferulic acid, chlorogenic acid, quercetin and rutin are inhibitory to insect pest, *Spodoptera litura* (Fabricius) (22,50). The lepidopteran pest, *S. litura* is a polyphagous pest widely responsible for damage to many important crops (31,47). The economic losses caused by it range from 25.8-100 % depending on crop stage and its infestation level (12). The unjudicious use of chemical pesticides and insecticide resistance has resulted in its frequent outbreak (44,52).

Bracon hebetor (Say) (Hymenoptera: Braconidae) is a cosmopolitan, gregarious, ectoparasitoid that attacks the larval stage of various species of lepidopterans. The parasitoid has been used to control the population of cotton bollworm, *Helicoverpa armigera* (Hubner) and the Indian meal moth, *Plodia interpunctella* (Hubner) (7,21).

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One of the central themes in ecology is the interaction between the population of consumers (predators, parasitoids) and resources (prey, host). The importance of nutritional suitability of the hosts of the phytophagous insects for the successful development of parasitoids has now received an increased attention (1,29,32). The feeding, growth and development of the pest population greatly affects the tritrophic interactions between plants, herbivores and their natural enemies and can be altered by the quality of host plant (13,16,34). In the ecological system, allelochemicals in food chain not only affect the parasitoids, pathogens and predators but also influence the capability of these natural enemies to impact and alter the herbivore fitness and population growth. There are very few studies determining the effects of botanical compounds on parasitoids in the third trophic level. Plant allelochemicals in the diet of host not only adversely affects the growth of phytophagous insect but also impacts the parasitoid's growth and survival (5,40). Thus, before considering these compounds for pest management, it is essential to study their effects not only on the insect pest but also on its parasitoids as the latter play a key role in limiting insect pest population. Therefore, this study aimed to investigate the effects of ferulic acid (a plant allelochemical) on the tobacco cutworm, *S. litura* and to explore its potential in pest management programmes and also on its parasitoid *B. hebetor*.

MATERIAL AND METHODS

The study was done from April 2019 to June 2019 in Department of Zoology, Guru Nanak Dev University, Amritsar, Punjab, India (longitude 31.6340° N, and latitude 74.8723° E, Annual rainfall: 703 mm, minimum temp.: 3.9 °C and maximum temp: 43 °C). The cultures of *S. litura*, *B. hebetor* and rice moth, *Corcyra cephalonica* (Stainton) were maintained in laboratory at standard conditions [25±2˚C temperature, 65±5% relative humidity (RH) and 12:12 (D: L) photoperiod].

S. litura culture

The culture of *S. litura* larvae was maintained on fresh castor (*Ricinus communis* L.) leaves, in Insect Physiology laboratory. The pupae were kept in pupation jars (15 cm×10 cm) having 4-5 cm of moist sand covered with filter paper until the adult emergence. The adults were transferred to oviposition jars (15 cm×10 cm) lined with filter paper to facilitate egg laying, and a cotton swab soaked with water and honey solution (4:1) as food. All the jars were covered with muslin cloth, secured with rubber band to check their escape.

B. hebetor culture

The culture of parasitoid, *B. hebetor* was maintained on 5th instar larvae of *C. cephalonica*. The culture of *C. cephalonica* was reared on partially crushed sorghum grains at standard conditions (25±2 °C, 65±5 % RH). The freshly emerged adult parasitoids in ratio 1:2 (male:female) were transferred to glass chimneys having a cotton swab soaked in water and honey (4:1) solution to serve as food. Healthy 5th instar larvae of *C. cephalonica* were provided to the parasitoid for parasitization and parasitized larvae were observed for egg laying under microscope. The parasitized larvae were then kept inside tissue papers in plastic petri plate (90 mm×15 mm) until cocoon formation. The tissue papers having cocoons were shifted into sterile solo cups (4 cm × 6 cm) and were daily checked for emergence, and the emerged adults were allowed to mate for 24 h. These newly emerged *B. hebetor* adults were used for bioassay studies.

Chemical used

Ferulic acid with ≥ 95 % purity was obtained from Sigma Aldrich Pvt. Ltd., India and used in this study.

Bioassays with *S. litura*

Stock solution of ferulic acid (4000 ppm) was prepared in 0.5 % ethanol, which was diluted to get the experimental concentrations of 5, 25, 125, 625 and 3125 ppm. The antibiosis effects of ferulic acid on *S. litura* were recorded in 6-days old larvae fed on diet amended with 5, 25, 125, 625 and 3125 ppm of ferulic acid. Diet without ferulic acid was taken as control. The artificial diet was prepared according to protocol of Koul *et al.* (19). The larvae were kept in sterilized plastic containers (1 larva per container) containing treated diet and were observed daily for different parameters viz., larval period, total development period, larval mortality, pupal weight and adult emergence. There were 5-test larvae for each replicate and each experiment had six replicates. The experiment was repeated twice. The LC_{50} and LC_{30} calculated on the basis of larval mortality were 2573.33 ppm and 25.92 ppm concentrations, respectively.

Nutritional assays with *S. litura*

A 3-days experiment was done to find the effects of ferulic acid at 5, 25, 125, 625 and 3125 ppm concentrations with control (water) on nutritional physiology of *S. litura* larvae using 6-days old larvae as per the protocol of Koul *et al.* (16). The pre-weighed larvae were released into sterilized plastic containers with treated and control diet. The larvae were fed on treated and control diet for 72 h and the final weight of larvae, diet left and fecal matter (mg) was recorded. Their dry weights were also taken after incubating for another 72 h at 60 °C inside an incubator. The dry weight readings served the purpose of water loss under controlled conditions. The data obtained was also used to calculate the nutritional indices on dry weight basis after 3 days feeding as per Waldbauer (55). Each concentration including control was replicated 6 times with 5 larvae in each replicate and the experiment was repeated twice.

$$RGR = \frac{\text{Change in larval dry weight/day}}{\text{Starting larval dry weight}}$$

$$RCR = \frac{\text{Change in diet dry weight/day}}{\text{Starting larval dry weight}}$$

$$ECI = \frac{\text{Dry weight gain of insect}}{\text{Dry weight of food ingested}} \times 100$$

$$ECD = \frac{\text{Dry weight gain of insect}}{\text{Dry weight of food ingested - Dry weight of frass}} \times 100$$

$$AD = \frac{\text{Dry weight gain of insect - Dry weight of frass}}{\text{Dry weight of food ingested}} \times 100$$

Where, RGR: Relative growth rate, RCR: Relative consumption rate, ECI: Efficiency of conversion of ingested food, ECD: Efficiency of conversion of digested food, AD: Approximate digestibility.

