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Feeding performance and life table parameters of Khapra Beetle, *Trogoderma granarium* Everts (Coleoptera: Dermestidae) on various barley cultivars

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Abstract

The Khapra beetle, *Trogoderma granarium* Everts (Coleoptera: Dermestidae), is a common pest of cereal grains and other stored products. In this study, the effects of ten barley cultivars (Abidar, Bahman, Line20, Line22, Line30, Lisuei, Lokht11, Makuyi, Sahand, and Sahraa) were evaluated on life table parameters and nutritional indices of *T. granarium* under the following laboratory conditions: 33 ± 1°C, 60 ± 5% RH, and a photoperiod of 14: 10 (L: D) h. Life history parameters of *T. granarium* could be appropriate indices in resistance and susceptibility evaluation of barley cultivars. The maximum survival rate of immature stages was observed on Makuyi and Lisuei cultivars and the minimum rate was on Abidar and Line22 cultivars. The shortest development time was on Makuyi cultivar and the longest on Line22 cultivar. Pupal weight was ranged from 2.56 mg on Lokht11 to 4.86 mg on Makuyi. Fecundity and egg-hatching rates were highest on Lisuei cultivar and the adults were long-lived on Makuyi cultivar. The highest r_m values were observed on Makuyi and Lisuei cultivars but lower value of it resulted from rearing of *T. granarium* on Line22 cultivar (0.0350 female per female day^{-1}). The results showed that *T. granarium* larvae fed on Makuyi cultivar had higher values of relative consumption rate and relative growth rate. The results indicated that Makuyi and Lisuei cultivars were relatively susceptible barley cultivars and Line22 was the most inappropriate cultivar for feeding of *T. granarium*, which could prove useful in the development of Integrated Pest Management programs for this pest.

Keywords: *Trogoderma granarium*, barley, life table, nutritional response, resistant cultivar

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Introduction

The Khapra beetle, *Trogoderma granarium* Everts (Coleoptera: Dermestidae), is considered as one of the most destructive pests of cereals and other stored products in many parts of the world (Stuart *et al*., 1994; Ahmedani *et al*., 2009). The import restrictions are supported by the fact that feeding by Khapra beetle larvae reduces the quality, grade, and weight of grain (Burges, 2008). It is a destructive feeder and can cause enormous losses (Banks, 1977). The barley (*Hordeum vulgare* L.) is considered a major daily animal feed in the world, as well as an important source of the required carbohydrates for most of the plant-feeding animals (Khodabandeh, 2003; Neelhirajan *et al*., 2007).

In recent years, pest control of stored products (including *T. granarium*) is undergoing a rapid change from an insecticide-based approach to an integrated management. Host plant resistance is an alternative approach for pest management, as it is both economically and environmentally acceptable (Golizadeh & Razmjou, 2010). Evaluating the

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resistance of various cultivars and crop species to pests may offer useful information about their suitability or unsuitability for the target pest species (Tsai & Wang, 2001; Golizadeh *et al.*, 2016). The appropriate use of resistant varieties in pest management techniques requires knowledge of life table and biological parameters of the pests (Golizadeh *et al.*, 2014; Hosseininejad & Naseri, 2015; Golizadeh & Abedi, 2016).

Host-plant resistance allows the plants to avoid, tolerate or recover from the effects of insect pest invasion (Tingey, 1986; Panda & Khush, 1995). Growth, development, and reproduction of insect populations strongly depend on the quality and quantity of the food consumed by them (Scriber & Slansky, 1981). Poor quality host plants may reduce insect survival rate, size or weight, adult longevity, and fecundity potential, which increase the developmental time of insects (Sarfraz *et al.*, 2006). Plant species and varieties differ greatly in suitability as host for a specific pest in terms of survival, development, and reproductive rates (Sedaratian *et al.*, 2009). In addition, insect growth is directly attributable to nutrient input (Hwang *et al.*, 2008) and the importance of maintaining the balance of nutrients is clear in most insects (Borzoui & Naseri, 2016). Nutritional regulation by an insect represents the integrated outcome of a highly complex set of interacting processes (Rahimi Namin *et al.*, 2014).

Recently, Golizadeh & Abedi (2016) evaluated the performance of *T. granarium* in response to feeding on different wheat cultivars and noted that Gaskojen and Kouhdasht cultivars are relatively susceptible and resistant cultivars for feeding of *T. granarium*, respectively. Naseri & Borzoui (2016) studied the life history and nutritional physiology of *T. granarium* fed with different wheat cultivars and reported that Parsi and Morvarid cultivars were the most unsuitable cultivars for the development and feeding of this pest. Seifi *et al.* (2015) investigated the nutritional indices and digestive enzymatic activity of this pest on some barley cultivars and demonstrated that Bahman cultivar was the most unsuitable host for *T. granarium*.

In spite of the economic importance of *T. granarium* on barley cultivars in Iran and many tropical and subtropical countries of the world (Hosseininaveh *et al.*, 2007; Seifi *et al.*, 2015), no published information is available about the population growth parameters of this pest on various barley cultivars. Demographic parameters along with nutritional properties are appropriate indices for the evaluation of susceptibility and resistance of feeding diets. Therefore, our objective of this study was to assess the response of *T. granarium* to feeding on ten barley cultivars. Findings of this research could contribute to IPM (Integrated Pest Management) programs of *T. granarium* on barley.

Materials and methods

Barley cultivars

Seeds of ten barley (*H. vulgare*) cultivars, including Abidar, Bahman, Line20, Line22, Line30, Lisuei, Lokht11, Makuyi, Sahand, and Sahraa were obtained from Agricultural and Natural Resources Research Center of Ardabil, Iran. These cultivars are commonly grown in barley-growing plantations in Iran. The grains were broken and were then used for the experiments.

Insect rearing

The initial population of *T. granarium* larvae was collected from the stored rice seeds from Karaj, Iran. They were separately reared on seeds of each barley cultivar and maintained at 33 ± 1°C, relative humidity of 65 ± 5%, and an approximate photoperiod of 14:10 (L:D) h, as described by Borzoui *et al.* (2015). The breeding cage was a clear cylindrical cage (25 cm in diameter and 20 cm in height) with two holes in its cap covered by fine mesh gauze containing 200 g of each cultivar grains. Before beginning the experiments, the population of *T. granarium* was reared for three generations on each cultivar and the individuals of the fourth generation were used to conduct the following experiments.

