



RESEARCH

Effects of caprifig disinfection on *Aspergillus* transmission, wasp survival and fig quality

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Abstract

Aspergillus flavus is a major contaminant of figs, producing aflatoxins that pose serious risks to human health and reduce fruit quality. This study investigated the role of caprifig disinfection in controlling fungal transmission to edible figs (*Ficus carica* cv. Sabz) and assessed its effect on pollinating wasps (*Blastophaga psenes* L.) and fruit attributes. A factorial experiment was conducted using three caprifig cultivars (Pouzdonbali, Daneh-Sefid, and Koochi) under five treatments: (i) uninoculated and disinfected with mancozeb, (ii) uninoculated and without disinfection, (iii) inoculated with *A. flavus* and disinfected, (iv) inoculated but not disinfected, and (v) Control (Neither injecting nor water spraying). The results showed that figs inoculated with *A. flavus* without disinfection exhibited the highest levels of pulp and skin contamination, accompanied by reduced wasp survival and increased syconium abscission. Mancozeb disinfection reduced pulp fungal contamination, increased female wasp survival, and decreased syconia abscission by 21.1, 36.9 and 21.05% compared with the non-disinfected treatment, respectively. The Daneh-Sefid caprifig positively influenced fruit size and skin color, thereby enhancing marketability. Overall, these findings indicate that targeted fungicide application on caprifig syconia can partially suppress *A. flavus* contamination while maintaining pollination efficiency and fruit quality. However, further studies are required to evaluate the feasibility of wasp-transmissible biocontrol agents as an alternative management strategy.

Keywords *Blastophaga* · *Ficus* · Fungal contamination · Pollinator · Syconium

1 Introduction

Ficus carica L., belonging to the family Moraceae that originated primarily in West Asia and subsequently spread throughout the Mediterranean region (Gündeşli et al. 2020). Iran is currently the third-largest producer of dried figs and the fifth-largest producer of fresh figs worldwide, with a harvested area of 15,072 ha and a total production of 67,860.55 tons (FAO 2024).

The fig is a compound fruit (syconium type) with an ostiole partially sealed by scales. Its development follows a double sigmoid growth curve. Based on cropping behavior and caprification requirements, figs are classified into four horticultural types: common, San Pedro, Smyrna, and caprifig. Among these, Smyrna and San Pedro figs require pollination by the fig wasp (*Blastophaga psenes* L.) to produce the main crop (Flaishman 2022). The predominant cultivar cultivated in Estahban, Iran, belongs to the Smyrna type, and relies on *B. psenes* entering the ostiole for successful pollination. In addition to Sabz cultivar from Iran, other globally important dried fig cultivars,

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such as Sarilop from Turkey and Zaidi from Tunisia, are also Smyrna-type figs, for which pollination and fertilization are essential for achieving high fruit quality (Özer 2022). Pollen needed for fertilization of Smyrna figs is supplied by the syconia of caprifigs, and caprification occurs when *B. psenes* transfers pollen from caprifigs to edible figs.

However, *Blastophaga* wasps can inadvertently act as vectors of *Aspergillus* fungi (Farjood and Banihashemi 2012). The most critical periods for fungal transmission occur when wasps move from overwintering mamme syconia to profichi syconia of caprifigs, and subsequently from profichi to edible fig syconia during caprification (Özer 2022). For this reason, caprifig syconia considered a primary source of *Aspergillus* infection transmitted by *Blastophaga* wasps are often disinfected with fungicides (Michailides et al. 1996). Spores of *Aspergillus flavus* may adhere to the spines of the wings or body surfaces of wasp at infected sites. When these wasps enter caprifig cavities, they introduce fungal spores, which germinate on the stigmas of caprifig flowers and persist until the emergence of the next wasp generation. Consequently, caprifig syconia serve as reservoirs of *A. flavus* spores, that are subsequently carried into edible figs during pollination. Although the spores remain relatively quiescent on stigmas during early fruit development, they proliferate rapidly during ripening, leading to smut formation (Flaishman et al. 2022). Moreover, *A. flavus* is capable of producing aflatoxins in figs at multiple stages, including ripening, drying, and storage (González-Curbelo and Kabak 2023).

