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Stored-product Insect Pests in Saudi Dates: Host-pest Interactions, Parasitoid Incidence and Implications for Storage Biosecurity

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ABSTRACT

Background: Stored-product insects represent a major biosecurity challenge in agricultural supply chains, including commodities supporting food and feed systems. This study assessed infestation dynamics in Saudi date consignments during the 2023 season to characterize pest species, evaluate cultivar susceptibility and document the occurrence of natural enemies. Ten commercially important date cultivars were examined to identify the pest complex, quantify infestation intensity and link infestation patterns to cultivar traits and storage conditions.

Methods: Detailed assays quantified progeny output of *Oryzaephilus surinamensis* relative to biochemical traits (carbohydrates, fiber, ash, protein, moisture and pH) and assessed the effect of relative humidity (30-90%) on pest reproduction and fruit mass. Incidence of the larval parasitoid Bracon hebetor was recorded as a natural regulatory factor.

Result: The almond moth *Ephestia cautella* was the dominant pest across regions, followed by *O. surinamensis*. Susceptibility varied between cultivars, with Sefri and Shibeibi most affected, whereas Barni and Ruziz were comparatively resistant. Biochemical analysis indicated that high carbohydrate and glucose-fructose dominant profiles favored O. surinamensis reproduction, while higher fiber, ash and moisture negatively correlated with progeny output. Increasing relative humidity enhanced fruit mass; pest reproduction peaked at 70% RH and declined at 90% RH. *B. hebetor* was detected at low frequencies, indicating limited natural suppression in storage environments. Pest prevalence, host biochemical traits and storage humidity jointly influenced infestation outcomes. These findings support integrated pest management strategies to improve storage biosecurity across agricultural supply chains linked to food and feed security.

Key words: Cultivar resistance/susceptibility, Date palm (*Phoenix dactylifera*), *Ephestia cautella*, *Oryzaephilus surinamensis,* Relative humidity (RH), Stored-product pests.

Abbreviations: ANOVA: Analyzed using one-way analysis of variance, AOAC: Association of official analytical chemists, CRD: Completely randomized design, F: First filial generation, HPLC: High-performance liquid chromatography, HSD: Honestly significant difference, IPM: Integrated pest management, KOH: Potassium hydroxide, RH: Relative humidity.

INTRODUCTION

Date palm (*Phoenix dactylifera* L.) is one of the oldest cultivated fruit crops and has been a key agricultural species in the Middle East and North Africa for over 5000 years. In Saudi Arabia, date palms are not only an economic resource but also a cultural and religious symbol, with dates being an essential part of traditional diets and religious observances. The fruit's high energy density, storability and nutritional composition make it a national staple and a globally traded commodity. As part of its Vision 2030 initiative, Saudi Arabia has prioritized the enhancement of date production and export competitiveness.

In 2022, Saudi Arabia ranked among the world's three leading date-producing countries, with more than 33 million palm trees cultivated over ~157,000 ha and an annual production exceeding 1.6 million metric tons (Hassan *et al*., 2025). Similar surveys in other stored agricultural commodities have also shown that storage ecosystems may harbor diverse pest complexes together with associated natural enemies, underlining the importance of system-level pest monitoring in stored products (Harish *et al*., 2018). This production accounts for around 17% of the global date output. Major production zones include Al-Ahsa, Qassim, Al-Madinah, Riyadh, Al-Kharj and Wadi Al-Dawasir. These regions contribute to the diversity of over 400 recognized cultivars, of which about 60 are commercially important. This study prioritizes five common cultivars: Khodri, Ruziz, Hatmi, Shibeibi and Khushram, given their commercial relevance and contrasting physicochemical traits. The five focal cultivars differ in agronomic performance, sugar profiles, fiber/ash content and market preference, providing a suitable contrast for pest-susceptibility analysis (Assirey, 2015).

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Dates are highly nutritious, being rich in sugars, mainly glucose and fructose, alongside dietary fiber, amino acids, vitamins (A, B-complex, C) and essential minerals including potassium, calcium, magnesium and iron (Siddiq and Greiby, 2013; Tang *et al*., 2013). However, their high moisture and sugar content make them prone to insect infestation during postharvest storage. In Saudi Arabia, the most destructive insect pests of stored dates are the almond moth *Ephestia cautella (*Walker) (Lepidoptera, Pyralidae) and the sawtoothed grain beetle *Oryzaephilus surinamensis* (L.) (Coleoptera, Silvanidae), both of which can lead to significant quantitative and qualitative losses (Husain *et al*., 2017; Alwaneen *et al*., 2019). *Ephestia cautella* is notorious for causing internal damage and producing webbing in date packages, while *O. surinamensis* exploits cracks in the fruit to feed on stored sugars and reproduce under optimal humidity conditions. In addition to cultivar characteristics and storage practices, abiotic factors such as temperature and relative humidity strongly influence the population dynamics and development rate of *E. cautella* and other stored-date pests, with higher temperatures generally favoring faster development and higher survival (Alwaneen *et al*., 2019). Moreover, storage biosecurity is becoming increasingly challenging due to the development of resistance to commonly used fumigants and insecticides, increasing regulatory restrictions on pesticide use and residue limits and growing consumer demand for safer and residue-free food products. These limitations reduce the long-term effectiveness of chemical control and highlight the importance of alternative and sustainable strategies, including the use of naturally tolerant cultivars, as a key component of integrated pest management programs in stored date systems.

