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How Greenhouse Construction Type Modulates the Chemical Control Efficacy Against Two-Spotted Spider Mite (*Tetranychus urticae*)

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ABSTRACT

Greenhouse cultivation in Iran has expanded significantly, yet the influence of greenhouse structural characteristics on the efficacy of pest management remains poorly understood. This study evaluated the efficacy of four commonly used acaricides, abamectin, bifenazate, hexythiazox, and spirodiclofen, against the two-spotted spider mite (*Tetranychus urticae* Koch) in two distinct greenhouse structural types: gothic multispan (height: 600 cm, fan-and-pad ventilation) and wood-framed (height: 223-245 cm, hand-operated ventilation). The experiments were conducted in four cucumber greenhouses in Isfahan Province, Iran, during July 2022. Acaricides were applied at recommended concentrations, and mite mortality was assessed at 3, 7, and 14 days after treatment (DAT) using the Henderson-Tilton formula. Results revealed significantly higher acaricide efficacy in gothic multispan greenhouses compared with wood-framed structures across all sampling intervals. At 14 DAT, the highest efficacy recorded in gothic greenhouses (bifenazate: 85.22%) was nearly double that observed in wood-framed structures (43.27%). Bifenazate and hexythiazox demonstrated superior residual activity (85.22% and 79.10% at 14 DAT in gothic greenhouses, respectively), while abamectin and spirodiclofen exhibited the lowest persistence, particularly in wood-framed structures (33.95% and 30.98% at 14 DAT, respectively). The reduced efficacy observed in wood-framed greenhouses may be associated with suboptimal environmental conditions, including inadequate ventilation, poor air circulation, and limited spray coverage due to lower height. The findings suggest that investing in modern greenhouse infrastructure can substantially improve acaricide performance, potentially reducing spray frequency and delaying resistance development. However, as this study focused exclusively on chemical control, future research should investigate the compatibility of these findings with biological control agents within integrated pest management programs.

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1. Introduction

Greenhouse cultivation has become a cornerstone of Iran's agricultural transformation, driven by the urgent need to address severe water scarcity, climate change, and food security challenges (Thipe *et al*., 2017; Farvardin *et al*., 2024; Gholami Jalal *et al*., 2025). According to the latest Agricultural Statistics of Iran (2024), the total area under greenhouse cultivation has reached 15,663 hectares. The five leading greenhouse crops based on cultivated area are cucumber (8,619 ha), cut flowers (3,564 ha), bell pepper (2,552 ha), tomato (2,069 ha), and eggplant (1,043 ha), which together dominate the country's protected cultivation systems. Geographically, greenhouse production is concentrated in four key provinces, including Tehran (3,173 ha), Southern Kerman (3,005 ha), Yazd (2,866 ha), and Isfahan (2,267 ha), which collectively account for the majority of the national greenhouse area (Ministry of Agriculture-Jahad of Iran, 2024). This controlled-environment approach offers remarkable advantages, including reduced water consumption, average yields up to ten times higher than those of open-field cultivation, and enhanced product quality through better insect pest and disease management (Thipe *et al*., 2017; Etemadi *et al*., 2019; Hafizi *et al*., 2020; Farvardin *et al*., 2024). However, the rapid expansion of greenhouse cultivation has also introduced new challenges, particularly increased pest pressure, as warm and dry greenhouse conditions favor outbreaks of key arthropod pests (Gerson and Weintraub, 2012).