Development time, survival rate, and body weight

All the experiments on each barley cultivar were carried out under the following laboratory conditions: 33 ± 1°C, relative humidity of 65 ± 5 %, and a photoperiod of 14:10 (L:D) h. To obtain *T. granarium* eggs of the same age on each barley cultivar, 25 male–female pairs of the newly emerged beetles (reared from the same host plant) of the fourth laboratory generation were transferred to oviposition containers. The adult stage of males and females was distinguished based on size and especially antennae features (Bagheri Zenouz, 1997; Kulkarni *et al.*, 2015). The oviposition container consisted of a clear Plexiglas container (20 × 10 × 5 cm^3). In order to assess the developmental time and survival rate, 61-day-old eggs of *T. granarium* were transferred into Petri dishes (diameter of 6 cm and depth of 2 cm) containing the related barley cultivar grains and were used in the experiments. The eggs were inspected daily until hatching time. Once hatching, each newly hatched larva of *T. granarium* was encoded and released into each Petri dish (diameter of 6 cm and depth of 2 cm). Petri dishes were monitored daily until the preimaginal stages of *T. granarium* completed development or died. Pupal weight of *T. granarium* was measured 24 h after pupation on each barley cultivar. Thus, developmental performance of the individuals, duration of immature stages, and their survival were recorded. The weights of 1-day-old female and male *T. granarium* adults reared on the corresponding barley cultivar were recorded.

Adult life history parameters

One-day-old, virgin female and male *T. granarium* adults reared on the corresponding barley cultivar were paired. Each pair was transferred into a plastic tube fitted with mesh lids (2 cm diameter and 5 cm height). Experimental tubes were checked daily and the number of *T. granarium* eggs deposited in each tube was recorded. In this order, each pair was daily transferred to the new tube provided with fresh food and the number of eggs laid by the adults was recorded. We evaluated the fecundity of 25 adult pairs (25 replicates) on each barley cultivar. Moreover, all the eggs collected in this study were maintained for 15 days to determine the number of larvae emerging from these eggs (hatching rate).

Life table parameters

The development time, immature survival rate, and adult fecundity were used for calculation of life table parameters. The life table parameters, age-specific survival rate (l_x), and fecundity (m_x) were calculated for *T. granarium* fed on ten barley cultivar grains. For this purpose, for each barley cultivar, age-specific survival and age-specific fecundity were used to

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calculate the intrinsic rate of natural increase (r_m) using the following formula (Birch, 1948; Carey, 1993):

$$\sum_{x=1}^{\omega} e^{-r_m x} l_x m_x = 1,$$

where ω is the oldest age class, and l_x and m_x are the proportion of surviving individuals at age x and the number of females offspring per female in the age interval x, respectively. In addition, net reproductive rate (R_0), mean generation time (T), finite rate of increase (λ), and doubling time (DT) were calculated based on Carey's formulae (Carey, 1993).

Nutritional indices experiment

Nutritional indices, including the larval weight gain and food consumption by the larvae, were calculated gravimetrically according to the method of Waldbauer (1968). Nutritional indices were evaluated on the basis of dry weight. The weight of each barley cultivar was measured and the cultivar was then transferred into plastic plates (6 cm in diameter and 2 cm depth) for larval feeding. The initial weight of the newly ecdysed sixth-instar larvae was recorded and it was then reared on barley cultivar. Final larval weight and remnant food was recorded until feeding stopped and the prepupal stage was reached. The initial fresh food and the food remnant at the end of each experiment were weighed. The quantity of food ingested was calculated by subtracting the weight of remaining food at the end of each experiment from the weight of fresh food supplied. To obtain the dry weight percentage of food and larvae, 20 specimens for each were weighed, oven-dried at 60°C for 48 h, and then weighed again (Sartorius AG Germany GCA803S, $d = 0.001$ ct). Nutritional indices of *T. granarium* larvae were calculated using formulae described by Waldbauer (1968): conversion efficiency of ingested food (ECI) = P/E; relative consumption rate (RCR) = $E/A \times T$; and relative growth rate (RGR) = $P/A \times T$, where A represents the mean dry weight of larvae over unit time (mg), E the dry weight of food consumption (mg), P the dry weight gain of larvae (mg), and T the duration of feeding period (day).

Physical and biochemical traits of barley cultivars

In order to understand any possible correlation between the most important life table parameter and nutritional indices with some physical and biochemical traits of barley cultivars, the percentage of humidity, grain hardiness, and protein content of barley cultivars was determined. Percentage of humidity and hardiness index of barley cultivars were quantified according to the method of AACC (American Association of Cereal Chemists, 1996). Also, protein concentrations of the tested cultivars were measured using BSA (bovine serum albumin) as a standard (Bradford, 1976).

Statistical analysis

All the data were examined for normality by Kolmogorov–Smirnov test using the SPSS v. 16.0 statistical program (SPSS, 2007). Differences in r_m, R_0, T, DT, and λ values were tested for significance using the Jackknife procedure (Maia *et al.*, 2000). Jackknife pseudo-values computed for life table parameters on ten barley cultivars were analyzed by one-way ANOVA (SAS Institute, 2002) (Meyer *et al.*, 1986; Maia *et al.*, 2000). Additionally, developmental data, weights of sixth-instar larvae and pupa, as well as nutritional indices were analyzed by ANOVA with mean separation at 5% level of significance by Tukey test (SPSS, 2007). Correlation between some important life history parameters with physical and biochemical traits of barley cultivars were evaluated through Pearson Correlation test. A dendrogram of barley cultivars based on life table parameters and nutritional indices of *T. granarium* on tested barley cultivars was constructed by Ward's method using SPSS.