Consumption of aflatoxin-contaminated figs poses serious health risks, including hepatocarcinogenic effect, acute aflatoxicosis, and even mortality in humans (Cobanoglu et al. 2010). Economically, *A. flavus* contamination causes substantial yield and quality losses. Control of fungal decay in figs is particularly challenging because infections are predominantly internal. Therefore, preventing contamination of edible figs through disinfection of caprifig syconia has been proposed as a promising management strategy. Approaches such as fungicide application to caprifig syconia and biocontrol methods have shown partial success in reducing internal contamination of caprifig cultivars in California (Michailides et al. 2008). Nevertheless, information on managing fungal contamination in caprifig genotypes from other regions remains limited.

Thus, effective control of fungal contamination in caprifig syconia, together with evaluation of fungicide side effects on pollinating wasps and edible fig quality, represents a major challenge. The objectives of the present study were to (i) reduce the transmission of *A. flavus* from caprifigs to edible figs via *Blastophaga* wasps and

(ii) evaluate the side effects of control measures on wasp survival and fig fruit quality.

2 Materials and methods

2.1 Location of the experiment

The experiment was conducted at the Fig Research Station (29°06'52" N, 54°04'27" E, 1760 m altitude), Estahban, Iran. The average annual precipitation in the study area is 272 mm, with a mean annual temperature of 16.8 °C and an average relative humidity of 37.5%.

2.2 Plant material and treatments

Syconia of three caprifig cultivars Pouzdonbali, Daneh-Sefid, and Koochi (Fig. 1) were used as pollinators for the



Fig. 1 Syconia of three caprifig cultivars Pouzdonbali, Daneh-Sefid, and Koochi

caprification of fig cv. Sabz. The experiment was conducted as a factorial trial in a randomized complete block design with three replication and two factors:

- Factor A: Caprifig cultivar (1: Pouzdonbali, 2: Daneh-Sefid, 3: Koochi).
- Factor B: Pathogen inoculation and fungicide treatment:
 1. Uninoculated caprifigs disinfected with mancozeb (only water was injected into syconium)
 2. Uninoculated caprifigs without mancozeb disinfection (Water was injected into syconium and sprayed on syconia)
 3. Caprifigs inoculated with *Aspergillus flavus* and disinfected with mancozeb.
 4. Caprifigs inoculated with *A. flavus* but not disinfected with mancozeb (Water was sprayed on syconia)
 5. Control (Neither injecting nor spraying of water)

At the end of May, six uniform fig trees, equally spaced, were selected. On each tree, 15 branches (Two branches as an experimental unit) with similar size and distance from the crown were marked and enclosed with a fine mesh net (0.1 mm). The netting prevented escape of *Blastophaga* wasps, ensuring controlled pollination. In June, when profichi syconia of the caprifigs ripened, two syconia were placed in each treatment unit.

2.3 Preparation of fungal suspensions

An active culture of *A. flavus* (accession number IBRC-m30029) was obtained from the National Centre for Genetic and Biological Resources, University of Tehran. To prepare the inoculum, the fungus was first cultured on potato dextrose agar (PDA) and subsequently transferred to a 300 ml Erlenmeyer flask containing liquid PDA, then incubated at 22–24 °C for two weeks. Conidia were harvested by adding 45 ml of Tween-80 solution to the culture and gently agitating the suspension to release spores. The mixture was centrifuged, and the resulting spore pellet was resuspended in 300 µl of sterile distilled water. The spore concentration of the suspension was determined using a hemocytometer and adjusted to approximately 1×10^6 conidia mL⁻¹ (Buchanan et al. 1975).

2.4 Inoculation of caprifigs with *A. flavus*

Under sterile condition, 20 µl of the *A. flavus* spore suspension was inoculated into the syconium of each caprifig through the ostiole using a micropipette without causing



Fig. 2 Spore suspension was inoculated into the syconium of caprifig cultivars

mechanical injury (wound). For the control, 20 µl of sterile distilled water was applied (Fig. 2). Treated syconia were placed in paper cups sealed with cellophane and stored at 4 °C for 20 h to allow spore germination. This low temperature also prevented premature emergence of *Blastophaga* wasps without harming them.