The greenhouse structure plays a significant role in enhancing water and energy productivity, ensuring uniform temperature and relative humidity distribution, and consequently improving airflow and ventilation within the greenhouse (Thipe *et al*., 2017; Sharifian *et al*., 2025). In Iran, greenhouse structures vary widely, ranging from fully automated or mechanized systems to highly traditional ones, characterized by wooden frames and a lack of climate control equipment. Controlling environmental factors such as temperature, light, humidity, and ventilation remains a prerequisite for achieving optimal production (Etemadi *et al*., 2019; Momeni, 2025). Despite the expansion of greenhouse cultivation, management practices still largely rely on traditional methods, resulting in significant inefficiencies (Barati *et al*., 2024). Greenhouses are broadly classified into two main structural types: wooden (traditional) and metal (modern). Traditional wooden structures are typically 2 to 3 meters in height, lack adequate heating and ventilation systems, and have low initial construction costs, but production per unit area is considerably lower compared to modern greenhouses (Hassandokht, 2013). Historically, approximately 20% of the greenhouse structures in Iran dedicated to vegetable and ornamental plant production were wooden (Zarei, 2017). However, in line with the national greenhouse development program, significant efforts have been made to modernize and renovate traditional wooden greenhouses. Regardless of structural type, effective pest management remains a critical determinant of greenhouse productivity and sustainability, as suboptimal structural features such as poor ventilation, inadequate heating, and limited automation can exacerbate pest outbreaks and compromise crop quality (Gerson & Weintraub, 2012; Sharifian *et al*., 2025). For example, passive microclimate modification through ventilation and roof configuration has been reported to reduce disease pressure and chemical inputs (Moreno-Teruel *et al*., 2026), while simultaneously enhancing crop yield (Akpenpuun *et al*., 2023). Greenhouse structural characteristics, particularly height and canopy architecture, can significantly influence spray deposition and coverage, which are critical determinants of chemical control efficacy. Greater height in modern multispan greenhouses allows for better spray boom positioning and more uniform droplet distribution, whereas lower height in traditional wooden structures restricts equipment maneuverability and may result in uneven coverage, particularly on lower leaf surfaces where the insect pests predominantly feed (Braekman *et al*., 2009). Improved spray distribution through automated systems has been shown to enhance pest management outcomes and reduce the need for repeated applications (Wang *et al*., 2023; Benalia *et al*., 2025).

The two-spotted spider mite, *Tetranychus urticae* Koch (Acari: Tetranychidae), is globally recognized as one of the most economically damaging arthropod pests in greenhouse cultivation, posing a significant threat to a wide range of vegetable, fruit, and ornamental crops (El-Laithy, 1996; Gerson and Weintraub, 2012; Maleknia *et al*., 2016; Sangak *et al*., 2018; Parmagnani *et al*., 2023). This polyphagous pest feeds on plant cell contents by piercing leaf tissues, resulting in characteristic stippling, chlorosis, leaf desiccation, and premature defoliation, which collectively lead to substantial reductions in photosynthetic capacity, crop yield, and product quality (Arbabi *et al*., 2015; Wang *et al*., 2018; Azadi-Qoort *et al*., 2019; Alinejad *et al*., 2025). Under favorable conditions, a single generation can be completed in as little as 5-7 days, enabling explosive population growth. Numerous studies have investigated the biology of *T. urticae* on various host plants (Balci and Ay, 2023; Parmagnani *et al*., 2023). For example, Maleknia *et al*. (2016) evaluated the life table parameters of the two-spotted spider mite on 12 commercial greenhouse cucumber cultivars and found that the intrinsic rate of increase (*r*) ranged from 0.249 day^{-1} on the resistant cultivar Caspian to 0.331 day^{-1} on the susceptible cultivar Vida, indicating considerable variation in host plant suitability. However, Azadi-Qoort *et al*. (2019) demonstrated that tomato exhibited the strongest negative bottom-up effects on *T. urticae,* with the lowest intrinsic rate of increase (0.104 day^{-1}) and highest immature mortality (65.31%), while cucumber was the most suitable host (r = 0.239 day^{-1}). The warm, dry, and protected environment of greenhouses provides ideal conditions for the mite's development, allowing it to thrive year-round (El-Laithy, 1996; Arbabi and Baniameri, 2016). Moreover, the mite's remarkable ability to develop resistance to a wide array of acaricides, with over 90 active ingredients currently compromised, has rendered chemical control increasingly challenging, making *T. urticae* a formidable obstacle to sustainable greenhouse production worldwide and a priority target for integrated pest management (IPM) strategies (Alpkent *et al*., 2020; Han *et al*., 2024). Although several studies have investigated the effects of various acaricides on *T. urticae* under greenhouse conditions (Arbabi *et al*., 2015; Arbabi and Baniameri, 2016; Wang *et al*., 2018; Arbabi *et al*., 2022), none have evaluated the influence of greenhouse structural characteristics on acaricide efficacy. Consequently, understanding how greenhouse design and structural features affect pest dynamics and chemical control effectiveness has become critically important for sustainable production in Iran's expanding protected agriculture sector. Therefore, the present study aimed to evaluate the efficacy of four commonly used acaricides, abamectin, bifenazate, hexythiazox, and spirodiclofen, against *T. urticae* in two main greenhouse structures (gothic multispan and wood-framed) across four cucumber greenhouses in Isfahan Province, Iran. These acaricides were selected based on their official registration by the Plant Protection Organization (PPO) of Iran, their diverse modes of action (IRAC groups 6, 20D, 10A, and 23, respectively), and their common use in Iranian greenhouse production systems.