Immune response of *S. litura*

To evaluate the effects of ferulic acid on immune response of *S. litura*, larvae were fed on diet supplemented with LC_{30} (25.92 ppm) and LC_{50} (2573.33 ppm) concentrations for 24, 48, 72, 96 and 120 h. The treated larvae and the larvae fed on control diet were kept at standard conditions of temperature and humidity (25±2 °C and 65±5 %, respectively). For each treatment interval the haemolymph was collected using a sterile needle from randomly selected 10-larvae by piercing the prothoracic leg. The haemolymph collected was pooled and used to study the total haemocyte count (THC) and deformities in haemocytes as per the protocol of Tauber and Yeager (51) and Arnold and Hinks (3), respectively. All the experiments for immune response were replicated twice.

Bioassays with *B. hebetor*

To study the effects of ferulic acid on parasitization and fecundity of *B. hebetor*, newly emerged parasitoids were allowed to mate for 24 h. The adults in the ratio 2:1 (female: male) were then transferred to a glass chimney. The larvae of *S. litura* were reared on diet supplemented with LC_{30} (25.92 ppm) and LC_{50} (2573.33 ppm) concentrations of ferulic acid as well as on control (unamended diet) until it reached the third instar stage. A single treated 12-days old larva was then introduced for parasitization in the chimney for 24 h and then transferred to petri plates (90 mm×14 mm) on tissue paper. The paralyzed larvae were observed daily under stereo microscope (Magnus) at 40X magnification to observe the parasitoid eggs for recording various parameters. In this way, *S. litura* larvae were fed artificial diet containing various concentrations of ferulic acid till the female died in each treatment. The effects of ferulic acid on development of *B. hebetor* was evaluated by introducing 2-days old mated females in the glass chimneys (2-wasps per chimney) and allowed to oviposit on larvae of *S. litura* reared on artificial diet amended with different concentrations of ferulic acid. After 24 h, the parasitized larvae were removed from the chimneys and fresh hosts were given daily to the wasps. The parasitized larvae were transferred individually in petri plates and were checked daily for development of parasitoid larvae. Cocoons of the parasitoid were inspected daily to assess time of emergence of wasps. On emergence, the number and sex ratio of the progeny were recorded. There were 6-replications with two females per replication and a total of 60 larvae were exposed to parasitoid wasps in each treatment and control.

Statistical analysis

The data were represented as their means ± SE. The one-way analysis of variance (ANOVA) along with Tukey's test at $p \leq 0.05$ was done to check the differences in means. SPSS software for windows version 16.0 (SPSS Inc, Chicago), Microsoft office Excel 2007 (Microsoft Corp., USA) and ASSISTAT software were used to perform the statistical analysis.

RESULTS AND DISCUSSION

EFFECTS ON *S. LITURA*

(i). Growth and development

The effects of ferulic acid on the growth, development and nutritional physiology of *S. litura* larvae are shown in Figures 1 and 2. The mortality was high in treated larvae and maximum mortality was observed at 3125 ppm, (36.66 % increase in larval mortality over control) (Fig. 1). Similarly, high mortality was also observed at higher concentrations of quercetin in Egyptian cotton leafworm, *Spodoptera littoralis* (Boisd.) (26). A significant inhibition in adult emergence occurred in all treatments (Fig. 1). Another phenolic compound, gallic acid too increased the larval mortality and reduced the adult emergence of melon fruit fly, *Bactrocera cucurbitae* (Coquillett) with increase in concentration (46). The treatments significantly prolonged the larval period and the total development period when compared with control. Maximum prolongation was noticed at the highest concentration (Fig. 1).

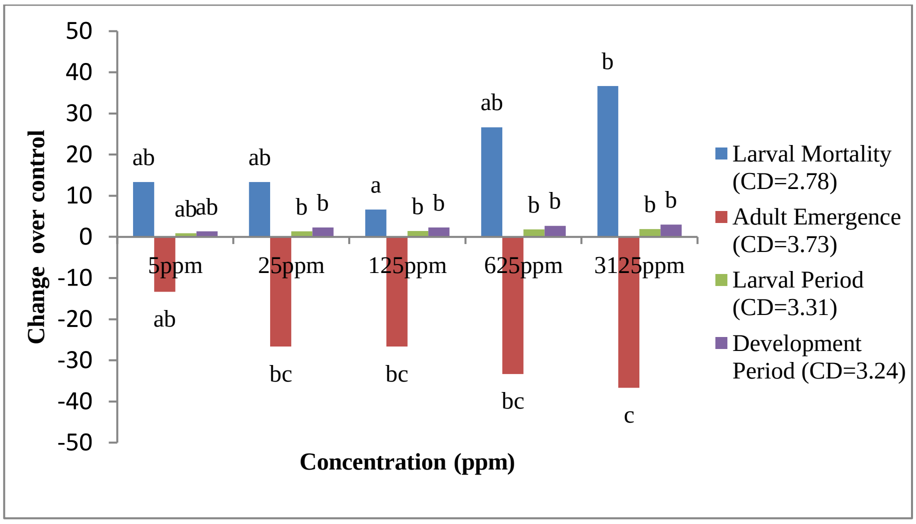

Figure 1. Effects of ferulic acid diet on the 6-days old instar larvae of *S. litura* on larval mortality, adult emergence, larval period, and total developmental period with respect to control. CD= Critical difference at 1%.