Several studies have demonstrated that insect pest susceptibility in dates is cultivar-dependent. Husain *et al*. (2017) showed significant differences in the development and fecundity of *E. cautella* on distinct Saudi cultivars, including Khodri, under controlled conditions. Abdel-Banat *et al*. (2024) reported that increased infestation rates are associated with higher storage humidity and prolonged storage duration. Additionally, Latifian *et al*. (2020) found that *O. surinamensis* progeny numbers were strongly correlated with high glucose and fructose levels in dates, while fiber and ash content acted as limiting factors for larval survival. These findings emphasize the role of biochemical composition in mediating pest development and reproductive success and further support the potential of cultivar-related traits as a biologically based resistance mechanism to reduce pest infestation risk. This interpretation is consistent with reports in other stored crop systems showing that susceptibility is strongly influenced by host biochemical characteristics; in particular, higher sugars and proteins tend to favor pest development, whereas phenols and tannins may contribute to resistance (Chaitanya *et al*., 2025).

Although previous studies have provided valuable insights into pest susceptibility and development in dates, few have integrated entomological, physicochemical and environmental data across multiple cultivars and regions under real-world storage conditions. Most research has been confined to laboratory settings, which often do not account for practical variables present in commercial storage, particularly fluctuating humidity and cultivar-dependent susceptibility. To address this gap, the present study was conducted during the 2023 date season to systematically survey insect infestations in date consignments from six major Saudi production regions. It focuses specifically on five commercially relevant cultivars, Khodri, Ruziz, Hatmi, Shibeibi and Khushram, to quantify infestation levels of the two major pests, *E. cautella* (Walker) and *O. surinamensis* (L.) and to compare infestation patterns among cultivars and regions. Natural enemies were detected within the stored-date system, with *Bracon* spp. consistently associated with populations of *E. cautella* infesting stored date fruits. The diversity and relative frequency of the larval ectoparasitoid *Bracon hebetor* (Hymenoptera: Braconidae) was predominant and its occurrence was quantified throughout the survey period. In parallel, fruit proximate composition and physicochemical attributes such as carbohydrates (sugars), protein, fat, fiber, ash and moisture. The study further quantifies how relative humidity modulates pest reproduction in these cultivars under controlled conditions, offering an integrated, multifactorial perspective that links pest biology with biochemical and environmental variables in a commercial storage setting. We predict that differences in infestation risk are partly driven by variation in fruit moisture/water activity and sugar content, as well as cultivar-dependent structural and biochemical resistance traits.

MATERIALS AND METHODS

Sampling and survey of insect pests infesting selected date cultivars in different regions of Saudi Arabia

During the 2023 date season (July to September 2023), a systematic survey was carried out to characterize insect infestations in major date cultivars across key production regions of Saudi Arabia. The surveyed cultivars and regions included: Serri (Wadi Al-Dawasir); Khodri and Khushram (Al-Kharj); Ruziz, Shibeibi and Hatmi (Al-Ahsa); Sefri and Selag (Riyadh); Barni (Al-Madinah); and Shaqri (Al-Qassim). For each cultivar region combination, dates were obtained as composite samples from commercial date storehouses: several sacks were randomly selected within each storehouse and fruits were taken from different positions in each sack (top, middle and bottom) to ensure representativeness. All date samples were collected from commercial storage facilities routinely applying standard pest-management practices, including general sanitation and routine inspection, but without chemical treatment at the time of sampling. No fumigation or insecticidal

intervention had occurred prior to sampling. In these facilities, storage is typically temporary, as dates are subsequently transferred for processing and longer-term storage, so the observed infestation levels reflect typical commercial storage conditions in each region. The subsamples were pooled, thoroughly mixed and then reduced by quartering to obtain batches of approximately 10 kg per cultivar. Each 10 kg batch of each date cultivar was placed in a jute sack, labeled and maintained separately in a clean wooden cabinet at ambient laboratory temperature (24-28°C). For inspection, eight replicates per month (50 date fruits each and four replicates every 15 days) were randomly selected from each lot and examined for infestation both externally and internally using the naked eye and/or a binocular microscope. During inspection, fruits were examined for all visible life stages of the target pests, including larvae, pupae and adults of *E. cautella* and *O. surinamensis*. A fruit was scored as infested when at least one life stage of either species was detected internally or externally, or other insect-related residues were observed. The insect species detected were identified and recorded. The number of infested fruits per species was counted throughout the 3-month survey period and the infestation percentage was reported. In this study, overall infestation (%) was defined as the sum of infestation percentage of fruits infested by the two main pests, *E. cautella* and/or *O. surinamensis*, calculated as:

$$\frac{\text{Number of fruits infested by } \textit{E. cautella} \text{ and/or } \textit{O. surinamensis}}{\text{Total number of fruits examined}} \times 100$$

Sampling inspection and recording of parasitoid

The natural occurrence of parasitoid species was assessed during routine inspection of date fruit samples collected from different storage sites. All date samples were carefully examined under laboratory conditions using a stereomicroscope. Inspections focused on detecting any life stages of *B. hebetor* associated with *E. cautella* larvae or pupae. The frequency of occurrence was calculated as the percentage of samples in which at least one individual or a clear sign of parasitism was recorded relative to the total number of inspected samples.