Fungal growth in all inoculated syconia was confirmed microscopically. Inoculation was performed early in the morning (before 9:00 AM) to prevent wasp escape, which increases under warmer conditions.

2.5 Disinfection with mancozeb fungicide

Caprifig syconia were placed in sterilized paper cups covered with 0.1 mm mesh. Mancozeb solution (2 g L⁻¹) prepared based on label recommendations, was applied at a rate of approximately 1 mL per three caprifig syconia.

2.6 Caprification, and sample collection

Caprifigs syconia were transferred to branches of Sabz fig trees enclosed in nets. The duration of caprification was determined based on fruit diameter, stigma color, esterase



Fig. 3 Dead female *Blastophaga* wasps in pulp



Fig. 4 Dead female *Blastophaga* wasps in drupelets

activity, tissue softness, and ostiole opening. Two caprifig syconia were placed in each net for one pollination cycle. Four caprification periods were conducted over four consecutive weeks, from 1 to 28 June.

Following pollination, the 0.1 mm mesh was replaced with 0.8 mm mesh to improve ventilation. Caprification typically lasted 30 days. Fruits were harvested at the dried stage, under strict hygienic conditions. Dried fruits were collected

in each net, packed in UV-sterilized zip-lock bags, and stored at 4 °C until analysis.

2.7 Mortality of *blastophaga* wasps

The percentage of dead female *Blastophaga* wasps in pulp (Fig. 3) and drupelets (Fig. 4) was calculated using the following formulas:

$$\text{the percentage of dead female blastophaga wasp in the pulp} = \frac{\text{the dead female wasps number in the pulp}}{\text{Total number of live female wasps} + \text{dead female wasps in pulp and drupelet}} \times 100$$

$$\text{the percentage of dead female blastophaga wasp in the drupelet} = \frac{\text{the dead female wasps number in the drupelet}}{\text{Total number of live female wasps} + \text{dead female wasps in pulp and drupelet}} \times 100$$

2.8 Survival of female wasps

To estimate female wasp survival, syconia from each treatment were placed in separate paper cups covered with plastic, and were not used directly for pollination on the trees. The number of female wasps emerging from these syconia was counted and considered as an estimate of the potential number of wasps available for pollination from similarly treated syconia. A key methodological limitation

should be noted: the number of live female wasps successfully emerging from the syconia used for actual pollination (those placed inside mesh bags on tree branches) could not be directly counted, as the wasps dispersed freely within the nets after emergence. Therefore, wasp survival was estimated indirectly using a parallel set of syconia and may not precisely represent the true survival rate within the syconia used for caprification.

The percentage of live female *Blastophaga* wasps was calculated using the following equation:

$$\text{the percentage of alive female blastophaga wasp} = \frac{\text{the number of live female wasps}}{\text{Total number of live female wasps} + \text{dead female wasps in pulp and drupelet}} \times 100$$

2.9 Syconia abscission percentage

Syconia abscission was assessed by counting the number of unpollinated and shed syconia of edible fig cv. Sabz and

expressed as a percentage. The percentage of syconia abscission was calculated as follows:

$$\text{The percentage of the syconium abscission} = \frac{\text{number of abscised syconia}}{\text{total number of syconia}} \times 100$$

2.10 Fruit quality evaluation

Fruit quality was evaluated based on ostiole-end opening, fruit size, and skin color.

- **Ostiole-end opening:** Dried fruits were categorized as open or closed by a panel of two evaluators. Fruits were classified as open when a visible gap (>0.5 mm) at the ostiole allowed visual confirmation of the internal cavity. This classification is consistent with commercial grading standards in the dried fig market.
- **Fruit size:** The diameter of each dried figs was measured at its widest point using a digital caliper. Fruits with a diameter > 23 mm were classified as large, while fruits ≤ 23 mm were classified as small.
- **Skin color:** Fruit skin color was evaluated using a standardized reference color chart for dried figs (Yellow and Brown). Fruits were assigned to a color category based on predominant skin hue when more than 90% visual agreement was reached between evaluators. For all quality traits, results for each treatment were expressed as the percentage of fruits falling into each category.