A concentration dependent increase in larval mortality, larval period and total development period of *S. litura* larvae was also reported with pyrogallol (8). Similar findings were reported by Alves *et al*. (2) in fall army worm, *Spodoptera frugiperda* (J.E. Smith) treated with the phenolic acids (gallocatechin, catechin, gallic acid, epicatechin, ellagic acid, and salicylic acid) isolated from jaboticaba, *Myrciaria cauliflora* (Mart.). Phenolic compounds (hydroquinone, chlorogenic acid, gallic acid and syringic acid) present in the seed coat extract of red gram too suppressed the growth and development of hairy caterpillar, *Creatanotos gangis* (L.) (9). Phenolic compounds can act as gut toxins causing mortality in insects. Steinly and Berenbaum (49) reported that tannin forms degenerative lesions in the gut of swallowtail caterpillar, *Papilo polyxenes* (F.). Lindroth and Peterson (20) also reported that the southern armyworm, *Spodoptera eridania* (Stoll) larvae fed on phenols (salicortin and tremulacin) developed degenerative lesions in the tissues of midgut.

(ii). Nutritional physiology

The ferulic acid significantly affected the nutritional physiology of *S. litura* larvae (Fig. 2). The relative consumption rate significantly declined with all concentrations of ferulic acid and maximum decline (36.15 %) occurred at 125 ppm compared to control (Fig. 2). The RGR (relative growth rate) of treated larvae slightly declined in comparison with control. Ganter *et al.* (14) had also reported low level acceptance of filbert aphid, *Myzocallis coryli* Goetze for the leaves of hazel (*Corylus* L.) cultivars rich in phenolic acids (gallic acid and caeffic acid). In ferulic acid treated larvae, the ECI (Efficiency of conversion of ingested food) and ECD (Efficiency of conversion of digested food) were higher than control at all concentrations except at 3125 ppm, where they were significantly lower than control. On the other hand, the AD (approximate digestibility) was reduced at all concentrations except at 3125 ppm, where it was higher than control (Fig. 2). These findings indicated that ferulic acid was not toxic to insect at lower concentrations but the highest concentration induced post ingestive toxicity in larvae. ECI is the measure of the food consumed, that is metabolized into biomass and its decreased value indicates that only limited amount of food is converted into biomass and rather it might have been metabolized for energy (10). The decreased value of ECD suggested the diversion of energy from producing biomass into detoxifying the compound (11). Wang *et al.* (57) reported negative impact of gramine and

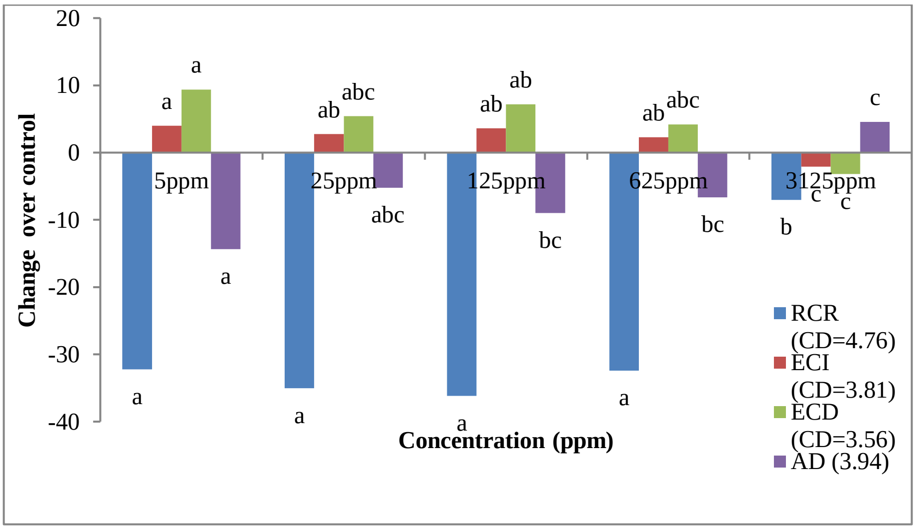

Figure 2. Effects of ferulic acid diet on the 6-days old instar larvae of *S. litura* on RCR (Relative growth rate), ECI (Efficiency of conversion of ingested food), ECD (Efficiency of conversion of digested food), AD (Approximate digestibility).
CD= Critical difference at 1%.

ferulic acid on the nutritional physiology of the cotton bollworm as the RGR, AD and ECD declined with treatment. Similar findings were reported in southern armyworm, *Spodoptera eridania* (Cramer) larvae treated with tremulacin (20) and in white marked tussock moth, *Oryzia leucostigma* (L.) treated with condensed tannins obtained from paper birch, *Betulla papyrifera* (Marshall) (18). Reitz and Trumble (41) too had reported that linear furanocoumarin increased the mortality in cabbage looper, *Trichoplusia ni* (Hubner) and parasitoid *Copidosoma floridanum* (Ashmead) along with decreased RCR of *T. ni*. The decreased AD values suggest poor digestibility of insect.

(iii). Immune response

The total haemocyte count in *S. litura* larvae fed on diet amended with LC_{30} and LC_{50} concentrations of ferulic acid declined significantly than control in all treatment intervals (Fig 3a). At LC_{50} concentration, the haemocyte count was much lower than at LC_{30} concentration in all treatment intervals. The percent haemocyte deformities calculated at different time intervals from 24 h to 120 h were significantly increased over control (Fig. 3b). Various types of morphological deformities (change in haemocyte shape, aggregation, multinucleated cells, vacuolization, necrosis etc.) were observed (Fig. 4a, b).