Results

Development time, survival rate, and body weight

The effect of various barley cultivars on developmental time of *T. granarium* is given in figs 1 and 2. Significant differences were observed in the duration of egg ($F = 5.52$; df = 9, 469; $P < 0.0001$), larval ($F = 13.37$; df = 9, 416; $P < 0.0001$), and pupal ($F = 4.53$; df = 9, 385; $P < 0.0001$) stages between the tested cultivars. Moreover, the immature development time (from egg to adult emergence) was different among the cultivars ($F = 12.72$; df = 9, 385; $P < 0.0001$). Regarding the results, *T. granarium* showed the longest egg incubation period on Line30 cultivar, while the shortest period was on Line20 cultivar. The longest larval period was detected on Line22 and Line30 cultivars and the shortest on cultivar Makuyi. The pupal period was longer on Lokht11 cultivar and shorter on Lisuei cultivar. Also, the shortest development time was on Makuyi cultivar (52.4 ± 0.6 days) and the longest was on Line22 cultivar (67.8 ± 0.78 days) (fig. 2). The descending order of immature survival rates were 71.7, 70. 0, 68.3, 66.7, 65.0, 61.7, 61.7, 60.0, 58.3, and 58.3 % on Makuyi, Lisuei, Line20, Sahraa, Sahand, Bahman, Line30, Lokht11, Abidar, and Line22 cultivars, respectively. The age-specific survival rate (l_x) of *T. granarium* on different cultivars is shown in fig. 3. Age-specific survival rate generated similar curves among the cultivars. However, female adults were long-lived on Lisuei cultivar and l_x curve was more extended on this cultivar.

Figures 4 and 5 indicate the weight of sixth-instar larvae, pupa, female, and male adults of *T. granarium* when reared on various barley cultivars. According to the obtained results, the weight of sixth-instar larvae differed from 4.49 mg on Line30 to 5.96 mg on Line20 cultivar ($F = 10.31$; df = 9, 416; $P < 0.0001$). Moreover, pupal weight showed a significant difference among the tested barley cultivars ($F = 26.12$; df = 9, 385; $P < 0.0001$). The heaviest weights were measured on Makuyi cultivar and the lightest ones were recorded on Lokht11 (fig. 4). Also, female ($F = 14.68$; df = 9, 249; $P < 0.0001$) and male ($F = 5.65$; df = 9, 249; $P < 0.0001$) adult weights differed among the cultivars with female and adult weights being the highest on Line20 and Lisuei cultivars, respectively (fig. 5).

Adult life history parameters

The results of total fecundity (number of eggs laid per female) and daily fecundity per female of *T. granarium* are shown in table 1. The total fecundity significantly differed among the tested barley cultivars ($F = 132.10$; df = 9, 249; $P < 0.0001$). The highest fecundity was recorded for females developed from larvae fed on Lisuei cultivar, while the fecundity of *T. granarium* was not different among Abidar,

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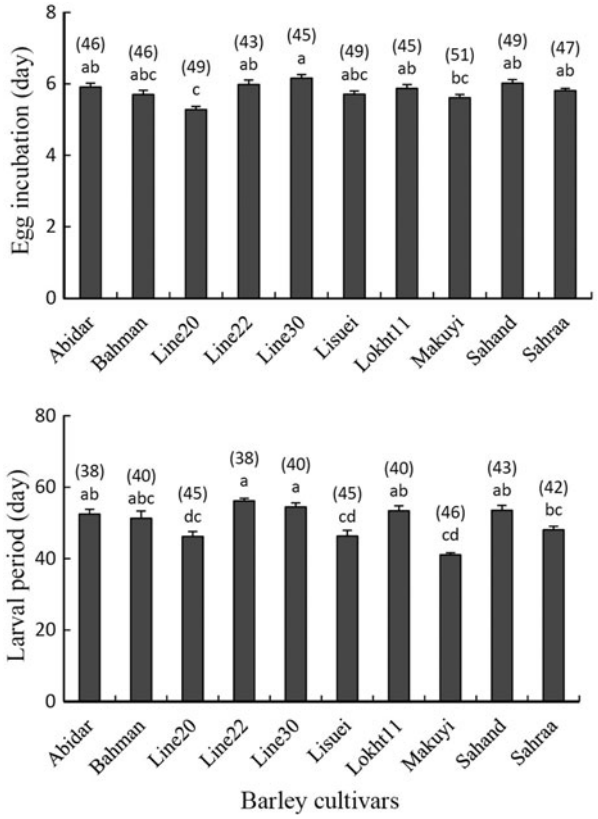

Fig. 1. Egg incubation and larval periods (mean ± SE) of *Trogoderma granarium* reared on various barley cultivars (the number in parenthesis is sample size).

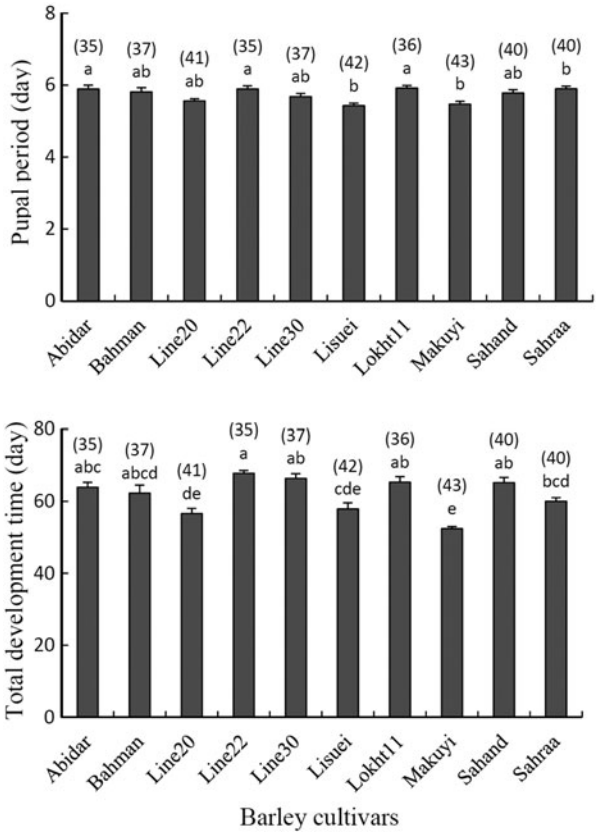

Fig. 2. Pupal period and total developmental time (mean ± SE) of *Trogoderma granarium* reared on various barley cultivars (the number in parenthesis is sample size).