Preference of *O. surinamensis* for date palm cultivars

Adults of the saw-toothed grain beetle (*O. surinamensis* L.) collected from infested date samples during the field survey were used to evaluate the relative susceptibility of five date cultivars: Khodri, Hatmi, Ruziz, Shibeibi and Khushram. No-choice infestation bioassays were conducted under controlled laboratory conditions using artificial infestation to determine the relative susceptibility of each cultivar. Adults were standardized for age and newly emerged beetles (48-72 h old) were used in all progeny assays to ensure uniform reproductive condition. Each cultivar was infested at a rate of 50 pairs of adult insects per 500 g of dates, with four replicates per cultivar. During the one-week exposure period, all infested samples were maintained at 27±1°C and 70±5% relative humidity. After one week, the adult insects were removed and the samples were then incubated under the same conditions (27±1°C and 70±5% relative humidity) until the emergence of the first generation. The relative humidity was set at 70±5% because this value lies within the upper range reported for non-conditioned date storage environments in Saudi Arabia and provides conditions favorable for *O. surinamensis* development, thereby representing a conservative scenario for comparing cultivar susceptibility under pest-favorable conditions. After adult removal, the jars were incubated until first-generation emergence. Emerged adults were counted and divided by the number of introduced females (assuming 1:1 sex ratio) to calculate progeny per female. Date consumption was measured as the difference between initial and final weights after removing frass and debris. The following parameters were recorded: number of progenies produced per female and the amount of date material consumed during this generation, which reflects the degree of infestation for each cultivar.

Insect infestation and water activity

The effect of moisture content on the infestation and development of *O. surinamensis* was examined using the Ruziz date cultivar. Moisture levels were adjusted by equilibrating date samples at 27±1°C to seven controlled relative humidity (RH) conditions (30, 40, 50, 60, 70, 80 and 90% RH), generated using potassium hydroxide (KOH) solutions in airtight plastic containers following Solomon (1951). Date samples were maintained under each RH condition until moisture equilibrium was achieved prior to insect introduction (≈14 days), in order to standardize initial fruit moisture/water activity and minimize bias in early feeding behavior. For each RH level, 500 g of conditioned dates were placed in glass jars and artificially infested with 50 pairs of adult beetles, with four replicates per treatment. Adults were removed after seven days and the jars were incubated at 27±1°C under their respective RH conditions until the first generation emerged. The developmental period, number of progenies per female (assuming a 1:1 sex ratio) and the amount of date material consumed were recorded to quantify infestation intensity and to determine the moisture conditions most favorable for the growth and reproductive performance of *O. surinamensis* on Ruziz dates.

Proximate composition, sugar analysis and pH measurement of date samples

The proximate composition of the date cultivars was determined using standard Association of Official Agricultural Chemists (AOAC) (2005) methods, including analyses of fiber, ash, carbohydrates, fat, crude protein and nitrogen content. Individual sugars (glucose, fructose and sucrose) were quantified by high-performance liquid chromatography (HPLC) according to Goodall *et al*. (1995) with minor modifications. Briefly, 5 g of pitted date flesh

were homogenized with 50 mL of distilled water, centrifuged and the supernatant was filtered through a 0.45 µm membrane filter. Sugar analysis was performed using an HPLC system (1260 Infinity, Agilent Technologies, Santa Clara, CA, USA) equipped with a refractive index detector and an Aminex HPX-87C column (300 × 7.8 mm; Bio-Rad, Hercules, CA, USA). Deionized water was used as the mobile phase at a flow rate of 0.6 mL/min, with the column temperature maintained at 80°C. Sugars were identified by comparison with authentic standards and quantified using external calibration curves. The pH of date samples was measured according to Mustafa *et al*. (1982) with minor modifications: 4 g of pitted date flesh were mixed with 10 mL of distilled water, vortexed for 5 min, allowed to reach room temperature and then measured using a calibrated digital pH meter (Model 3510, Jenway, Stone, UK) with pH 4.0 and 7.0 buffer standards; measurements were performed in triplicate.