2. Materials and Methods

2.1. Experimental design

In this study, the efficacy of four acaricides, abamectin, bifenazate, hexythiazox, and spirodiclofen, was evaluated against the two-spotted spider mite, *T. urticae*, under greenhouse conditions. The acaricides were applied at their recommended and registered concentrations of 600, 300, 500, and 500 ppm, respectively, along with a control treatment. These rates were based on the official recommendations of the Plant Protection Organization of Iran (PPO, 2025) and represent the manufacturer-recommended and nationally registered field application rates. Specifications of the acaricides used are presented in Table 1.

Table 1. Characteristics of the acaricides tested against *Tetranychus urticae* under greenhouse conditions.

Common name	Formulation	IRAC[1] group	Chemical class	Company
Abamectin	EC 1.8%	6	Avermectins-Milbemycins	Melli Shimi Keshavarz
Bifenazate	SC 24%	20D	Bifenazate	Raha Andish Kavan
Hexythiazox	EC 10%	10A	Clofentezine-Hexythiazox-Diflovidazin	Kavosh Kimia Kerman
Spirodiclofen	SC 24%	23	Tetronic and Tetramic acid derivatives	Moshkfam Fars

[1] The Insecticide Resistance Action Committee (IRAC)

The greenhouses for this study were selected in Isfahan Province, one of the leading regions for greenhouse cucumber production in Iran, which is characterized by a wide diversity of greenhouse structural types. Two wooden-framed greenhouses and two gothic multispan greenhouses with polyethylene covers were selected for the evaluations. Detailed characteristics of the investigated greenhouses are provided in Table 2. All infestations used in this study occurred naturally, and no artificial mite introduction was performed. Furthermore, no cages were employed to isolate infested plants from the rest of the greenhouse crop. Because of the pest's heterogeneous distribution, treatment plots were restricted to areas where natural infestations were already present. To minimize confounding effects, all four greenhouses were cultivated with the same cucumber variety (Nagene 792 F1) and followed similar planting schedules and standard local crop management practices for fertilization, irrigation, and pest monitoring. No other pesticides were applied during the experimental period. However, as the study was conducted under commercial production conditions, some variations in management practices across greenhouses cannot be ruled out.