Bahman, Line22, Line30, Lokht11, and Sahand cultivars. In addition, the mean number of eggs produced per female day^{-1} of *T. granarium* was affected by the tested cultivars ($F = 44.42$; df = 9, 249; $P < 0.0001$) (table 1). The egg-hatching rate was the highest on Lisuei cultivar ($F = 2.94$; df = 9, 249; $P < 0.01$). Age-specific fecundity rates of *T. granarium* on tested cultivars are shown in fig. 3. The width of the m_x peak (i.e., the fecundity period) was higher on Lisuei, Line20, and Makuyi than the other cultivars.

Various barley cultivars had a significant influence on the longevity of female ($F = 17.46$; df = 9, 249; $P < 0.0001$) and male ($F = 8.23$; df = 9, 249; $P < 0.0001$) adults of *T. granarium*. The shorter and longer longevity of female adults of *T. granarium* were observed on Bahman (7.60 days) and Makuyi (10.64 days), as well as Sahraa (10.28 days) cultivars, respectively. Also, a longer longevity of male adults was observed on Line20 cultivar (10.64 days), while the shorter longevity was on cultivar Line22 (7.92 days) (table 1).

Life table parameters

The population growth parameters of *T. granarium* reared on various barley cultivars are shown in table 2. The population reared on Lisuei had a higher net reproductive rate (R_0 value) and those reared on Line22 had a lower R_0 value ($F = 133.05$; df = 9, 249; $P < 0.0001$). The intrinsic rate of increase (r_m) of *T. granarium* was found to be significantly different ($F = 24.49$; df = 9, 249; $P < 0.0001$) depending on the barley cultivars on which they were reared. The r_m values ranged from 0.035 to 0.059 female progenies per female day^{-1} on the tested barley cultivars (table 2). The value of the intrinsic rate of increase (r_m) was highest when *T. granarium* was reared on Makuyi cultivar. The lower r_m value resulted from rearing the *T. granarium* on Line22. The variations in finite rate of increase (λ) were similar to the intrinsic rate of increase and the former parameter was significantly influenced by different cultivars ($F = 24.13$; df = 9, 249; $P < 0.0001$). The mean generation time (T) of *T. granarium* was also different among the tested cultivars ($F = 3.28$; df = 9, 249; $P = 0.0009$) with the cultivar Makuyi promoting the fastest generation times. Furthermore, significant differences were observed for *T. granarium* doubling time (DT) when reared on the studied barley cultivars ($F = 14.81$; df = 9, 249; $P < 0.0001$). The DT values on Line22 cultivar were relatively higher than on Makuyi cultivar (table 2).

Nutritional indices of larvae

Nutritional indices of sixth-instar larvae of *T. granarium* were significantly different on various barley cultivars (table 3). The higher weight gain of larvae ($F = 4.22$; df = 9, 49; $P < 0.0007$) was on Makuyi cultivar and those on Lokht11 had a lower weight gain. A higher value of ECI ($F = 5.41$; df = 9, 49; $P < 0.0001$) came from larvae that were fed on Makuyi

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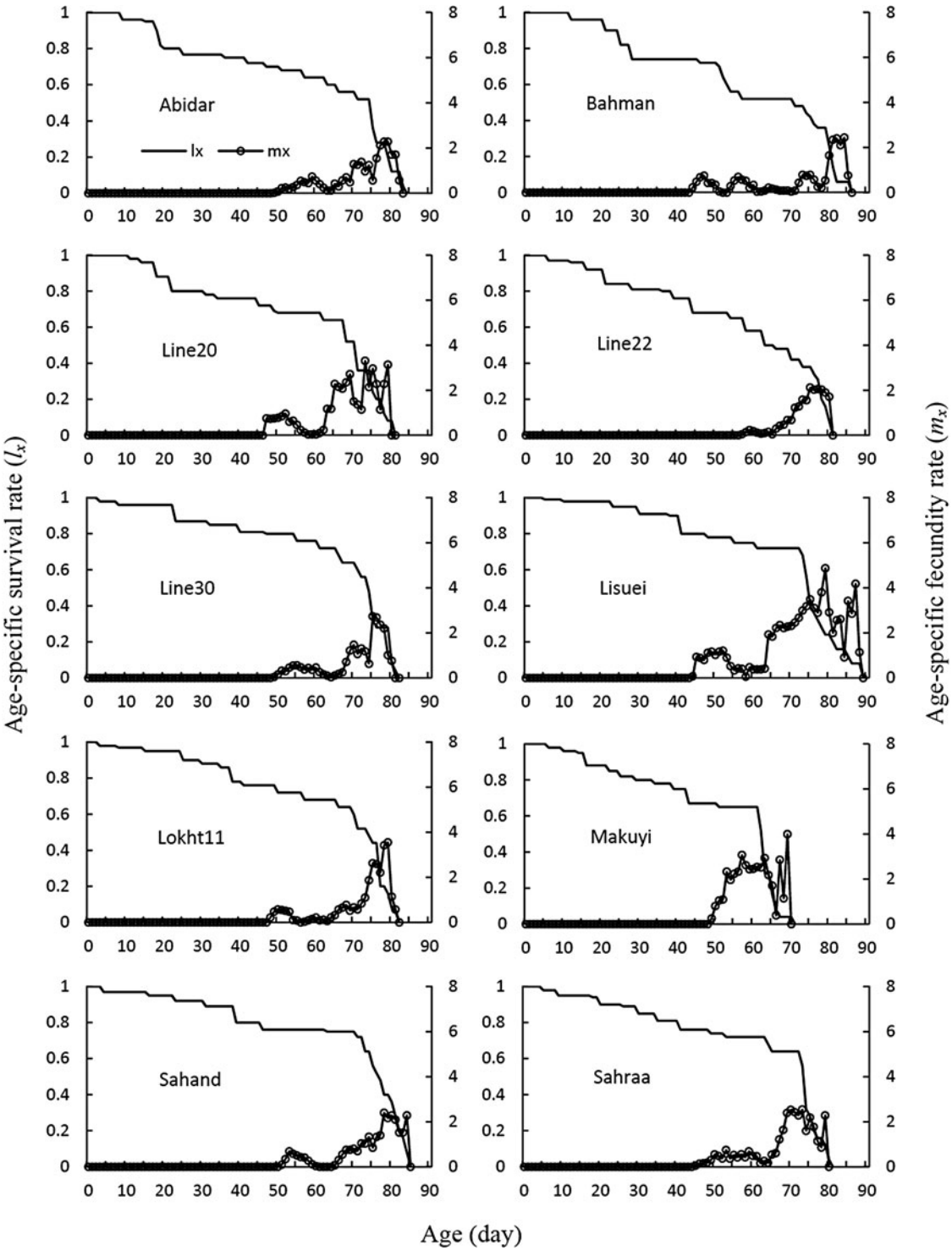