Statistical analysis

Experiments were conducted under a completely randomized design (CRD). Infestation percentages of insect species, laboratory no-choice bioassays (progeny per female, fruit weight loss and consumed date), the relative humidity experiment (progeny per female and consumption), as well as proximate composition, pH, sugar contents and progeny output, were all analyzed using one-way ANOVA with region, cultivar, or humidity level as the fixed factor. Normality and homogeneity of variances were assessed using the Shapiro-Wilk test and Levene's test, respectively, with arcsine transformation applied when necessary. Data were presented as mean±SD based on 24 replicates (infestation data) or 3 replicates (physicochemical analyses). Significant differences ($p<0.05$) were further examined using Tukey's HSD test (Steel and Torrie, 1981). Pearson correlation coefficients were calculated to assess relationships between physicochemical traits and progeny output. Correlation strength was interpreted as strong ($r > 0.8$), moderate ($0.5 < r \leq 0.8$), or weak ($r \leq 0.5$), following the classification of Mukaka (2012). All statistical analyses were performed using IBM SPSS Statistics version 25.0 (IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSION

Assessment of infestation levels in date samples

Insect pests infesting date cultivars across different regions of Saudi Arabia

Infestation by the date moth, *Ephestia cautella*, differed significantly among regions, with the highest levels recorded in Al-Kharj and Al-Qassim and the lowest levels in Al-Madinah. In contrast, infestation by the sawtoothed grain beetle, *Oryzaephilus surinamensis*, was generally low and occurred mainly in Riyadh and Al-Kharj, while remaining minimal in the other regions. Consequently, overall insect infestation showed substantial regional variation and broadly followed the same pattern observed for *E. cautella*. Among natural enemies, the ectoparasitoid wasp *Bracon hebetor* (Hymenoptera: Braconidae) was the only parasitoid detected during inspections and it was recorded attacking *E. cautella* larvae in infested fruits; its occurrence was restricted to a subset of the surveyed regions, as shown in Table 1.

Susceptibility of date cultivars to insect pest infestation

Significant cultivar-dependent differences were observed in infestation intensity by *E. cautella* and *O. surinamensis*. Overall, cultivars such as Sefri and Shibeibi exhibited the highest susceptibility, largely driven by elevated infestation by *E. cautella*. In contrast, Barni and Ruziz consistently showed the lowest infestation levels, indicating comparatively greater resistance under the surveyed storage conditions. Several cultivars (including Khodri, Khush-ram, Serri and Selag) displayed intermediate susceptibility, reflecting moderate levels of infestation. Infestation by *O. surinamensis* remained low across all cultivars and was detected only sporadically, supporting its role as a secondary pest in stored dates. Moreover, minimal non-insect contamination (*e.g.*, mold) was detected across samples. These cultivar-level patterns are summarized in Table 2.

Table 1: Mean percentage of *E. cautella, O. surinamensis* and their natural enemy, *B. hebetor,* infesting date palm cultivars across different regions of Saudi Arabia.

Region	*E. cautella* (%±SD)	*O. surinamensis* (%±SD)	Overall infestation (%±SD)	*B. hebetor* frequency (%)
Al-Ahsa	12.50^{b}±1.48	0.20^{c}±0.30	12.70^{b}±1.76	1.11
Al-Kharj	20.40^{a}±3.01	1.10^{a}±1.60	21.50^{a}±4.72	1.92
Al-Madinah	5.48^{c}±1.23	0.20^{c}±0.34	5.68^{c}±1.50	0.00
Al-Qassim	19.56^{a}±1.68	0.20^{c}±0.67	19.76^{a}±2.08	2.14
Riyadh	15.68^{ab}±1.45	1.90^{a}±1.75	17.58^{a}±2.34	0.00
Wadi Al-Dawasir	9.50^{bc}±1.72	0.30^{bc}±1.61	9.80^{b}±1.96	0.00
F F(df)	9.86* (5, 138)	8.10* (5, 138)	5.50* (5, 138)	
P value	<0.001*	<0.001*	<0.001*	

Values are expressed as mean±standard deviation (SD) (n = 24 replicates, 50 date fruits each). Within each column, means followed by different superscript letters are significantly different at $P \leq 0.05$ based on Tukey's HSD test. F-statistics are reported as $F(df_{between}, df_{within})$.

Preference and susceptibility of date cultivars to *O. surinamensis*

Progeny production of *O. surinamensis* differed significantly among date cultivars, indicating clear variation in host suitability. Cultivars Khodri, Hatmi and Ruziz supported the highest adult emergence per female after one generation, whereas Shibeibi and Khush-ram consistently produced the lowest progeny, reflecting reduced susceptibility. These cultivar-dependent differences in reproductive performance are illustrated in Fig 1.

Weight loss caused by feeding activity of the first-generation offspring of *O. surinamensis* differed among the tested date cultivars (Fig 2). Khodri and Hatmi showed the highest progeny production (11.6 adults/female), followed by Ruziz (11.1 adults/female), whereas Shibeibi and Khush-ram showed lower progeny production (7.6 and 7.5 adults/female, respectively). The corresponding mean weight loss values were 0.35 for Khodri, 0.90 for Hatmi, 0.80 for Ruziz, 0.20 for Shibeibi and 0.17 for Khushram.