2.11 Fungal contamination of fruits

Skin and pulp tissue segments (approximately 1 × 1 mm) were cultured on PDA and incubated at 22–25 °C for 5 days. Emerging fungal colonies were identified microscopically.

2.12 Statistical analysis

Data were analyzed using ANOVA with SAS software (version 9.4). Mean comparisons were performed using Fisher's least significant difference (LSD) test at a significance level of $P < 0.05$.

3 Results

3.1 Mortality of female *Blastophaga* wasps

The highest mortality of female *Blastophaga* was recorded in drupelets of syconia from Koochi caprifig cultivar when syconia were inoculated with *A. flavus* but not disinfected. In contrast, the lowest mortality was observed in Pouzdombali syconia

Table 1 Effect of caprifig cultivar and treatment on dead percentage of female wasp in drupelet and pulp of caprifig syconium

Caprifig	Treatment	Dead wasp in drupelet (%)	Dead wasp in pulp (%)
Pouzdonbali	uninoculated and disinfected with mancozeb	5.6 [*]	7.5 ^{fg}
	uninoculated and without disinfection	26.1 ^{cd}	18.4 ^{cd}
	inoculated with <i>A. flavus</i> and disinfected	26.3 ^{cd}	16.2 ^d
	inoculated but not disinfected	41.0 ^b	27.1 ^{ab}
	Control (Neither injection nor spraying of water)	5.3 ^f	10.8 ^{ef}
Daneh-Sefid	uninoculated and disinfected with mancozeb	14.3 ^e	6.9 ^g
	uninoculated and without disinfection	22.5 ^d	17.5 ^d
	inoculated with <i>A. flavus</i> and disinfected	30.2 ^c	15.7 ^d
	inoculated but not disinfected	31.5 ^c	25.6 ^b
	Control (Neither injection nor spraying of water)	7.7 ^f	10.8 ^{ef}
Koochi	uninoculated and disinfected with mancozeb	14.7 ^e	9.5 ^{efg}
	uninoculated and without disinfection	15.0 ^e	21.0 ^c
	inoculated with <i>A. flavus</i> and disinfected	31.3 ^c	16.9 ^d
	inoculated but not disinfected	50.6 ^a	29.3 ^a
	Control (Neither injection nor spraying of water)	10.8 ^{ef}	11.7 ^e

^{*}Means with the same letters in each column are not significantly different using LSD Fisher test at $p \leq 0.05$

Fig. 5 Effect of caprifig cultivar and treatment on live female *Blastophaga* wasp emerging from caprifig syconium. (1) uninoculated and disinfected with mancozeb, (2) uninoculated and without disinfection, (3) inoculated with *A. flavus* and disinfected, (4) inoculated but not disinfected, and (5) Control (Neither injection nor spraying of water)