Fig. 3. Age-specific survival rate (l_x) and age-specific fecundity (m_x) of *Trogoderma granarium* on ten barley cultivars.

cultivar. Similarly, the larvae fed on Makuyi cultivar showed a higher value of RCR ($F = 6.87$; df = 9, 49; $P < 0.0001$). In addition, a higher value of RGR ($F = 6.65$; df = 9, 49; $P < 0.0001$) was found on Makuyi cultivar, while the lower value was observed on Lokht11 cultivar.

Percentage of humidity, grain hardiness, and protein content of barley cultivars

The results of the percentage of humidity, hardiness index, and protein content of various barley cultivars are shown in

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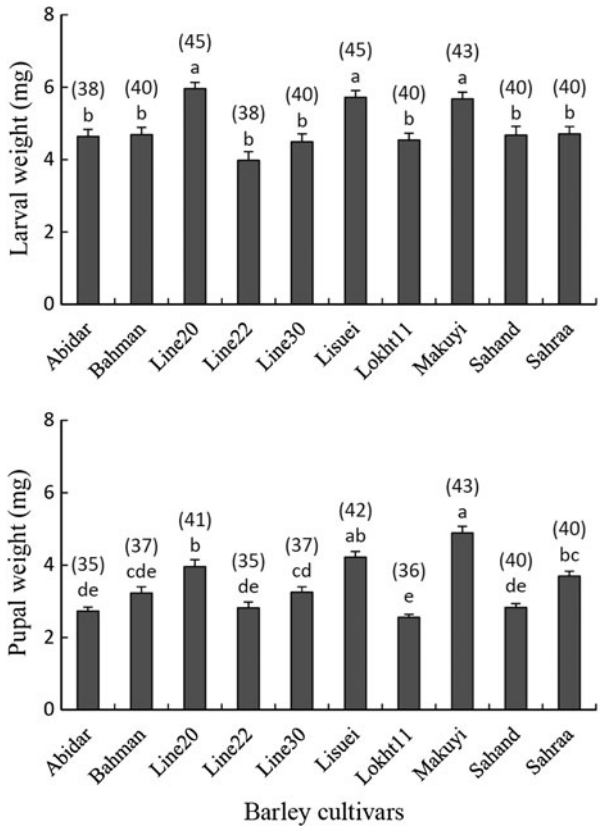

Fig. 4. The weight (mean ± SE) of sixth-instar larvae and pupa of *Trogoderma granarium* reared on various barley cultivars (the number in parenthesis is sample size).

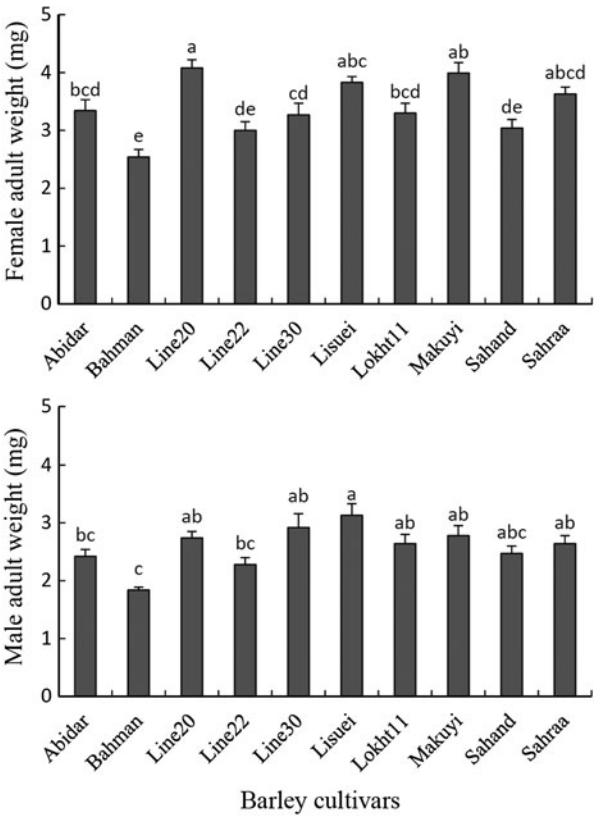

Fig. 5. The weight (mean ± SE) of female and male adults of *Trogoderma granarium* reared on various barley cultivars (sample size on each cultivar was 25).

Table 1. Biological parameters of *Trogoderma granarium* adults reared on various barley cultivars.

Barley cultivar	Sample size	Fecundity	Mean number of eggs per female day^{-1}	Hatching rate (%)	Female longevity	Male longevity
Abidar	25	21.92 ± 1.34 d	2.53 ± 0.12 d	66.9 ± 1.73 bc	8.60 ± 0.25 cde	9.48 ± 0.45 abcd
Bahman	25	20.16 ± 0.05 d	2.64 ± 0.09 cd	63.9 ± 1.31 c	7.60 ± 0.26 e	9.32 ± 0.36 abcde
Line20	25	33.92 ± 1.16 c	3.46 ± 0.15 c	71.5 ± 1.82 abc	9.96 ± 0.25 ab	10.64 ± 0.28 a
Line22	25	19.02 ± 0.93 d	2.52 ± 0.14 d	67.9 ± 1.62 bc	7.76 ± 0.29 de	7.92 ± 0.38 e
Line30	25	21.60 ± 1.02 d	2.82 ± 0.17 cd	67.4 ± 1.65 bc	7.88 ± 0.25 de	9.16 ± 0.23 bcde
Lisuei	25	62.96 ± 2.15 a	6.75 ± 0.44 a	76.0 ± 1.71 a	9.76 ± 0.33 abc	10.04 ± 0.28 abc
Lokht11	25	22.28 ± 0.91 d	2.83 ± 0.15 cd	66.3 ± 1.71 bc	8.04 ± 0.19 de	8.68 ± 0.27 cde
Makuyi	25	45.56 ± 1.34 b	4.40 ± 0.21 b	72.3 ± 2.09 ab	10.64 ± 0.33 a	10.28 ± 0.27 ab
Sahand	25	24.01 ± 0.88 d	2.73 ± 0.12 cd	67.4 ± 1.75 bc	8.92 ± 0.17 bcd	8.12 ± 0.37 de
Sahraa	25	31.56 ± 0.96 c	3.15 ± 0.13 cd	69.0 ± 1.78 abc	10.28 ± 0.32 a	9.92 ± 0.19 abc