In the control treatment, water spraying was applied to the active mite population. Acaricide applications were carried out when the mean density of active life stages (nymphs and adults) on the underside of cucumber leaves reached at least three individuals per leaf. The experiment was conducted in July 2022, during the mid-fruiting stage of the cucumber plants, approximately 50-60 days after transplanting, when the plants had reached full vegetative development. Spraying was performed in the early morning hours. Acaricide applications were performed uniformly across all rows of cucumber plants using a 200-L trolley-mounted sprayer equipped with a single-nozzle hand lance. Prior to spraying, the pH of the water in the spray tank was measured using a portable pH meter. The water used for preparing the spray solutions was neutral, with a pH value of 7.0. No further spray applications were made to the treated cucumber plants during the 16-day experimental period. The experimental design was a randomized complete block design (RCBD) with five treatments (including the control). Each treatment was applied to at least three rows, each 10 meters in length. For sampling, 10 cucumber plants were randomly selected per treatment, and five leaves were collected from different parts of each plant. The samples were individually placed in ventilated containers (11×10×4 cm) and transferred to the laboratory for counting. A binocular microscope (×20 magnification) was used to count the active mite population on the lower leaf surfaces.

Table 2. Location, structural characteristics, and cultivation specifications of the four soil-based cucumber greenhouses surveyed in Isfahan Province, Iran.

Abbr.	County	Site	Coordinates	AMSL[1]	Variety	Structure	Cover	Height (Ridge) cm	Ventilation	Planting Density (cm)	Total Area (m^2)
G1	Mobarakeh	Zibashahr city	32°23’42” N, 51°31’47” E	1655	Nagene 792 F1	Gothic multispan	Polyethylene	600	Fan & pad	45 × 120	7680
G2	Central part of Isfahan	Ruran village	32°28’31” N, 51°53’59” E	1536	Nagene 792 F1	Gothic multispan	Polyethylene	600	Fan & pad	43.5 × 115	6400
G3	Falavarjan	Qaleh-ye Sorkh village	32°29’37” N, 51°35’42” E	1636	Nagene 792 F1	Wood-framed	Polyethylene	245	Hand-operated	42.5 × 105	4500
G4	Dorcheh	Jowlarestan village	32°35’28” N, 51°33’42” E	1599	Nagene 792 F1	Wood-framed	Polyethylene	223	Hand-operated	37.5 × 95	3000

[1] Above Mean Sea Level (meter)

Sampling was conducted one day before application (pre-treatment) and at 3, 7, and 14 days after treatment (DAT). All samplings were performed between 8:00 and 10:00 AM.

2.2. Statistical analysis

Raw data were recorded and converted into percentage efficacy using the Henderson-Tilton formula (1955) in Microsoft Excel as follows:

$$\text{Acaricide efficacy\%} = \left(1 - \frac{T_a}{C_a} \times \frac{C_b}{T_b}\right) \times 100$$

where T_a and T_b represent the number of live mites on treated plants after and before spraying, respectively, and C_a and C_b represent the number of live mites on control plants after and before spraying, respectively. Statistical analyses were performed using IBM-SPSS version 22.0 software (IBM Corp., 2013). Data normality was assessed using the Kolmogorov–Smirnov test. Mean efficacy percentages were calculated for each treatment. Percentage data were subjected to arcsine square-root transformation prior to statistical analysis. To evaluate the significance of differences in acaricide efficacy across sampling days and greenhouse types, a one-way analysis of variance (ANOVA) was conducted. Treatment means were compared using Tukey's honestly significant difference (HSD) test at the 5% significance level.

3. Results

The results demonstrated a significant disparity in acaricide efficacy between the two greenhouse structural types evaluated. Acaricide efficacy was consistently and significantly higher in gothic multispan greenhouses (G1 and G2) compared to wood-framed greenhouses (G3 and G4) across all sampling days (Figure 1). At 3 days after treatment (DAT), the mean efficacy across all acaricides in gothic structures ranged from 69.66% to 88.53%, whereas in wood-framed structures, it ranged from 55.50% to 69.63%. This difference became more pronounced over time, with the gap between the two structural types widening substantially by 14 DAT. At 14 DAT, the highest efficacy recorded in gothic structures (bifenazate in G1: 85.22%) was nearly double the highest efficacy recorded in wood-framed structures (bifenazate in G4: 43.27% and in G3: 35.25%) (Table 3; Figure 1).