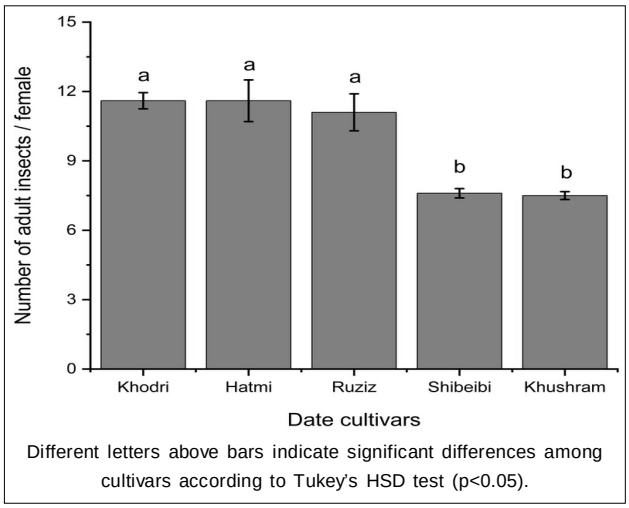


Fig 1: Mean number of adult insects produced per female of *O. surinamensis* reared for one generation on some common date cultivars. Bars represent mean±SD (n = 4).

Effect of water activity on *O. surinamensis* reproduction and weight gain in Ruziz

Fig 3 illustrates the nonlinear effects of relative humidity (RH) on both *O. surinamensis* reproduction and date weight gain. Progeny production remained stable at 30-50% RH (≈7.5-8 insects/female), increased to a maximum at 70% RH (≈11 insects/female) and declined sharply at higher RH, indicating that moderate humidity enhances reproduction while excessive moisture creates unfavorable conditions. In contrast, date weight increased steadily with RH, reaching its highest at 90% RH (≈20%), reflecting the hygroscopic nature of dates and the facilitative effect of insect activity on moisture uptake. The relationship shows partial coupling: moderate moisture gain enhances insect suitability, but further weight increases do not boost progeny production. Overall, controlling RH is critical during date storage to balance insect infestation risk and fruit quality preservation.

Proximate composition, pH and reproductive performance of *O. surinamensis* of date samples

Marked cultivar-dependent variation was observed in proximate composition, pH and reproductive performance of *O. surinamensis* (Table 3). Overall, Khodri, Ruziz and Hatmi supported the highest progeny output per female, indicating that these cultivars are comparatively more suitable hosts under the tested conditions. In contrast, Shibeibi and Khushram exhibited significantly reduced progeny production, suggesting lower host suitability and a degree of natural resistance.

Differences in reproductive success were closely aligned with cultivar chemistry. Higher progeny output was associated with lower fiber and ash contents, whereas cultivars characterized by higher fiber and mineral (ash) levels tended to suppress reproduction. The correlation analysis supports this pattern, showing strong negative

Table 2: Mean percentage of insect pest infestation in some date cultivars.

Cultivar	*E. cautella* (%±SD)	*O. surinamensis* (%±SD)	Overall infestation (%±SD)
Barni	6.14^{c}±1.23	0.00^{c}±0.00	6.14^{d}±1.51
Hatmi	9.16^{c}±1.05	0.18^{c}±0.55	9.34^{cd}±1.16
Khodri	18.50^{bc}±1.77	0.84^{b}±0.72	19.34^{bc}±2.07
Khushram	18.84^{bc}±1.99	0.50^{b}±0.95	19.34^{bc}±2.18
Ruziz	7.84^{c}±1.19	0.00^{c}±0.00	7.84^{cd}±1.21
Selag	11.06^{bc}±2.12	0.18^{c}±0.30	11.24^{bcd}±1.44
Serri	15.66^{bc}±2.78	0.00^{c}±0.00	15.66^{bcd}±2.34
Sefri	24.90^{a}±5.80	0.52^{a}±0.10	25.42^{a}±5.89
Shibeibi	22.34^{ab}±3.13	0.16^{c}±0.49	22.50^{b}±3.23
Shaqri	9.22^{c}±1.65	0.58^{a}±0.20	9.80^{bcd}±1.77
F F(df)	148.74* (9, 230)	*9.84 (9, 230)**	154.34* (9, 230)
P value	<0.001*	<0.001*	<0.001*

Values are presented as mean±standard deviation (SD) (n = 24 replicates, 50 date fruits each). Within each column, means followed by different superscript letters are significantly different at P≤0.05 based on Tukey's HSD test. F-statistics are reported as F ($df_{between}$, df_{within}).

relationships between progeny production and fiber, ash and moisture content, while positive correlations were observed with carbohydrate, protein and pH. These relationships suggest that nutritional quality and matrix structure jointly shape beetle performance, where increased fiber/mineral content may reduce feeding efficiency and/or nutrient assimilation, ultimately limiting progeny production. Although larval mortality was not quantified separately, the observed reduction in adult progeny likely reflects constraints on larval development and survival within less suitable fruit matrices.