Mean values in a column followed by different lowercase letters are significantly different on the basis of ANOVA with Tukey test ($P < 0.05$).

table 4. Significant difference was observed in moisture content among the examined cultivars ($F = 3.35$; df = 9, 29; $P = 0117$) and humidity of grain was the highest in Makuyi cultivar. The grain hardiness index ($F = 3.89$; df = 9, 29; $P = 0.005$) significantly differed among the barley cultivars and the highest and lowest values were observed in cultivars Line22 and Makuyi, respectively. Similarly, the highest protein content ($F = 384.14$; df = 9, 29; $P < 0.0001$) was measured in cultivar Makuyi, whereas the lowest content was detected in cultivar Line22. Significant correlations were observed between life history parameters and physical and biochemical traits of barley cultivars (grain humidity, hardiness, and protein content) (table 5). Fecundity, net reproductive rate, and RCR were not significantly correlated with grain protein content. Both r_m and RGR were negatively correlated with grain hardiness and positively correlated with grain humidity and protein content. A dendrogram based on life table parameters and nutritional indices of *T. granarium* on different barley cultivars is shown in fig. 6. Two separate main clusters (labeled A and B) are apparent in the dendrogram. The main clusters (A and B)

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Table 2. The mean (±SE) life table parameters of *Trogoderma granarium* reared on various barley cultivars.

Barley cultivar	Sample size	Net reproductive rate (R_0, female/female)	Intrinsic rate of increase (r_m) (female per female day^{-1})	Finite rate of increase (λ, female day^{-1})	Generation time (T, days)	Doubling time (DT, days)
Abidar	25	12.33 ± 0.73 d	0.040 ± 0.002 de	1.041 ± 0.002 de	61.99 ± 2.10 abc	17.08 ± 0.88 ab
Bahman	25	11.49 ± 0.59 d	0.043 ± 0.002 d	1.044 ± 0.002 d	55.93 ± 2.89 bc	15.86 ± 0.93 bc
Line20	25	19.81 ± 0.61 c	0.051 ± 0.005 bc	1.052 ± 0.006 bc	58.57 ± 1.82 abc	13.58 ± 0.49 cde
Line22	25	10.83 ± 0.53 d	0.035 ± 0.008 e	1.036 ± 0.005 e	67.86 ± 1.15 a	19.73 ± 0.55 a
Line30	25	12.40 ± 0.58 d	0.041 ± 0.001 de	1.042 ± 0.004 de	60.55 ± 2.54 abc	16.65 ± 0.73 b
Lisuei	25	35.82 ± 1.25 a	0.056 ± 0.002 ab	1.059 ± 0.003 ab	61.54 ± 2.60 abc	12.24 ± 0.42 de
Lokht11	25	12.70 ± 0.52 d	0.040 ± 0.004 de	1.041 ± 0.002 de	62.56 ± 2.50 abc	17.05 ± 0.82 ab
Makuyi	25	26.38 ± 0.78 b	0.059 ± 0.004 a	1.060 ± 0.003 a	55.08 ± 0.57 c	11.65 ± 0.15 e
Sahand	25	13.68 ± 0.49 d	0.040 ± 0.001 de	1.041 ± 0.001 de	65.16 ± 2.26 ab	17.26 ± 0.66 ab
Sahraa	25	17.60 ± 0.58 c	0.047 ± 0.003 dc	1.048 ± 0.001 dc	61.16 ± 1.86 abc	14.78 ± 0.48 bcd

Mean values in a column followed by different lowercase letters are significantly different on the basis of ANOVA with Tukey test ($P < 0.05$).

Table 3. The mean (±SE) nutritional indices of *Trogoderma granarium* larvae reared on various barley cultivars.

Barley cultivar	Sample size	Larval weight gain (mg)	ECI (%)	RCR (mg mg^{-1} day^{-1})	RGR (mg mg^{-1} day^{-1})
Abidar	75	0.036 ± 0.005 ab	11.85 ± 1.53 bcd	0.27 ± 0.02 cd	0.039 ± 0.004 cd
Bahman	75	0.033 ± 0.001 ab	14.21 ± 0.97 abcd	0.31 ± 0.03 abcd	0.040 ± 0.005 bcd
Line20	75	0.042 ± 0.002 a	17.62 ± 1.35 ab	0.42 ± 0.03 abc	0.058 ± 0.004 abc
Line22	75	0.031 ± 0.005 ab	14.01 ± 1.13 abcd	0.30 ± 0.04 abcd	0.035 ± 0.006 dc
Line30	75	0.033 ± 0.003 ab	11.77 ± 1.47 dc	0.27 ± 0.37 bcd	0.035 ± 0.006 dc
Lisuei	75	0.042 ± 0.002 a	17.25 ± 1.22 abc	0.44 ± 0.03 ab	0.065 ± 0.003 ab
Lokht11	75	0.018 ± 0.002 b	10.63 ± 1.11 d	0.19 ± 0.04 d	0.027 ± 0.003 d
Makuyi	75	0.048 ± 0.004 a	18.44 ± 1.35 a	0.46 ± 0.05 a	0.071 ± 0.004 a
Sahand	75	0.037 ± 0.007 ab	11.41 ± 0.46 dc	0.23 ± 0.02 d	0.038 ± 0.008 dc
Sahraa	75	0.046 ± 0.005 a	16.06 ± 1.39 abcd	0.41 ± 0.02 abc	0.041 ± 0.006 bcd

The mean followed by different letters in the same column are significantly different (Tukey test, $P < 0.05$).
ECI, efficiency of conversion of ingested food; RCR, relative consumption rate; RGR, relative growth rate.