Among the acaricides, hexythiazox showed the highest overall efficacy at 7 DAT in gothic structures, achieving 90.17% mortality in G1 and 84.25% in G2, while maintaining relatively higher performance in wood-framed greenhouses with 67.18% and 70.53% in G3 and G4, respectively. Bifenazate also showed strong activity, particularly in gothic greenhouses, with efficacy remaining above 82% at both 3 and 14 DAT in G1. Abamectin efficacy declined from 78.24% at 3 DAT to 66.08% at 14 DAT in G1, and from 55.50% to 33.95% in G3 over the same period (Table 3). Spirodiclofen showed moderate efficacy, declining to 30.98% in G3 and 39.88% in G4 at 14 DAT (Table 3).

Table 3. Mean percentage efficacy (± SE) of abamectin, bifenazate, hexythiazox, and spirodiclofen against *Tetranychus urticae* at 3, 7, and 14 days after treatment (DAT) in gothic multispan (G1, G2) and wood-framed (G3, G4) cucumber greenhouses.

Greenhouse	Acaricide	Efficacy (%) ± SE [1]		
		3 DAT[2]	7 DAT	14 DAT
G1	Abamectin	78.24 ± 3.52 a	73.41 ± 2.24 b	66.08 ± 3.76 c
	Bifenazate	88.53 ± 3.55 a	82.75 ± 2.28 ab	85.22 ± 1.08 a
	Hexythiazox	84.96 ± 3.94 a	90.17 ± 2.37 a	79.10 ± 4.06 ab
	Spirodiclofen	81.15 ± 3.64 a	78.83 ± 3.09 b	71.27 ± 3.16 bc
	F	1.497	7.845	6.840
	df	3, 39	3, 39	3, 39
	P	= 0.232	<0.0001	<0.001
G2	Abamectin	69.66 ± 3.15 a	71.92 ± 2.40 b	55.95 ± 3.36 a
	Bifenazate	79.16 ± 2.29 a	73.83 ± 2.61 ab	69.57 ± 3.72 a
	Hexythiazox	75.28 ± 2.47 a	84.25 ± 1.36 a	68.14 ± 4.40 a
	Spirodiclofen	78.52 ± 3.08 a	73.11 ± 4.11 b	60.47 ± 2.66 a
	F	2.450	4.150	3.222
	df	3, 39	3, 39	3, 39
	P	= 0.079	<0.013	= 0.034
G3	Abamectin	55.50 ± 5.04 a	50.87 ± 3.16 b	33.95 ± 3.54 a
	Bifenazate	65.56 ± 2.79 a	56.47 ± 3.64 ab	35.25 ± 2.83 a
	Hexythiazox	69.63 ± 3.32 a	67.18 ± 2.91 a	46.23 ± 5.65 a
	Spirodiclofen	60.05 ± 4.76 a	53.11 ± 3.19 b	30.98 ± 3.49 a
	F	2.291	4.982	2.747
	df	3, 39	3, 39	3, 39
	P	= 0.095	<0.005	= 0.057
G4	Abamectin	57.36 ± 4.80 a	60.11 ± 3.47 ab	36.35 ± 5.48 a
	Bifenazate	67.06 ± 3.72 a	61.93 ± 4.10 ab	43.27 ± 6.08 a
	Hexythiazox	63.67 ± 4.60 a	70.53 ± 2.84 a	48.71 ± 3.77 a
	Spirodiclofen	60.90 ± 4.04 a	55.29 ± 3.76 b	39.88 ± 3.98 a
	F	0.912	3.173	1.140
	df	3, 39	3, 39	3, 39
	P	= 0.445	<0.036	= 0.346