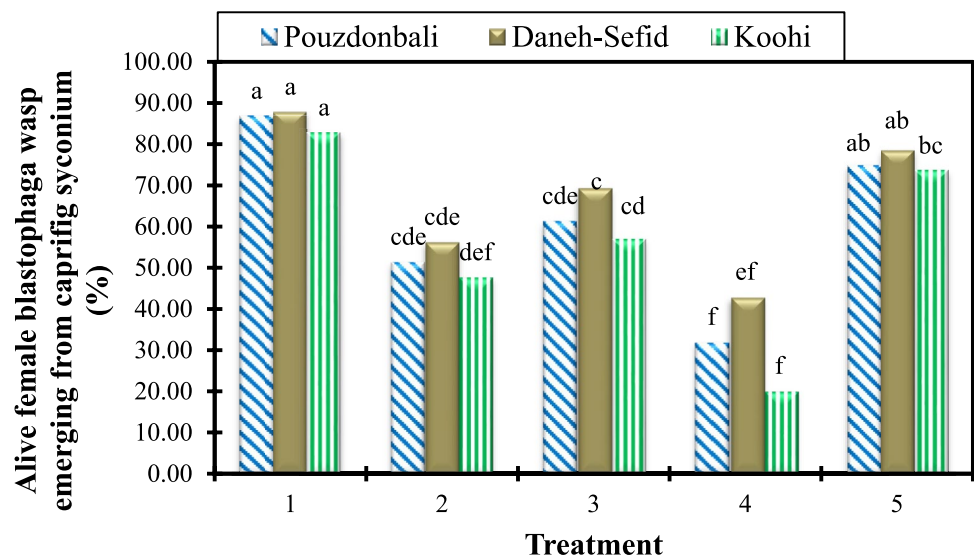
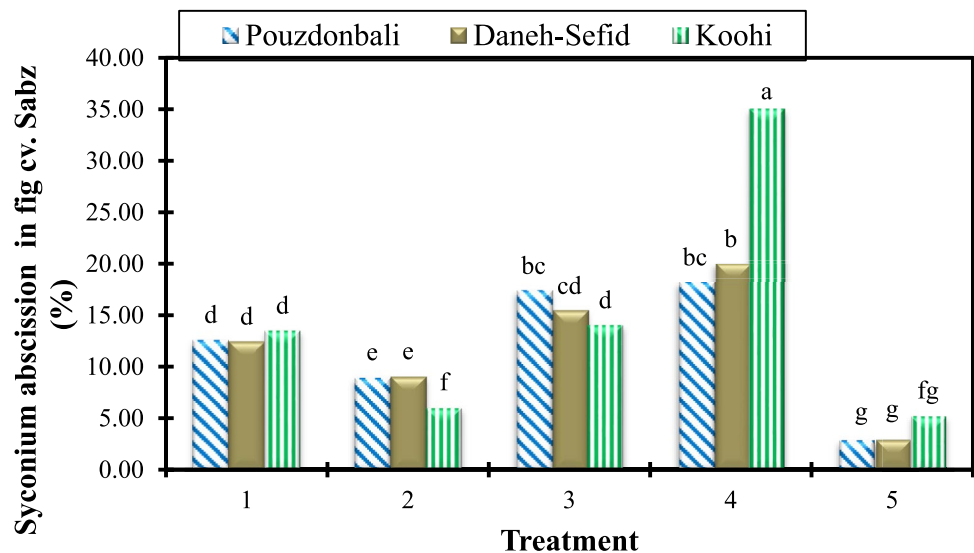


Fig. 6 Effect of cultivar and treatment on syconium abscission in fig cv. Sabz. (1) uninoculated and disinfected with mancozeb, (2) uninoculated and without disinfection, (3) inoculated with *A. flavus* and disinfected, (4) inoculated but not disinfected, and (5) Control (Neither injection nor spraying of water)



without inoculation and fungicide application. However, these differences were not statistically significant with uninoculated and mancozeb-disinfected Pouzdonbali syconia or with the control treatments of the other two caprifig cultivars (Table 1).

In the pulp, mortality of female wasps was highest in Koohi and Pouzdonbali syconia subjected to inoculation with *A. flavus* without disinfection, whereas the lowest mortality was observed in Daneh-Sefid syconia that were uninoculated and disinfected with mancozeb (Table 1).

3.2 Survival of female wasps

Survival of female wasps was reduced in the inoculated but non-disinfected treatment across all three caprifig cultivars. In contrast, the highest survival rates were recorded in the uninoculated and mancozeb-disinfected treatment for all cultivars (Fig. 5).

3.3 Syconia abscission

The highest percentage of syconia abscission in Sabz Fig. (35.07%) occurred when pollination was performed using Koohi syconia that were inoculated with *A. flavus* but not disinfected. The lowest abscission percentage was recorded in control treatment (Neither injection nor spraying of water). However, differences among caprifig treatments were not statistically significant ($P < 0.05$) (Fig. 6).