Table 4. Percentage of grain humidity, hardiness index and protein (mean ± SE) of various barley cultivars used for feeding of *Trogoderma granarium*.

Barley cultivar	Humidity (%)	Hardiness index (%)	Protein content (mg ml^{-1})
Abidar	7.48 ± 0.86 abc	72.24 ± 3.33 a	0.57 ± 0.006 ef
Bahman	6.46 ± 0.88 abc	69.52 ± 2.18 a	0.69 ± 0.008 e
Line20	7.75 ± 0.19 abc	56.75 ± 1.28 ab	2.17 ± 0.030 a
Line22	5.46 ± 0.34 bc	78.15 ± 1.87 a	0.17 ± 0.001 g
Line30	6.47 ± 0.86 abc	70.15 ± 2.58 a	0.74 ± 0.007 de
Lisuei	8.59 ± 0.71 ab	55.20 ± 1.45 ab	0.91 ± 0.007 dc
Lokht11	5.13 ± 0.57 c	64.81 ± 1.97 ab	0.47 ± 0.080 f
Makuyi	9.14 ± 1.02 a	44.68 ± 3.12 b	2.26 ± 0.049 a
Sahand	7.26 ± 0.49 abc	64.74 ± 2.58 ab	1.47 ± 0.041 b
Sahraa	6.59 ± 0.28 abc	62.15 ± 3.51ab	0.95 ± 0.010 c

Mean values in a column followed by different lowercase letters are significantly different on the basis of ANOVA with Tukey test ($P < 0.05$).

were divided to two sub-clusters (A1, A2 and B1, B2, respectively).

Discussion

Host-plant resistance can be a useful component of an integrated pest management system compatible with other methods of control (Sedaratian *et al.*, 2009). Variation in host plant and the quality of varieties are known to affect the development, survivorship, reproduction, and population growth of insects (Tsai & Wang, 2001). Several authors have studied the susceptibility and resistance of this pest on various stored crops and different cultivars (Saliheen, 2005; Musa & Dike, 2009; Borzoui *et al.*, 2015; Al-Iraqi *et al.*, 2015; Naseri & Borzoui, 2016). Resistance of wheat cultivars against *T. granarium* has been previously reported by Mohamed (2003), Rao *et al.* (2004), Sayed *et al.* (2006), Ahmedani *et al.* (2009), and Golizadeh & Abedi (2016). This study was intended to improve the existing knowledge about the life table parameters of *T. granarium* and to examine them with various barley cultivars. The resistant cultivars can be recommended to be grown in areas where the damage of *T. granarium* is high for protecting or at least delaying the infestation of barley by this pest. This study shows that different barley cultivars have a significant effect not only on the life history and population growth parameters of *T. granarium*, but also on the nutritional indices of this insect.

There were six larval instars on all the tested barley cultivars, which was one instar more than that reported by Golizadeh & Abedi (2016) on wheat cultivars. Moreover, the larval periods on barley cultivars were longer than those on wheat cultivars. The number of larval instars and the duration of larval stages could be influenced by differences in the host species (Naseri *et al.*, 2014). These results are in agreement with the findings of Bernays & Chapman (1994), Naseri *et al.* (2014),

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Table 5. Correlation coefficients (*r*) of some life history parameters of *Trogoderma granarium* fed on different barley cultivars with percentage of grain humidity, hardiness index, and protein of various barley cultivars.

Parameter	Humidity (%)		Hardiness index (%)		Protein content	
	r	P_{value}	*r*	P_{value}	*r*	P_{value}
Immature survival rate	0.796	0.006	−0.929	0.001	0.811	0.004
Total development time	−0.816	0.004	0.919	0.001	−0.795	0.006
Pupa weight	0.802	0.005	−0.868	0.001	0.722	0.018
Female adult weight	0.645	0.044	−0.772	0.009	0.660	0.038
Fecundity	0.764	0.010	−0.780	0.008	0.447	0.195
Female adult longevity	0.751	0.012	−0.848	0.002	0.758	0.011
Net reproductive rate	0.772	0.009	−0.791	0.006	0.466	0.174
Intrinsic rate of increase	0.840	0.002	−0.938	0.001	0.721	0.019
RGR	0.910	0.001	−0.842	0.002	0.734	0.016
RCR	0.719	0.019	−0.707	0.022	0.586	0.075

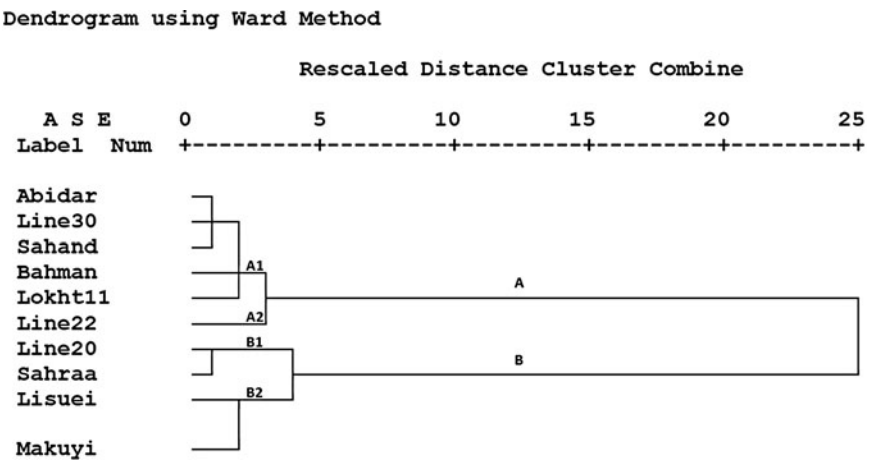

Fig. 6. Dendrogram of different barley cultivars based on life table parameters and nutritional indices of *Trogoderma granarium* reared on barley cultivars (two distinct clusters A (including subclusters A1 and A2) and B (including subclusters B1 and B2)).

and Borzoui *et al*. (2015). Based on Borzoui *et al*. (2015), the prolonged larval period of *T. granarium* on unsuitable cultivars is meant to gain nourishment.