1 Means followed by different letters within each column are significantly different ($P < 0.05$, Tukey's test)

2 Days after treatment (DAT)

4. Discussion

The present study investigated the efficacy of four commonly used acaricides, abamectin, bifenazate, hexythiazox, and spirodiclofen, against *T. urticae* in two distinct greenhouse structural types: gothic multispan and wood-framed. The results revealed a clear and consistent disparity in acaricide efficacy between the two greenhouse types, with significantly higher efficacy observed in gothic multispan greenhouses compared with wood-framed structures across all sampling intervals. This finding suggests that greenhouse structural characteristics influence chemical control efficacy against arthropod pests. In agreement with the present results, Moreno-Teruel *et al*. (2026) demonstrated that greenhouse sectors equipped with a double-roof system and increased natural ventilation exhibited lower temperature and humidity levels, resulting in consistently reduced severity of fungal diseases across multiple crop cycles. The relevance of this finding to our study lies in the fact that lower temperatures and more stable humidity conditions in better-ventilated structures may also slow the photodegradation and volatilization of acaricides, thereby prolonging their residual efficacy. Similarly, Akpenpuun *et al*. (2023) investigated the effect of thermal curtain position on energy consumption in single-span greenhouses and concluded that structural modifications can influence microclimate, yield, and energy productivity. In the context of our findings, improved microclimate stability in gothic greenhouses likely contributed to more consistent acaricide performance by reducing environmental stressors that accelerate pesticide breakdown. Collectively, these studies support our finding that greenhouse structural characteristics play a critical role in modulating both pest control efficacy and overall system performance. However, a limitation of this study is the small number of replicate greenhouses (only two per structural type). Although the observed trends were consistent, the limited sample size warrants caution in generalizing the findings.