3.4 Fruit quality

The highest proportion of fruits with open ostioles in Sabz Figs. (39.9%), a trait considered commercially favorable in Iran, was observed when pollination was performed using Daneh-Sefid syconia that were uninoculated and disinfected with mancozeb. However, caprifig under this treatment

Table 2 Effect of caprifig cultivar and treatment on fruit percentage with close ostiole, open ostiole, yellow skin, brown skin, large size, and small size in fig cv. Sabz

Caprifig	Treatment	Open Ostiole (%)	Close Ostiole (%)	Yellow Skin (%)	Brown Skin (%)	Large Size (%)	Small Size (%)
Pouzdonbali	uninoculated and disinfected with mancozeb	25.6 ^{b*}	74.4 ^f	47.9 ^b	52.1 ^g	29.1 ^b	70.9 ^g
	uninoculated and without disinfection	10.2 ^{d-g}	89.8 ^{a-d}	30.3 ^f	69.7 ^c	16.2 ^{fg}	83.8 ^{bc}
	inoculated with <i>A. flavus</i> and disinfected	22.6 ^b	77.4 ^f	38.5 ^d	61.5 ^e	25.5 ^{bcd}	74.5 ^{efg}
	inoculated but not disinfected	8.3 ^{fg}	91.7 ^{ab}	22.5 ^g	77.5 ^b	10.6 ^h	89.4 ^a
	Control (Neither injection nor spraying of water)	14.1 ^{cd}	85.9 ^{de}	35.1 ^{de}	64.9 ^{de}	20.7 ^e	79.3 ^d
Daneh-Sefid	uninoculated and disinfected with mancozeb	39.9 ^a	60.1 ^g	60.1 ^a	39.9 ^h	34.9 ^a	65.1 ^h
	uninoculated and without disinfection	13.0 ^{c-f}	87.0 ^{b-e}	31.3 ^{ef}	68.7 ^{cd}	18.3 ^{ef}	81.7 ^{cd}
	inoculated with <i>A. flavus</i> and disinfected	23.8 ^b	76.2 ^f	42.3 ^c	57.7 ^f	25.6 ^{bcd}	74.5 ^{efg}
	inoculated but not disinfected	6.1 ^g	93.9 ^a	24.1 ^g	75.9 ^b	10.7 ^h	89.4 ^a
	Control (Neither injection nor spraying of water)	17.4 ^c	82.6 ^e	37.1 ^d	62.9 ^e	22.0 ^{de}	78.0 ^{de}
Koohi	uninoculated and disinfected with mancozeb	25.2 ^b	74.8 ^f	43.9 ^c	56.1 ^f	27.2 ^{bc}	72.8 ^{fg}
	uninoculated and without disinfection	8.7 ^{efg}	91.3 ^{abc}	28.9 ^f	71.1 ^c	14.0 ^{gh}	86.0 ^{ab}
	inoculated with <i>A. flavus</i> and disinfected	17.6 ^c	82.4 ^e	38.2 ^d	61.8 ^e	25.1 ^{cd}	74.9 ^{ef}
	inoculated but not disinfected	7.6 ^g	92.4 ^a	18.7 ^h	81.3 ^a	10.6 ^h	89.4 ^a
	Control (Neither injection nor spraying of water)	13.3 ^{cde}	86.7 ^{cde}	35.1 ^{de}	64.9 ^{de}	20.5 ^e	79.5 ^d

* Means with the same letters in each column are not significantly different using LSD Fisher test at $p \leq 0.05$

reduced the proportion of fruits with closed ostioles to 60.1%. The lowest percentage of fruits with open ostioles was recorded in the treatment inoculated with *A. flavus* but not disinfected with mancozeb (Table 2).

The highest percentage of yellow-skinned dried fruits was observed when Sabz figs were pollinated with Daneh-Sefid syconia that were uninoculated and disinfected with mancozeb (60.1%). In contrast, pollination with Koohi syconia that were inoculated but not disinfected resulted in the highest proportion (81.3%) of brown-skinned fruits (Table 2).

The highest percentage of large fruits (34.9%) was obtained when Sabz figs were pollinated with Daneh-Sefid without *A. flavus* inoculation and disinfected with mancozeb. Conversely, caprification with caprifigs syconia that inoculated without fungicide application produced the highest proportion of small fruits (Table 2).