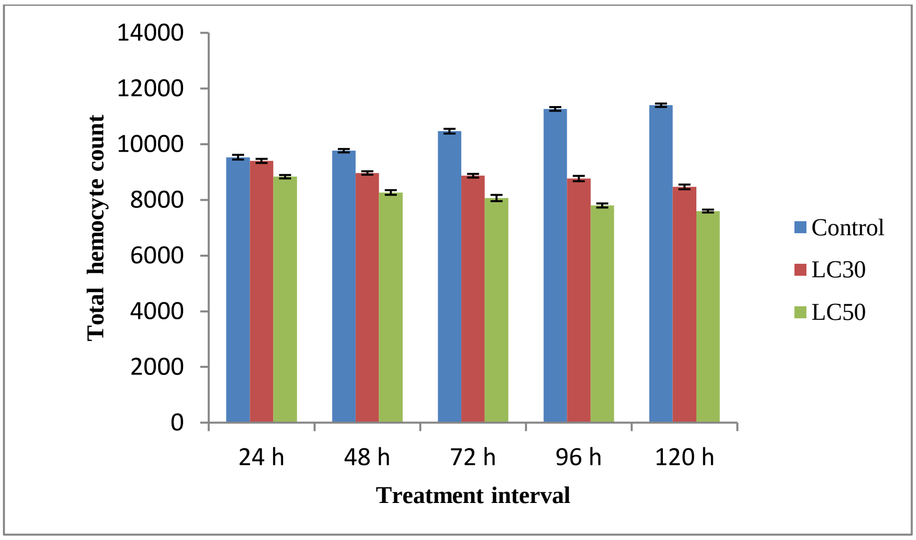

Figure 3a. Influence of ferulic acid on total haemocyte count (Means±S.E.) of *S. litura* larvae.

These findings suggested the negative impact of ferulic acid on *S. litura's* immune response. A lower immune response weakens the insect's defense against its parasitoids and pathogens. Haemocyte deformities as well as dose dependent decrease in total haemocyte count of *S. litura* larvae occurred after treatment with essential oil of sweet flag, *Acorus calamus* L. rhizomes (45). Azadirachtin caused 20-25 % decrease in total haemocyte count in last instar nymphs of American cockroach, *Periplaneta americana* L. (37). It also declined (31-41 %) the total haemocyte count in final instar female nymphs of brown spotted locust, *Cyrtacanthacris tatarica* L. (32). Zibaee and Bandani (59) also reported decrease in

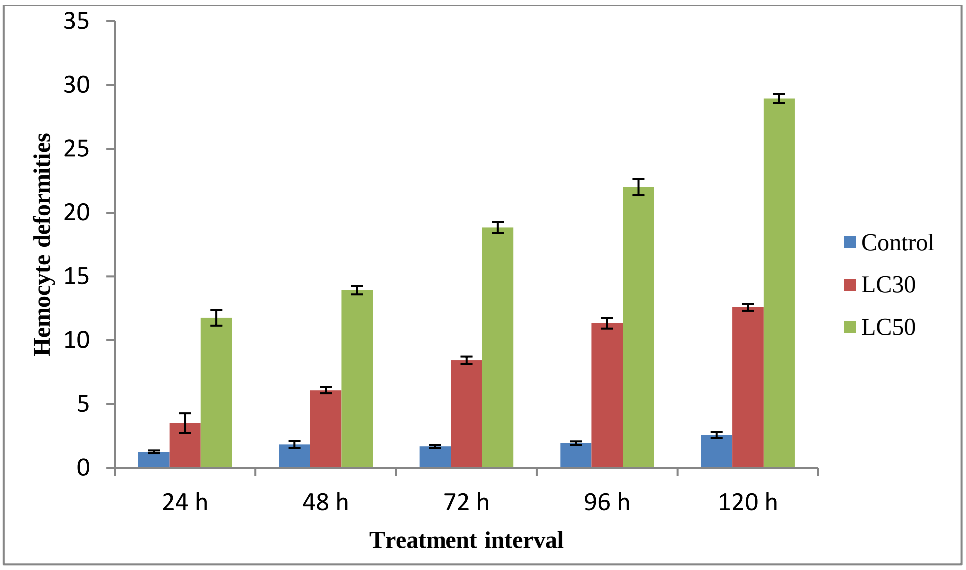

Figure 3b. Influence of ferulic acid on morphological deformities (Means ± S.E.) in *S. litura* larvae.

the total and differential haemocyte count in adult Sunnpest, *Eurygaster integriceps* (Puton), when treated with *Artemisia annua* L. extract. Crude methanolic extract of *Pergularia tomentosa* (L.) also decreased the haemocyte count and caused cell lysis in migratory locust, *Locusta migratoria* (L.) (26).

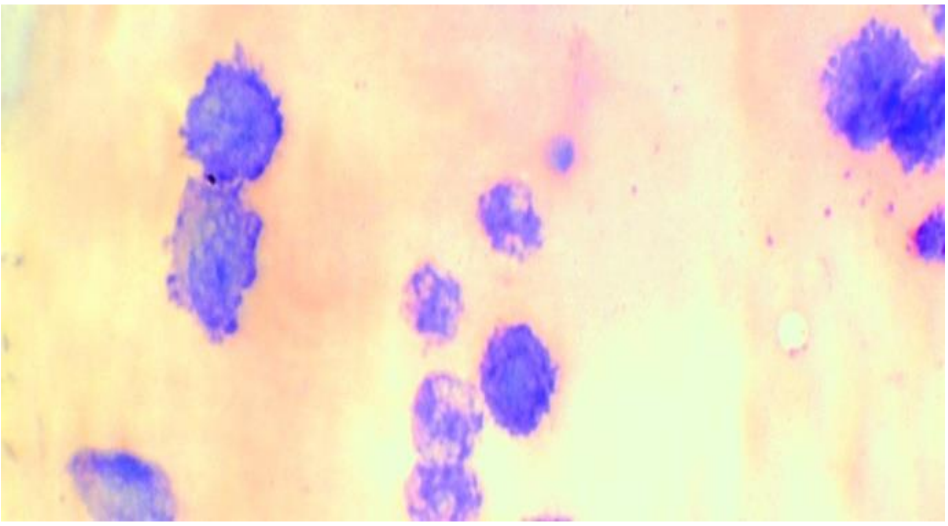

Figure 4a. Vacuolization and disintegration of plasma membrane in haemocytes in ferulic acid fed larvae.