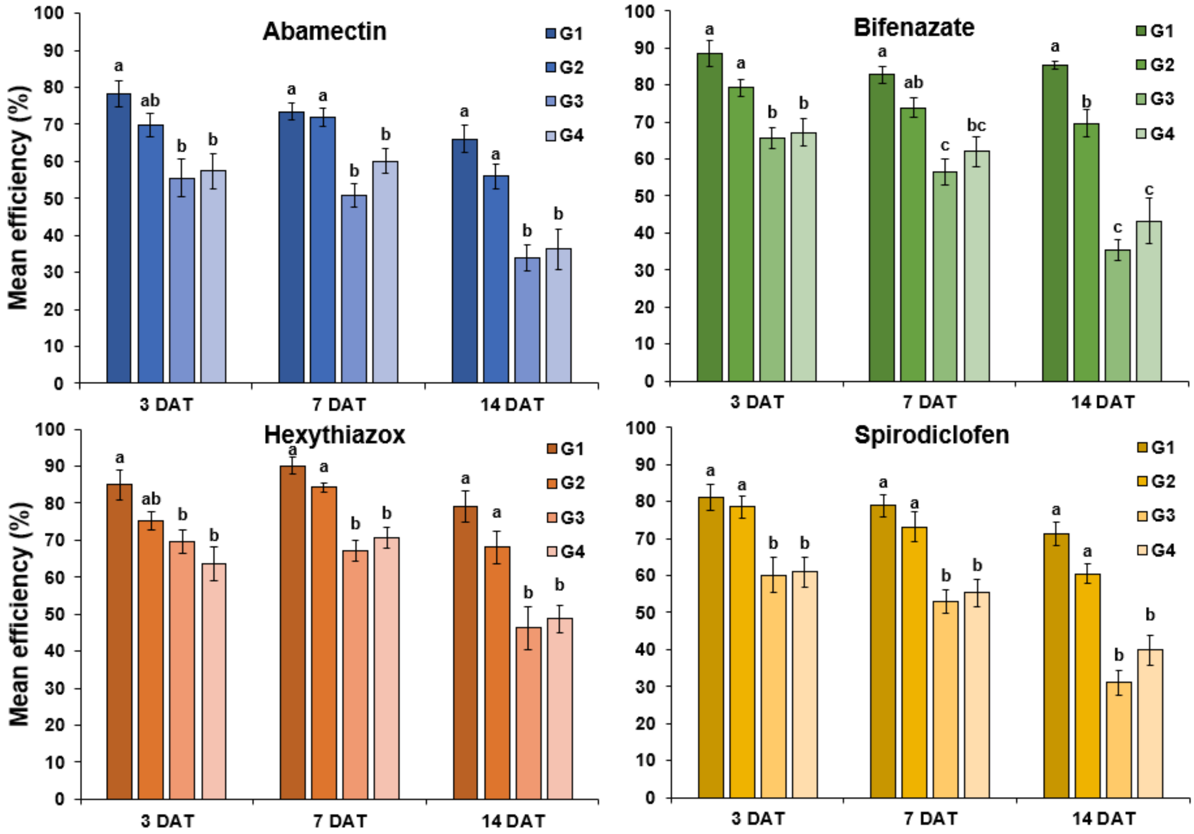

Figure 1. Acaricide efficacy of abamectin, bifenazate, hexythiazox, and spirodiclofen against *Tetranychus urticae* over time (3, 7, and 14 DAT) in two greenhouse structural types: gothic multispan (G1, G2) and wood-framed (G3, G4). Error bars represent standard errors of the means (n = 10). Bars within each panel bearing different letters are significantly different (one-way ANOVA, Tukey's HSD test, *P* < 0.05).

The superior performance of acaricides in gothic multispan greenhouses may be attributed to several structural and environmental factors. These greenhouses, with a ridge height of 600 cm and equipped with fan and pad ventilation systems, provide a more uniform microclimate, better air circulation, and improved environmental control compared to wood-framed structures (Pardossi *et al*., 2004; Sharifian *et al*., 2025). The greater height may have facilitated better spray coverage and penetration, ensuring more uniform distribution of acaricide droplets on the lower leaf surfaces where *T. urticae* predominantly feeds (Gerson and Weintraub, 2012). Additionally, the fan and pad ventilation system in gothic greenhouses may have contributed to more stable temperature and humidity conditions, possibly slowing acaricide degradation and prolonging residual activity (El-Laithy, 1996; Thipe *et al*., 2017). These findings are supported by Shipp *et al*. (2003) and Seo *et al*. (2022), who demonstrated that improved greenhouse microclimate management, specifically humidity control and ventilation, significantly enhanced the efficacy of pest control measures. While these studies focused primarily on biological control agents, their conclusions are equally relevant to chemical control: stable humidity and temperature conditions can prevent the rapid degradation of acaricide residues, thereby extending their period of activity. In contrast, wood-framed greenhouses, characterized by lower height (223–245 cm) and hand-operated ventilation, exhibited substantially lower acaricide efficacy. The suboptimal environmental conditions in these structures, including inadequate air circulation, restricted ventilation, and less uniform microclimate, may have accelerated acaricide photodegradation and volatilization, reducing both immediate and residual efficacy (Gerson and Weintraub, 2012; Momeni, 2025). Furthermore, the limited height in wood-framed greenhouses likely resulted in uneven spray coverage and reduced deposition on lower leaf surfaces, compromising overall pest control effectiveness (Braekman *et al*., 2009; Darabi *et al*., 2016). These findings are consistent with previous studies reporting that structural deficiencies, such as low height, poor ventilation, and inadequate climate control, are prevalent in low-technology greenhouses in Iran (Darabi *et al*., 2016; Zarei, 2017; Barati *et al*., 2024). Similarly, Matsuda and Izakaei (2025) demonstrated that even within a single rose greenhouse, *T. urticae* populations collected from different locations, particularly the northwest corner and the base of plants, exhibited up to 124.6-fold differences in LC_{50} values for amitraz, indicating that localized subpopulations can develop variable resistance levels depending on their exposure to pesticide selection pressure, which may be influenced by spray coverage heterogeneity within the greenhouse.