3.5 Fig fruit contamination with fungus

The highest level of skin contamination with *A. flavus* was observed in Sabz figs pollinated with Koohi syconia that

Table 3 Effect of caprifig cultivar and treatment on fig skin and pulp contamination percentage

Caprifig	Treatment	skin contamination (%)	pulp contamination (%)
Pouzdonbali	uninoculated and disinfected with mancozeb	0.0 ^{fs}	0.0 ^e
	uninoculated and without disinfection	63.7 ^{cd}	20.8 ^d
	inoculated with <i>A. flavus</i> and disinfected	2.7 ^f	49.1 ^b
	inoculated but not disinfected	72.5 ^b	65.7 ^a
	Control (Neither injection nor spraying of water)	0.0 ^f	0.0 ^e
Daneh-Sefid	uninoculated and disinfected with mancozeb	0.0 ^f	0.0 ^e
	uninoculated and without disinfection	62.1 ^d	0.0 ^e
	inoculated with <i>A. flavus</i> and disinfected	2.7 ^f	44.7 ^{bc}
	inoculated but not disinfected	71.6 ^b	51.8 ^b
	Control (Neither injection nor spraying of water)	0.0 ^f	0.0 ^e
Koochi	uninoculated and disinfected with mancozeb	0.0 ^f	0.0 ^e
	uninoculated and without disinfection	66.2 ^c	3.7 ^e
	inoculated with <i>A. flavus</i> and disinfected	31.2 ^e	40.2 ^c
	inoculated but not disinfected	80.6 ^a	61.3 ^a
	Control (Neither injection nor spraying of water)	0.0 ^f	0.0 ^e

*Means with the same letters in each column are not significantly different using LSD Fisher test at $p \leq 0.05$

were inoculated but not disinfected (80.6%). In contrast, caprification using syconia from all three caprifig cultivars under the control treatment (neither injection nor water spraying) and the uninoculated and mancozeb-disinfected treatment resulted in 0% skin contamination (Table 3). High levels of pulp contamination were recorded in Sabz figs pollinated with Pouzdonbali and Koochi syconia subjected to inoculation without disinfection (65.7% and 61.3%, respectively). Control (Neither injection nor spraying of water) treatments of all three caprifig cultivars resulted in low levels of pulp contamination, and no significant differences were detected between these treatments and the uninoculated and mancozeb-disinfected treatment, the uninoculated and non-disinfected treatment in Daneh-Sefid, or the uninoculated and mancozeb-disinfected treatment in Pouzdonbali and Koochi caprifigs (Table 3).

4 Discussion

In this study, caprifigs syconia inoculated with *Aspergillus flavus* without fungicide treatment developed the highest pulp and skin contaminations in the edible figs, confirming the high susceptibility of figs to fungal colonization. Dried figs represented an excellent substrate for aflatoxigenic fungi due to their high sugar content, low water activity, and natural exposure during ripening and drying (Iamanaka et al. 2007; González-Curbelo and Kabak 2023). The dynamics of fungal contamination were influenced by multiple factors, including spore load, dispersal

efficiency, entry through ostioles or skin injuries, and the aggressiveness of the fungal strain (Buchanan et al. 1975). Environmental factors such as high temperature, drought stress, and insect activity further exacerbate fungal proliferation and aflatoxin production (Miraglia et al. 2009; Medina et al. 2017).