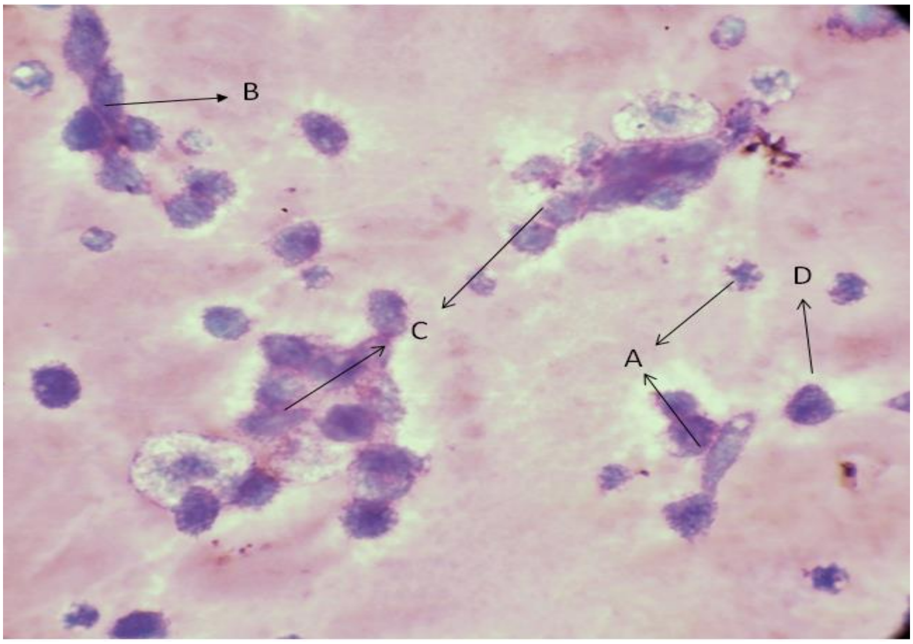

Figure 4b. Haemocyte deformities in *Spodoptera larvae*. A. Deformed haemocytes B. Change in shape of haemocytes C. Clustering of haemocytes D. Normal haemocyte

EFFECTS ON *B. HEBETOR*

The LC_{50} concentration of ferulic acid adversely affected the various growth parameters of *B. hebetor*, while LC_{30} concentration had much less effect than control. The mortality of *B. hebetor* larvae at LC_{50} concentration was significantly higher than at LC_{30} concentration as compared to control (Fig. 5). Significantly less number of larvae hatched at LC_{50} than at LC_{30} in comparison to control. At the higher concentration (LC_{50}), the adult emergence was reduced by 13 % and the female emergence was reduced by 20.36 % than control (Fig. 5). The cocoon period, larval period and the total development period of *B. hebetor* larvae was not much affected with treatment. There was no significant effect of ferulic acid on percent parasitization and the fecundity of *B. hebetor* but the eggs laid per host declined significantly with increase in concentration than control (Fig. 5).

Plant allelochemicals in the diet not only influence the fitness of host but also affect the development of parasitoid (48). The present study revealed that the parasitization, fecundity, cocoon period and the larval as well as total development period was not much affected in the parasitoid, *B. hebetor* when provided with host *S. litura* treated with LC_{50} (2573.22ppm) and LC_{30} (25.92 ppm) concentrations of the test compound. On the other hand, larval mortality, egg hatching and emergence were significantly affected with ferulic acid treatment. Barbosa *et al*. (4) reported that plant alkaloids (nicotine and hordenine) in the diet of tobacco horn worm negatively affected its survival, increased larval mortality,

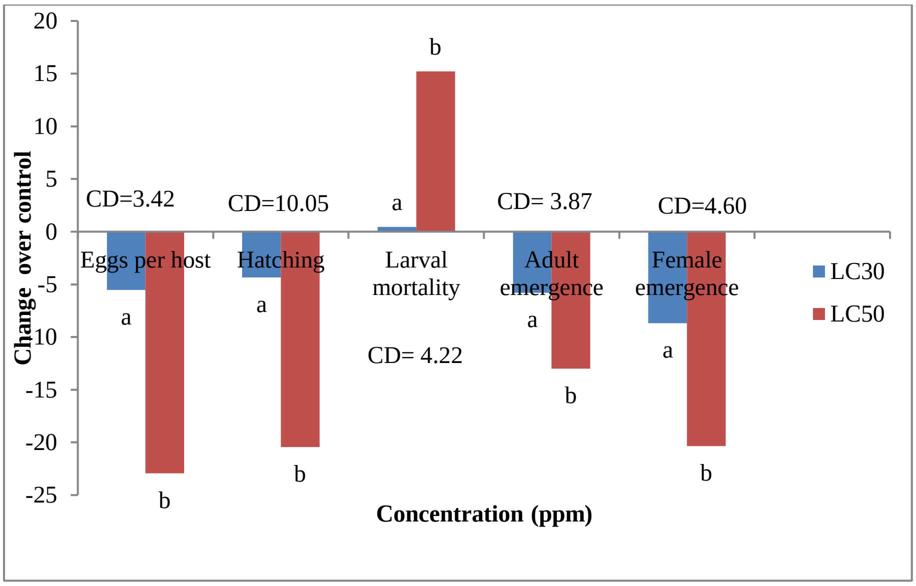

Figure 5. Effects of ferulic acid diet on development and survival of *B. hebetor* larvae emerged from *S. litura* larvae over control
CD= Critical difference at 1%.

parasitoid survival, adult mass, and development time of its parasitoid, *Cotesia congregata* (Say). Bloem and Duffey (6) reported that changes in artificial diet negatively impacted the growth of parasitoid *Hyposoter exiguae* (Viereck). Traugott and Stamp (54) also reported that the performance of predator spined soldier bug, *Podisus maculiventris* (Say) was negatively affected, when its prey tobacco hornworm, *Manduca sexta* (L.) was fed on chlorogenic acid and tomatine. Roth *et al*. (43) had reported that tannic acid and phenolic glycosides incorporated in the diet of gypsy moth, *Lymantria dispar* (L.) not only reduced its growth, decreased pupal weight and increased mortality but also affected the development time of its parasitoid *Cotesia melanoscela* (Ratzeburg). The increased level of CO_2 increased the total phenolic content of *Medicago truncatula* (Gaertn.) that affected the growth and survival of pink colour genotype of pea aphid, *Acyrthosiphon pisum* (Harris) and also decreased the parasitization rate of its parasitoid *Aphidius avenae* (Haliday) (58). Plant allelochemicals have negative effects on herbivore fitness along with reduced survival, clutch size, body size and fecundity of parasitoid (30).