Taken together, these findings provide mechanistic evidence that biochemical composition contributes to cultivar-specific susceptibility to *O. surinamensis*. From an applied perspective, cultivars showing lower beetle reproductive performance (*e.g.*, Shibeibi and Khushram)

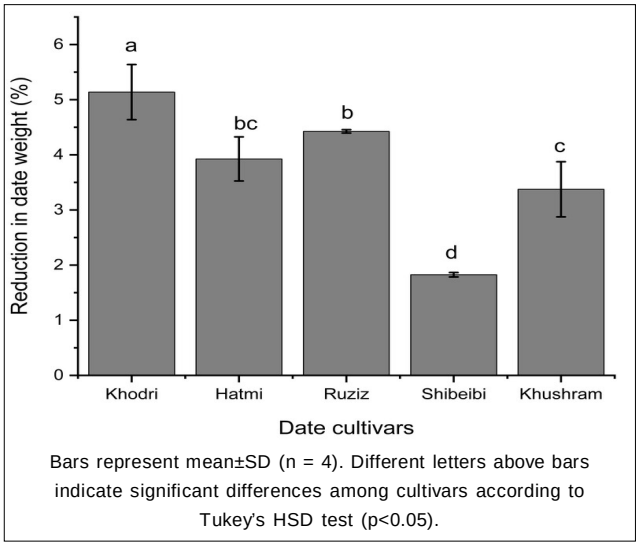


Fig 2: Percentage reduction in date weight resulting from feeding of the first generation produced from 100 adults of *O. surinamensis.*

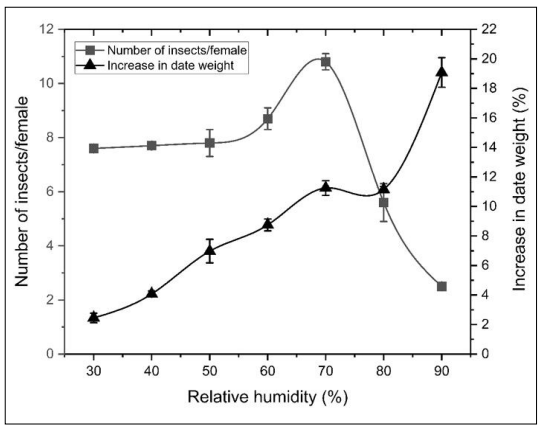


Fig 3: Percentage increase in the weight of Ruziz dates and mean number of adult *O. surinamensis* produced per female at different relative humidity levels after two months of storage.

Table 3: Proximate composition, pH and reproductive performance of *O. surinamensis* of date samples.

Cultivar	Fiber±SD% of dry weight	Ash±SD% of dry weight	Moisture±SD% of dry weight	Carbohydrate% of dry weight	Protein% of dry weight	Fat % of dry weight	pH±SD	Progeny/ female
Khodri	2.1^{a}±0.2	1.9^{a}±0.1	12.5^{b}±0.6	82.12^{b}±0.85	2.23^{b}±0.23	0.11^{a}±0.1	6.10^{ab}±0.10	11.6^{a}±2.11
Ruziz	2.4^{a}±0.3	2.2^{a}±0.2	13.4^{c}±0.7	81.41^{a}±0.35	2.23^{b}±0.20	0.135^{b}±0.01	6.00^{ab}±0.12	11.1^{a}±1.89
Hatmi	2.3^{a}±0.2	2.0^{a}±0.1	13.8^{c}±0.8	82.12^{b}±0.21	2.98^{c}±0.1	0.125^{b}±0.01	5.90^{ab}±0.11	11.6^{a}±2.12
Shibeibi	3.7^{b}±0.3	3.0^{b}±0.2	11.2^{a}±0.5	83.91^{c}±0.49	2.26^{b}±0.12	0.15^{c}±0.01	5.60^{b}±0.10	7.6^{b}±1.21
Khushram	4.1^{b}±0.4	3.4^{b}±0.3	10.6^{a}±0.5	86.23^{d}±0.14	0.97^{a}±0.12	0.11^{a}±0.01	5.50^{b}±0.10	7.5^{b}±1.4
Correlation with progeny output (r)	-0.91	-0.92	-0.95	0.94	0.74	0.62	0.88	-
FF(df)	29.71* (4, 10)	34.73* (4, 10)	14.32* (4, 10)	49.65* (4, 10)	59.93* (4, 10)	8.77* (4, 10)	17.78* (4, 10)	4.29* (4, 10)
P value	<0.001*	<0.001*	0.001*	<0.001*	<0.001*	0.003*	<0.001*	0.028*

Values are presented as mean±standard deviation (SD) (n = 3). Within each column, means followed by different superscript letters are significantly different at P≤0.05 based on Tukey's HSD test. F-statistics are reported as F ($df_{between}$, df_{within}).

may be prioritized in cultivar-based postharvest integrated pest management programs, while more susceptible cultivars (*e.g*., Khodri, Ruziz and Hatmi) may require stricter storage hygiene and humidity control to minimize secondary pest establishment.

Sugar analysis of date samples

Sugar profiling revealed clear cultivar-dependent differences in the relative proportions of glucose, fructose and sucrose, with monosaccharides dominating most cultivars and sucrose generally absent or present only at trace levels. Overall, Khodri was distinguished by comparatively higher glucose alongside substantial fructose, whereas Ruziz and Hatmi were characterized by fructose-rich profiles. Shibeibi showed a minor but detectable sucrose fraction, while Khushram exhibited the lowest glucose level among the tested cultivars.