Among the acaricides tested, hexythiazox and bifenazate consistently demonstrated superior residual activity across both greenhouse types. Hexythiazox, a member of the thiazolidine class (IRAC group 10A), acts as an ovicide and larvicide with prolonged residual effects (IRAC, 2025). Its high efficacy at 7 DAT in gothic greenhouses (90.17% in G1) and relatively better performance in wood-framed structures aligns with previous reports on its effectiveness against *T. urticae* in various cropping systems (Arbabi *et al*., 2015; Wang *et al*., 2018). Bifenazate, a carbazate acaricide (IRAC group 20D), also exhibited strong and sustained activity, particularly in gothic greenhouses, with efficacy remaining above 82% at both 3 and 14 DAT in G1. This finding is consistent with earlier studies demonstrating the high efficacy of bifenazate against *T. urticae* in greenhouse crops (Arbabi *et al*., 2015; Arbabi and Baniameri, 2016). Conversely, abamectin exhibited the lowest persistence among the tested acaricides, with efficacy declining sharply over time in both greenhouse types. While abamectin showed acceptable initial efficacy at 3 DAT (78.24% in G1 and 69.66% in G2), its performance dropped considerably by 14 DAT, particularly in wood-framed greenhouses (33.95% in G3). This rapid decline in efficacy may be attributed to the photolabile nature of abamectin, which is susceptible to degradation under ultraviolet radiation (Escalada *et al*., 2008; D'Auria *et al*., 2023). The lower height and inadequate ventilation in wood-framed structures may have exacerbated this degradation, as reduced air circulation and higher temperature fluctuations can accelerate the breakdown of photolabile compounds. However, this interpretation requires further investigation. Spirodiclofen, a tetronic acid derivative (IRAC group 23), showed moderate efficacy with substantial decline by 14 DAT, particularly in wood-framed greenhouses (30.98% in G3). Its performance was inferior to hexythiazox and bifenazate across all greenhouse types, suggesting that spirodiclofen may be less suitable for situations requiring prolonged residual activity. Interestingly, the efficacy results were consistent with the price ranking of the four acaricides in the Iranian pesticide market, which from highest to lowest was hexythiazox > bifenazate > spirodiclofen > abamectin.

Conclusion

The substantial disparity in acaricide efficacy observed between gothic multispan and wood-framed greenhouses, with efficacy in gothic structures nearly double that of wood-framed structures at 14 days after treatment, suggests that greenhouse structural design may play a role in integrated pest management (IPM) programs. Low-technology greenhouses may compromise the performance of acaricides, potentially leading to repeated applications, increased production costs, and accelerated resistance development. While previous studies have demonstrated the influence of greenhouse microclimate on pest management outcomes, the present study provides additional evidence that structural characteristics may affect acaricide efficacy against *T. urticae*. The superior performance of acaricides in gothic multispan greenhouses compared with wood-framed structures highlights the importance of structural design in optimizing chemical pest control. These findings may have practical implications for greenhouse growers and pest management practitioners, emphasizing the need for investment in modern greenhouse infrastructure and tailored acaricide selection strategies to enhance the sustainability and productivity of protected agriculture in Iran. A limitation of this study is that temperature, relative humidity, and photoperiod were not measured during the experiment. As these factors can affect both mite biology and acaricide degradation, their potential influence on the observed efficacy differences cannot be excluded. Additionally, this study focused exclusively on chemical control and did not evaluate the potential integration of biological control agents or other IPM components. Future research should incorporate comprehensive environmental monitoring and explore the compatibility of chemical and biological control strategies across different greenhouse structural types. Growers in wood-framed greenhouses may require supplementary measures to compensate for structural constraints, whereas taller greenhouses with active ventilation could improve both crop productivity and acaricide performance, reducing spray frequency and slowing resistance. These results should guide structure-specific IPM strategies for cucumber production in Iran.

Conflict of interest statement

The authors declare that there are no conflicts of interest regarding the publication of this article.

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