The parasitoid provided with *S. litura* larvae fed on higher concentration (2573.33 ppm) of ferulic acid was more affected than those fed on lower concentration (25.92 ppm) of ferulic acid than control (Fig. 5). Similarly, plant secondary metabolites such as ellagic acid and gallic acid negatively impacted the survival of *S. litura* and the parasitoid *B. hebetor* (35,36). Increasing concentration of linear furanocoumarin increased the mortality of both beet armyworm, *Spodoptera exigua* (Hubner) and its parasitoid, *Archytas marmoratus* (Townsend). Reudler *et al*. (42) had also reported that increase in concentration of iridoid glycosides not only reduced the fitness of herbivore, the wood tiger moth, *Parasemia plantaginis* (L.) but also provided defence against predators and parasitoids. Wang *et al*. (56) also reported that higher dose of gossypol prolonged the development period of *H. armigera* larvae and the parasitoid *Compoletis chlorideae* (Uchida) but lower dose of gossypol had no significant effects.

CONCLUSIONS

The natural enemies of insects have an essential role in regulating the population of insect pests and therefore, the understanding of their tritrophic interactions is crucial for designing the appropriate strategies for pest control. Our findings have revealed that ferulic acid at higher concentrations (2573.33 ppm) adversely affected the development of both *S. litura* as well as the parasitoid, *B. hebetor.* While at lower concentration (25.92 ppm), it only disrupted the development of *S. litura* but not that of *B. hebetor*. Thus, ferulic acid holds considerable promise in pest control strategies and the findings can help in breeding plants resistant to insect pests. However, the efficacy of the compound needs to be determined under natural field conditions.

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CONFLICT OF INTEREST

The authors announce that they have no conflict of interest.

REFERENCES

1. Alvarez-Baca, J. K., Alfaro-Tapia, A., Lavandero, B., Le Lann, C. and Van Baaren, J. (2020). Suitability and Profitability of a Cereal Aphid for the Parasitoid *Aphidius platensis* in the Context of Conservation Biological Control of *Myzus persicae* in Orchards. *Insects* **11**: 381.
2. Alves, A.P.C., Correa, A.D., Alves, D.S., Saczk, A.A., Lino, J.B.R. and Carvalho, G.A. (2014). Toxicity of the phenolic extract from jabuticabeira (*Myrciaria cauliflora*) (Mart.) O. Berg) fruit skins on *Spodoptera frugiperda*. *Chilean Journal of Agriculture Research* **74**: 200-204.
3. Arnold, J.W. and Hinks, C.F. (1979). Insect haemocyte under light microscopy: techniques. In: *Insect Haemocyte Development, Forms, Functions and Techniques* (Ed., A.P. Gupta). Cambridge University, Press Cambridge. pp. 531-538.
4. Barbosa, P., Gross, P. and Kemper, J. (1991). Influence of plant allelochemicals on the tobacco hornworm and its parasitoid, *Cotesia congregata*. *Ecology* **72**: 1567-1575.
5. Barbosa, P., Saunders, J.A., Kemper, J., Trumble, R., Olechno, J. and Martinat, P. (1986). Plant allelochemicals and insect parasitoids effects of nicotine on *Cotesia congregata* (Say) (Hymenoptera: Braconidae) and *Hyposoter annulipes* (Cresson) (Hymenoptera: Ichneumonidae). *Journal of Chemical Ecology* **12**: 1319-1328
6. Bloem, K.A. and Duffey, S.S. (1990). Interactive effects of protein and rutin on larval *Heliothis zea* and the endoparasitoid *Hyposoter exiguae*. *Entomologia Experimentalis et Applicata* **54**: 149-161.
7. Brower, J.H., Smith, L., Vail, P.V. and Flinn, P.W. (1996). Biological control. In *Integrated Management of Insects in Stored Products* (Eds., B. Subramanyam and D.W. Hagstrum). Dekker, New York, pp 223-286.
8. Chauhan, N.S. and Sohal, S.K. (2018). Disruptive effects of pyrogallol on development of *Spodoptera litura* (Fab.) larvae. *Journal of Biopesticides* **11**: 07-13.