These sugar patterns provide mechanistic support for the cultivar-specific performance of *O. surinamensis*. Cultivars exhibiting higher monosaccharide availability (glucose and/or fructose) tended to support greater reproductive output, consistent with the role of readily assimilable sugars in enhancing palatability and energy supply for development and fecundity. In contrast, cultivars with comparatively lower glucose and/or detectable sucrose were associated with reduced progeny production, suggesting lower nutritional suitability and/or altered feeding efficiency. Collectively, the sugar profiles corroborate the observed differences in cultivar susceptibility and reinforce the importance of biochemical composition as a practical component of cultivar-based postharvest risk management as shown in Table 4.

The present study demonstrates that insect pest infestation in stored Saudi date cultivars is governed by interaction among regional storage conditions and cultivar-specific physicochemical characteristics. Across all surveyed regions, *Ephestia cautella* clearly emerged as the predominant postharvest pest, corroborating earlier reports that consistently identify this species as the principal insect threat to stored dates in the Middle East (Husain *et al*., 2017; Alwaneen *et al*., 2019; Sukirno *et al*., 2021). The widespread dominance of *E. cautella* highlights its strong adaptation to date fruits and storage environments typical of arid and semi-arid regions. Marked regional variation in infestation levels was observed, with significantly higher overall infestation in Al-Kharj and Al-Qassim compared with Al-Madinah. These patterns are strongly associated with the warmer climates' characteristic of central Saudi Arabia, which have been shown to accelerate development, increase survival and enhance reproductive capacity of *E. cautella* (Sukirno *et al*., 2021; Berhe *et al*., 2022). Spatial patterns of infestation have been documented previously in Saudi Arabia and neighboring regions (Abo El Saad and El Shafie, 2013), reinforcing the consistency of this relationship.

In parallel with pest monitoring, the survey also documented natural enemies when encountered. *Bracon hebetor* (Say) is a well-known solitary ectoparasitoid of late-instar lepidopteran larvae and is widely recognized as an effective biological control agent against several stored-product moths, including *E. cautella*. The parasitoid attacks host larvae by paralyzing them and ovipositing externally on the host body, with larval development completed outside the host integument. The detection of this parasitoid, even at low frequency, confirms the existence of natural biological regulation within storage ecosystems and highlights its potential contribution to suppressing pest populations under favorable conditions. Comparable studies in other crop systems have likewise shown that documenting the abundance and diversity of natural enemies is important for developing biologically based pest-management programs and for strengthening IPM under storage or postharvest conditions (Roy *et al*., 2024).

While the infestation by the sawtoothed grain beetle (*Oryzaephilus surinamensis*) remained very low across all regions, with the highest levels recorded only in Riyadh and Al-Kharj. This limited and uneven distribution supports the interpretation that O. *surinamensis* functions as a secondary pest in stored dates, primarily exploiting fruits that are already damaged. Such behavior suggests that beetle occurrence is more closely linked to postharvest handling practices and storage conditions rather than field infestation, in agreement with Berhe *et al*. (2022) and

Table 4: Sugar analysis of date samples.

Date cultivar	Glucose±SD% of dry weight	Fructose±SD% of dry weight	Sucrose±SD% of dry weight	Progeny/female trend
Khodri	35.51^{c}±1.14	32.35^{a}±1.32	ND	High (11.6)
Ruziz	17.63^{b}±0.89	55.83^{b}±2.31	ND	High (11.1)
Hatmi	19.34^{b}±0.78	$72.24^{d±}$4.12	ND	High (11.6)
Shibeibi	16.64^{b}±0.56	64.49^{c}±2.12	2.96±0.88	Low (7.6)
Khushram	7.74^{a}±0.84	62.79^{c}±3.3	ND	Low (7.5)
F F(df)	409.59* (4, 10)	88.37* (4, 10)		
P value	<0.001*	<0.001*		

Values for glucose, fructose and sucrose are expressed as a percentage of dry weight (% DW). Progeny/female values are the mean number of adults per female. Data are presented as mean±standard deviation (SD) (n = 3). Within each column, means followed by different superscript letters are significantly different at p≤0.05 based on Tukey's HSD test. F-statistics are reported as F ($df_{between}$, df_{within}). ND: Not detected (Value below the HPLC detection limit.

Latifian *et al*. (2020), who reported reduced beetle performance under controlled storage environments.