Application of mancozeb reduced pulp fungal contamination of the edible fig fruits, consistent with its classification as a multisite fungicide that disrupts sulfhydryl-containing enzymes in fungal cells (Chaudhari et al. 2023). Mancozeb was applied externally because it is a non-systemic, contact dithiocarbamate fungicide with primarily protective activity. Unlike systemic fungicides, it did not translocate within plant tissues, and its efficacy depended on surface coverage, timing of application, and environmental conditions. In this study, an external application on caprifig syconia aimed to reduce surface-associated fungal inoculum and limit the transmission of *Aspergillus flavus* by pollinating wasps. Furthermore, the biological effects of mancozeb can be influenced by interactions with non-target organisms, highlighting the need for cautious interpretation of its efficacy. Therefore, mancozeb was included as a conventional external treatment to reflect typical management practices (Carniel et al. 2019). Mancozeb demonstrated broad-spectrum efficacy against several fungal pathogens (Santos et al. 2011; Lum and Takor 2021), and in this study, its role in suppressing *A. flavus* growth was modest. The limited efficacy of the fungicide may have been attributed to methodological constraints associated with internal fungal colonization of the syconium. Future approaches should integrate chemical fungicides with biological control agents (e.g., *Trichoderma* spp., *Bacillus subtilis*), capable of being

transported by wasps, along with postharvest practices (Man-naa and Kim 2018; Nesci et al. 2020).

Fruit quality characteristics such as ostiole opening, size, and skin color were markedly affected by both fungal contamination and the caprifig cultivar. Uninoculated and mancozeb disinfected Daneh-Sefid caprifig syconia resulted in the best quality attributes in the edible fig fruits, likely due to more efficient pollination and fertilization which enhanced ovary development and fruit expansion (Gillaspy et al. 1993). The positive influence of pollen source on external and internal fruit traits, including skin color and biochemical composition, has been previously reported (Pourghayoumi et al. 2012). In the present study, caprification with Daneh-Sefid cultivar produced more desirable yellow skin coloration in cv. Sabz, an attribute of considerable importance for consumer acceptance and export markets (Sedaghat and Rahimi 2018).

The survival of *Blastophaga psenes* was another critical factor. Caprifigs inoculated with *A. flavus* exhibited the highest mortality of pollinating wasps. This may have been attributed to the adhesion of fungal propagules to the cuticle of *Blastophaga* wasps. Spore adhesion to the wasp epicuticle, subsequent germination and formation of penetration structures were essential steps in the infection process (Ortiz-Urquiza and Keyhani 2013). Fungi produce different cuticle-degrading enzymes like chitinases, endoproteases, esterases, lipases, proteases and organic acids (de Carolina Sánchez-Pérez et al. 2014; Liaud et al. 2014). Following successful attachment, hyphal growth within the cuticle interstices and entry into the hemocoel occurred. Filamentous hyphal developed into small hyphal bodies within the hemocoel, circulated in the hemolymph as well as proliferated. The cellular form enhanced nutrient absorption and inhibited the wasp's immune system response. Septicemia occurred upon immune system suppression and the fungus returned to mycelial growth to invade the wasp's internal tissues, leading to nutrient depression. Mechanical damage, nutrient deficiency and toxins secretion in the wasp's body (toxicosis) contributed to the pollinator death (Vega et al. 2008). Reduced wasp survival compromised pollination efficiency, resulting in increased syconium abscission and reduced fruit set. Conversely, fungicide application indirectly supported wasp survival, thereby enhancing pollination success. These findings underscore the importance of managing fungal contamination not only for food safety but also for sustaining the specialized fig–wasp mutualism, essential for Smyrna-type fig production (Michailides and Morgan 1994).

5 Conclusion

Aspergillus flavus contamination of caprifig syconia significantly compromised both the quality and safety of edible figs by contaminating their pulp and skin. Mancozeb fungicide was moderately effective in suppressing fungal growth, reducing *A. flavus* transmission from caprifigs to edible

figs, improving the survival of *Blastophaga* wasps, and ultimately enhancing caprification success. Furthermore, the choice of caprifig cultivar influenced key fig quality traits including ostiole opening, size, and skin color, with Daneh-Sefid demonstrating favorable effects on fig appearance and marketability.

Overall, the findings highlight that chemical control was somewhat effective in suppressing fungal contamination of syconia under the experimental conditions. Integrating alternative strategies such as wasp-transmissible biocontrol agents, tolerant cultivars and optimized postharvest drying, could provide more sustainable solutions. An integrated management approach will not only reduce aflatoxin risk but also support pollinator survival and improve fig quality, thereby safeguarding consumer health and the nutritional value of dried fig.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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