9. Chenchaiah, K.C. and Bhattacharya, A.K. (2000). Effect of phenolic extract of seed coat of red gram on the growth and development of *Creatonotus gangis*. *Indian Journal of Entomology* **62**: 205-210.
10. Cohen, A.C. (2005). *Insect Diets: Science and Technology*. CRC PRESS, Florida. pp.168-171.
11. Da Silveira Ramos, V., Freire, M.G.M., Parra, J.R.P. and Macedo, M.L.R. (2009). Regulatory effects of an inhibitor from *Plathymenia foliolosa* seeds on the larval development of *Anagasta kuehniella* (Lepidoptera). *Comparative Biochemistry and Physiology Part A* **152**: 255-261.
12. Dhir, B.C., Mohapatra, H.K. and Senapati, B. (1992). Assessment of crop loss in groundnut due to tobacco caterpillar, *Spodoptera litura* (F.). *Indian Journal of Plant Protection* **20:** 215-217.
13. Fernandez-Conradi, P., Castagneyrol, B., Jactel, H. and Rasmann, S. (2021). Combining phytochemicals and multitrophic interactions to control forest insect pests. *Current Opinion in Insect Science* **44:** 101-106.
14. Ganter, M., Najda, A. and Piesik, D. (2019). Effects of phenolic acid content on acceptance of hazel cultivars by filbert aphid. *Plant Protection Science* **55:** 116-122.
15. Isman, M.B. and Grieneisen, M.L. (2014). Botanical insecticides research: Many publications, limited useful data. *Trends in Plant Science* **19**: 140-145.
16. Jeyabalan, D. and Murugan, K. (1996.) Impact of variations in foliar constituents of *Mangifera indica* L. on consumption and digestion efficiency of *Latoia lepida* Cramer. *Indian Journal of Experimental Biology* **34**: 472-474.
17. Kopper, B.J, Jakobi, V.N., Osier, T.L. and Lindroth, R.L. (2002). Effects of paper birch condensed tannin on white marked tussock moth (Lepidoptera: Lymantriidae) performance. *Environmental Entomology* **31**: 10-14.
18. Koul, O., Shankar, J.S., Mehta, N., Taneja, S.C., Tripathi, A.K. and Dhar, K.L. (1997). Bioefficacy of crude extracts of *Aglaia* species (Meliaceae) and some active fractions against lepidopteran larvae. *Journal of Applied Entomology* **121**: 245-248.
19. Koul, O., Singh, G., Singh, R. and Singh, J. (2005). Bioefficacy and mode-of-action of Aglaroxin B and Aglaroxin C from *Aglaia elaeagmoidea* (syn. *A. Iroxburghiana*) against *Helicoverpa armigera* and *Spodoptera litura*. *Biopesticides International* **1**: 54-64.
20. Lindroth, R.L. and Peterson, S.S. (1988). Effects of plant phenols of performance of southern armyworm larvae. *Oecologia* **75**: 185-189.
21. Mahmudunnabi, M., Dutta, N.K., Rahman, A.K.M.Z. and Alam, S.N. (2014). Development of biorational-based integrated pest management package against pod borer, *Helicoverpa armigera* Hubner infesting chickpea. *Journal of Biopesticide* **6**: 108-111.
22. Mallikarjuna, N., Kranthi, K.R., Jadhav, D.R., Kranthi, S. and Chandra, S. (2004). Influence of foliar chemical compounds on the development of *Spodoptera litura* (Fab.) in interspecific derivatives of groundnut. *Journal of Applied Entomology* **128:** 321-328.
23. Mandal, S.M., Chakraborty, D. and Dey, S. (2010). Phenolic acids act as signaling molecules in plant-microbe symbiosis. *Plant Signaling and Behaviour* **5**: 359-368.
24. Mareggiani, G. (2001). Manejo de insectos plaga mediante sustancias semioquímicas de origen vegetal. *Manejo Integrado de Plagas* (Costa Rica) **60**: 22-30.
25. Mesbah, H.A., Saad, A.S., Mourad, A.K., Taman, F.A. and Mohamed, I.B. (2007). Biological performance of quercetin on the cotton leaf-worm larvae, *Spodoptera littoralis* Boisd. (Lep: Noctuidae) and prevailing natural enemies in the Egyptian cotton fields. *Communications in Agricultural Applied Biological Science* **72**: 611-622.
26. Miladi, M., Abdellaoui, K., Hamouda, A.B., Boughattas, I., Mhafdhi, M., Acheuk, F. and Halima-Kamel, M.B. (2019). Physiological, histopathological and cellular immune effects of *Pergularia tomentosa* extract on *Locusta migratoria* nymphs. *Journal of Integrative Agriculture* **18**: 2823-2834.
27. Montes-Molina, J.A., Luna-Guido, M.L., Espinoza-Paz, N., Govaerts, B., Gutierrez-Miceli, F.A. and Dendooven, L. (2008). Are extracts of neem (*Azadirachta indica* A. Juss. (L.) and *Gliricidia sepium* (Jacquin) an alternative to control pests on maize (*Zea mays* L.)? *Crop Protection* **27**: 763-774.
28. Murugan, K. and George, A.S. (1992). Feeding and nutritional influence on growth and reproduction of *Daphnis nerii* (Linn.) (Lepidoptera: Sphingidae). *Journal of Insect Physiology* **38**: 961-968.
29. Nordlund, D.A., Lewis, W.J. and Altieri, M.A. (1988). Influences of plant produced allelochemicals on the host/prey selection behaviour of entomophagous insects. In: *Novel Aspects of Insect-Plant Interactions* (Eds., P. Barbosa and D.K. Letourneau). pp 65-78. John Wiley & Sons, New York.
30. Ode, P.J. (2006). Plant chemistry and natural enemy fitness: Effects on herbivore and natural enemy interactions. *Annual Review of Entomology* **51**: 163-185.
31. Patil, R.A., Mehta, D.M. and Jat, B.L. (2014). Life table studies of tobacco leaf eating caterpillar, *Spodoptera litura* (Fabricius) on bidi tobacco, *Nicotian tabacum*. *Journal of Insect Science* **27**: 23-28.