In addition to regional factors, cultivar-dependent susceptibility played a decisive role in determining infestation intensity. Cultivars exhibiting higher infestation levels, such as Sefri and Shibeibi, likely possess physicochemical attributes such as higher sugar availability, softer texture, or lower fiber content that facilitate larval penetration and development. Similar associations between fruit softness, moisture and susceptibility to internal feeders have been reported by Phillips and Throne (2010). Conversely, cultivars such as Barni and Ruziz displayed lower infestation levels, suggesting that increased firmness or less favorable chemical composition may confer partial resistance, consistent with observations by Rather *et al*. (2021). This resistance likely results from combined structural and biochemical factors, including relatively higher fiber and mineral contents, which may reduce feeding efficiency, impair nutrient assimilation and limit larval development. Increased fiber content can act as a physical barrier that restricts larval penetration and feeding, while mineral components may interfere with digestive processes or reduce palatability, ultimately lowering insect reproductive success. In addition to these structural constraints, phenolic compounds (including condensed tannins and other polyphenols) may further contribute to the comparatively resistant behavior of cultivars such as Barni and Ruziz. Phenolics are widely recognized as anti-feedant and growth-inhibitory metabolites in plant–insect interactions; they can reduce palatability, bind dietary proteins and inhibit digestive enzymes, thereby decreasing nutrient utilization and larval performance. Therefore, the lower infestation observed in Barni and Ruziz may reflect the additive (or synergistic) effects of a fiber-based physical barrier together with phenolic/tannin-mediated biochemical deterrence, ultimately reducing insect establishment and population growth.

Intermediate susceptibility observed in several cultivars aligns with earlier findings by Duble (1996) and Abbas *et al*. (2014), indicating that resistance is not absolute but exists along a continuum shaped by multiple fruit traits. The consistently low infestation of *O. surinamensis* across cultivars further emphasizes its secondary pest status, as previously highlighted by Hashem *et al*. (2021) and reflects its preference for already damaged fruits. These findings further support the concept that cultivar resistance in stored dates is a quantitative trait influenced by multiple interacting physicochemical and structural characteristics rather than a single determinant factor.

Environmental factors within storage facilities further modulated infestation patterns. Relative humidity (RH) emerged as a critical variable, as elevated RH not only accelerates physical deterioration of dates but also prolongs insect survival and reproductive potential (Kamal-Eldin *et al*., 2020; Abo-El-Saad *et al*., 2024; Zhang *et al*., 2025). These findings underscore the importance of RH management as a key component of postharvest protection strategies aimed at balancing fruit quality preservation with pest suppression. Additionally, excessive moisture may alter fruit matrix structure and microbial interactions, which can indirectly influence insect development and survival. This broader postharvest perspective agrees with previous reviews emphasizing that storage environment, packaging, pest control measures and general postharvest handling practices are central determinants of quantitative and qualitative losses during storage (Yimer, 2022).

Biochemical composition also exerted a strong influence on pest performance. Cultivars with higher glucose content supported greater insect development, consistent with studies showing that nutrient-rich substrates enhance stored-product insect growth and fecundity (Adamaki-Sotiraki *et al*., 2025). In contrast, higher fiber and mineral (ash) contents appeared to reduce feeding efficiency and progeny production, supporting the deterrent effects reported by previous authors (Alotaibi *et al*., 2019). Moisture and pH exerted comparatively minor effects, suggesting that nutritional quality outweighs these factors in determining host suitability. These biochemical characteristics provide a mechanistic explanation for the observed resistance patterns in cultivars such as Ruziz, where the combined effects of structural complexity and nutritional balance reduce insect fitness and population establishment.

Sugar composition provided further mechanistic insight into cultivar susceptibility. Cultivars with lower glucose levels and minimal sucrose content, such as Khushram, were less favorable for insect development, aligning with findings by Sheng *et al*. (2019), who demonstrated that sugar profiles significantly influence larval growth and infestation intensity. Overall, the resistance observed among certain cultivars appears to result from the integrated effects of physicochemical structure, nutrient composition and environmental interactions, which collectively determine host suitability and pest population dynamics.

CONCLUSION

This study shows that insect infestation in stored Saudi dates is largely driven by cultivar type and storage humidity. Across six production regions, *Ephestia cautella* was the main insect pest, while *Oryzaephilus surinamensis* occurred at lower levels, with Sefri and Shibeibi being highly susceptible, while Barni and Ruziz were comparatively tolerant. This tolerance is likely associated with physicochemical and structural characteristics, including higher fiber and mineral content and less favorable nutritional composition, which reduce insect feeding efficiency, impair development and limit reproductive success. Laboratory assays revealed that high beetle progeny was associated with elevated carbohydrates and sugars, whereas higher fiber, ash and moisture reduced reproduction and that *O. surinamensis* populations peaked at 70% relative humidity and declined at 90% RH.

The occasional detection of the parasitoid *Bracon hebetor* suggests scope for enhancing biological control. Overall, the findings support integrated pest management strategies that combine selection of less susceptible cultivars, improved humidity management and conservation of natural enemies to reduce losses and reliance on chemical control in date storage systems. These results highlight the importance of cultivar selection as a sustainable and biologically based strategy for improving storage biosecurity and reducing pest-related losses.

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Author contributions

Nawal Abdulaziz Alfuhaid: Conceptualization; methodology; software; validation; formal analysis; investigation; resources; data curation; writing-original draft preparation; writing-review and editing; visualization; supervision; project administration; funding acquisition. The author has read and agreed to the published version of the manuscript.

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Informed consent statement

Not applicable. No human participants were involved in this study.

Data availability statement

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare no conflicts of interest.

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