Variations in the duration of immature stages of *T. granarium* might be attributed to differences in the macronutrients, inhibitors, grain hardiness, and humidity of the tested wheat cultivars (Borzoui & Naseri, 2016; Golizadeh & Abedi, 2016). The short lifespan and high fecundity of pests on host plants indicate greater suitability of those plants (Lorenzen *et al*., 2001; Hemati *et al*., 2012). The shorter development time of *T. granarium* on Makuyi cultivar could be justified by the higher protein value and grain humidity in this cultivar. Moreover, the grain hardiness could be another factor affecting the development time and immature survival rates. The grain hardiness in Makuyi cultivar was lower than the other cultivars. The results regarding the larval and pupal period of *T. granarium* were in agreement with those achieved by Borzoui *et al*. (2015), who reported incubation periods of 56.57 and 5.55 days for *T. granarium* reared on barley, respectively.

It has been reported that body weight is associated with the quality and quantity of food and is one of the main biological indices of insect population dynamics (Li *et al*., 2004; Liu *et al*., 2004). The lowest pupal weight of the Khapra beetle on Lokht11 cultivar indicated that the larvae fed on Lokht11 had the lowest fitness compared with those fed on the other barley cultivars. Moreover, our findings suggest that the larvae fed on Makuyi cultivar achieved more nutrients than those fed on other barley cultivars. Also, the consequences of feeding on suitable cultivars are reflected in the weight of female and male adults (table 2). The females reared on Line20, Makuyi, and Lisuei cultivars were heavier. The weight range of pupal *T. granarium* on various barley cultivars tested in the current study was lower than that reported by Seifi *et al*. (2015). Such discrepancy might be attributed to either genetic differences in populations or variations in the experimental conditions and cultivars used for feeding of this pest.

Average fecundity of *T. granarium* on barley cultivars (30.4 eggs) was lower than that reported by Musa & Dike (2009) on stored groundnut kernels (80.2 eggs), as well as Golizadeh & Abedi (2016) report on wheat cultivars (40.8 eggs). Food quality can affect both the realized fecundity and egg fertility of female insects (Mebarkia *et al*., 2010). Regarding the larval and pupal weights, it is evident that the fecundity values can be correlated with the weight of sixth instar larva and pupa on respective cultivars (Daryaei *et al*., 2007; Naseri & Borzoui, 2016).

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The intrinsic rate of increase (r_m) is the most important population parameter for the study of population dynamics because it includes age, sex ratio, survivorship, and fecundity (Birch, 1948; Carey, 1993). Thus, this parameter could be the most appropriate index to evaluate the suitability of different host plants to an insect (Razmjou & Golizadeh, 2010). In this research, the highest r_m value of *T. granarium* was found on Makuyi and Lisuei, which was mainly the result of relatively higher fecundity, immature survival rate, and fast development on respective cultivars (table 4). The relatively higher net reproductive rate of *T. granarium* on Lisuei may cause a relatively higher fecundity of *T. granarium*. However, the shorter mean generation time, which is a result of short development time on Makuyi, led to the highest r_m value on this cultivar compared with Lisuei cultivar. This could be a function of higher protein content in Makuyi cultivar. The higher reproductive performance of *T. granarium* on Lisuei cultivar was found despite its lower protein content, which could be attributed to other factors such as fat content or secondary metabolites.

The food consumption and larval weight gain on barley cultivar was lower than that reported by Seifi *et al*. (2015) for *T. granarium* on the barley cultivars. This inconsistency can be due to differences in the barley varieties and experimental conditions or differences in *T. granarium* population. The larvae reared on Lokht11 cultivar had the lower values of ECI, indicating that the larvae feeding on this cultivar were less effective in converting the ingested and digested food to biomass. Similar results of ECI value were reported by Borzoui *et al*. (2015) with *T. granarium* reared on barley. The duration of the feeding period is an effective factor in RGR and RCR values (Hemati *et al*., 2012). In this study, RCR and RGR values were higher on Makuyi cultivar and Lisuei had the second rank. Our results indicated that the Makuyi cultivar was a high-nutrient food for the larvae and a shorter period of development time was needed to complete immature stages on this cultivar. The higher protein value and lower grain hardiness in Makuyi cultivar could be a reason for the higher nutritional indices on this cultivar.

In the present study, cluster analysis revealed that with respect to life table parameters and nutritional indices of *T. granarium*, different barley cultivars can be divided in four distinct classes: cluster A1, A2, B1, and B2. The grouping within each class might be due to a high level of physiological similarity of barley cultivars. Cluster A1 consisted of the Abidar, Line30, Sahand, and Lokht11 cultivars (partially unsuitable group) and cluster A2 consisted only of Line22 (most relative unsuitable group). Resistance in Line22 could be a result of the higher grain hardiness and the lower protein value. Cluster B1 consisted of Line20 and Sahraa cultivars (partially susceptible group) and cluster B2 consisted of Makuyi and Lisuei cultivars (most relative susceptible group).

In conclusion, the results of the life table parameters and nutritional indices of *T. granarium* reared on ten barley cultivars revealed that the two cultivars of Makuyi and Lisuei were the most suitable (least resistant) diets for *T. granarium* among the tested barley cultivars. The relatively shorter development time and the higher fecundity rate are reflected in the higher intrinsic increase rate of *T. granarium* on these cultivars. The higher intrinsic rate of increase along with higher nutritional indices on respective cultivars would result in a higher population growth that in turn should lead to higher subsequent infestations. In contrast, Line22 cultivar was relatively the least suitable (most resistant) barley cultivar for *T. granarium* and was less preferred by this pest. Information about the quality of barley cultivars and the way in which demographic parameters of *T. granarium* are affected by barley cultivars can help us understand the population dynamics and may assist in the development of better management programs for this pest. In the future studies, *T. granarium* response to digestive enzymatic activity is necessarily recommended for the management of this pest.

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