32. Peter, A.J. and Ananthakrishnan, T.N. (1995). Impact of azadirachtin on the haemodynamics of *Cyrtacanthacris tatarica* (Acrididae: Orthoptera). *Journal of Entomological Research* **19**: 285-290.
33. Price, J.P., Bouton, C.E., Gross, P., McPheron, B.A., Thompson, J.N. and Weis, A.E. (1980). Interactions among three trophic levels. Influence of plants on interactions between insect herbivores and natural enemies. *Annual Review of Ecology and Systematics* **11**: 41-65.
34. Price, P.W. (1986). Ecological aspects of host plant resistance and biological control: Interactions among tritrophic levels. In: *Interactions of Plant Resistance and Parasitoids and Predators of Insects* (Eds., D.J. Boethel and R.D. Eikenbary). pp 11-30. Wiley and Sons, New York, USA.
35. Punia, A., Chauhan, N.S., Kaur, S. and Sohal, S.K. (2020). Effects of ellagic acid on the larvae of *Spodoptera litura* (Lepidoptera: Noctuidae) and its parasitoid *Bracon hebetor* (Hymenoptera: Braconidae). *Journal of Asia-Pacific Entomology* **23**: 660-665.
36. Punia, A., Chauhan, N.S., Singh, D., Kesavan, A.K., Kaur, S. and Sohal, S.K (2021). Effects of gallic acid on the larvae of *Spodoptera litura* and its parasitoid *Bracon hebetor*. *Scientific Reports* **11:** 531.
37. Qadri, S.S.H. and Narsaiah, J. (1978). Effects of azadirachtin on the moulting processes of last instar nymphs of *Periplaneta americana* (L.). *Indian Journal of Experimental Biology* **16**: 1141-1143.
38. Raliya, R., Saharan, V., Dimkpa, C. and Biswas, P. (2017). Nanofertilizer for precision and sustainable agriculture: current state and future perspectives. *Journal of Agricultural and Food Chemistry* **66**: 6487-6503.
39. Regnault-Roger, C. and Philogene, B.J.R. (2008). Past and current prospects for the use of botanicals and plant allelochemicals in integrated pest management. *Pharmaceutical Biology* **46**: 41-52.
40. Reitz, S.R and Trumble, J.T. (1997). Effects of linear furanocoumarins on the herbivore *Spodoptera exigua* and the parasitoid *Archytas marmoratus*: host quality and parasitoid success. *Entomologia Experimentalis et Applicate* **84**: 9-16
41. Reitz, S.R. and Trumble, J.T. (1996). Tritrophic interactions among linear furanocoumarins, the herbivore *Trichoplusiani* (Lepidoptera: Noctuidae) and the polyembryonic parasitoid *Copidosoma floridanum* (Hymenoptera: Encyrtidae). *Environmental Entomology* **25**: 1391-1397.
42. Reudler, J.H., Lindstedt, C., Pakkanen, H., Lehtinen, I. and Mappes, J. (2015). Costs and benefits of plant allelochemicals in herbivore diet in a multi enemy world. *Oecologia* **179**: 1147-1158.
43. Roth, S., Knorr, C. and Lindroth, R.L. (1997). Dietary phenolics affects performance of the Gypsy Moth (Lepidoptera: Lymantriidae) and its parasitoid *Cotesia melanoscela* (Hymenoptera: Braconidae). *Environmental Entomology* **26**: 668-671.
44. Saleem, M., Hussain, D., Ghouse, G., Abbas, M. and Fisher, S.W. (2016). Monitoring of insecticide resistance in *Spodoptera litura* (Lepidoptera: Noctuidae) from four districts of Punjab, Pakistan to conventional and new chemistry insecticides. *Crop Protection* **79:** 177-184.
45. Sharma, P.R., Sharma, O.P. and Saxena, B.P. (2008). Effects of sweet flag rhizome oil (*Acorus calamus*) on hemogram and ultrastructure of haemocytes of the tobacco armyworm, *Spodoptera litura* (Lepidoptera: Noctuidae). *Micron* **39**: 544-551.
46. Sharma, R. and Sohal, S.K. (2016). Oviposition response of melon fruit fly, *Bactrocera cucurbitae* (Coquillett) to different phenolic compounds. *Journal of Biopesticides* **9**: 46-51.
47. Shekhawat, S.S., Shafiq Ansari, M. and Basri, M. (2018). Effect of host plants on life table parameters of *Spodoptera litura*. *Indian Journal of Pure and Applied Biosciences* **6:** 324-332.
48. Stadler, B. and Mackeur, M. (1996). Influence of plant quality on interactions between the aphid parasitoid, *Ephedruscali fornicus* Baker and its host, *Acrylhosiphon pisum* Harris. *Canadian Entomologist* **128**: 27-39.
49. Steinly, B.A. and Berenbaum, M. (1985). Histopathological effects of tannins on the midgut epithelium of *Papilio polyxenes* and *Papilio glaucus. Entomologia Experimentalis et Applicata* **39**: 3-9.
50. Su, Q., Zhou, Z., Zhang, J., Shi, C., Zhang, G., Jin, Z. and Li, C. (2018). Effects of plant secondary metabolites on common cutworm, *Spodoptera litura* (Lepidoptera: Noctuidae). *Entomological Research* **48**: 18-26.
51. Tauber, O.E. and Yeager, J.F. (1935). On total haemolymph (blood) cell counts of insects I. Orthoptera, Odonata, Hemiptera and Homoptera. *Annals of the Entomological Society of America* **28**: 229-240.
52. Thanki, K.V., Patel, G.P. and Patel, J.R. (2003). Population dynamics of *Spodoptera litura* on castor *Ricinus communis*. *Indian Journal of Entomology* **65**: 347-350.
53. Tlak Gajger, I. and Dar, S.A. (2021). Plant allelochemicals as sources of insecticides. *Insects* **12**: 189.
54. Traugott, M.S. and Stamp, N.E. (1996). Effects of chlorogenic acid and tomatine - fed caterpillars on behavior of an insect predator. *Journal of Insect Behavior* **9**: 461-476.
55. Waldbauer, G.P. (1968). The consumption and utilization of food by insects. *Advances in Insect Physiology* **5**: 229-288.
56. Wang, C., Yang, Q. and Zhou, M. (1997). Effects of gossypol on growth of the cotton bollworm and development of its parasitoid *Campoletis chlorideae*. *Insect Science* **4**: 182-188.

57. Wang, Y., Cai, Q.N., Zhang, Q.W. and Han, Y. (2006). Effects of secondary substances from wheat on the growth and digestive physiology of cotton bollworm *Helicoverpa armigera* (Lepidoptera: Noctuidae). *European Journal of Entomology* **103**: 255-258.
58. Yan, H.Y., Guo, H.G., Sun, Y.C. and Ge, F. (2020). Plant phenolics mediated bottom-up effects of elevated CO_2 on *Acyrthosiphon pisum* and its parasitoid *Aphidius avenae*. *Insect Science* **27**: 170-184.
59. Zibaee, A. and Bandani, A.R. (2009). Effects of *Artemisia annua* L. (Asteracea) on the digestive enzymatic profiles and the cellular immune reactions of the Sunn pest, *Eurygaster integriceps* (Heteroptera: Scutellaridae), against *Beauveria bassiana*. *Bulletin of Entomological Research* **100**: 185-196.

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