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Effects of yellow-light illumination and insect-proof netting on Spodoptera exigua populations, spear growth, and nutritional quality in greenhouse asparagus

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Abstract

The beet armyworm, *Spodoptera exigua*, is an important pest of greenhouse-grown asparagus. We evaluated the effects of yellow-light illumination and insect-proof netting, individually and in combination, on *S. exigua* populations, asparagus spear growth, and nutritional quality in a field experiment conducted in Taizhou, Jiangsu Province, China, from June to October 2025. Four treatments were evaluated, each in three independent greenhouses: yellow-light illumination, insect-proof netting, their combination, and an untreated control. The number of trapped adults generally remained low in the netting and combined treatments during most of the monitoring period. The combined treatment showed comparatively stable reductions in larval abundance, reaching a relative reduction of 100% in early September. Mean spear height reached the 370-mm harvest threshold in all treatments by 11 September, with no significant differences among treatments. Yellow-light illumination, alone or combined with netting, was associated with higher vitamin C and soluble sugar contents. The combined treatment also had the highest soluble protein content and the lowest nitrate nitrogen content. Overall, the greenhouse-replicated trial indicated that combining yellow-light illumination with insect-proof netting was associated with lower *S. exigua* pressure and changes in selected nutritional-quality traits, without a detectable adverse effect on spear growth. These results suggest that the combined approach warrants further evaluation as a non-chemical management option for *S. exigua* in greenhouse asparagus.

1. Introduction

Asparagus (*Asparagus officinalis* L.) is a perennial vegetable valued for its edible spears and their polysaccharides, polyphenols, anthocyanins, saponins, and other bioactive compounds (Guo et al. 2020). Pest management is an important concern in protected asparagus production. Sixteen pest species have been recorded in greenhouse asparagus (Choi et al. 2014), including the beet armyworm, *Spodoptera exigua* (Hübner), the common cutworm, *Spodoptera litura* (Fabricius), and the cotton bollworm, *Helicoverpa armigera* (Hübner). Among these, *S. exigua* is a notable concern because of its potential to damage asparagus under protected cultivation.

Spodoptera exigua (Lepidoptera: Noctuidae) is a widespread, polyphagous pest characterized by high reproductive potential and a propensity to develop insecticide resistance (Hafeez et al. 2022). In China, its potential overwintering range extends approximately from the Tropic of Cancer to the Yangtze River basin, whereas populations farther north are more closely associated with seasonal immigration (Zheng et al. 2012). Long-distance migration also facilitates its movement among production regions and host plants (Jiang et al. 2010). Although chemical insecticides remain widely used for its management, resistance to several insecticide groups has been documented in field populations, with substantial regional variation (Wang et al. 2021; Huang et al. 2021; Teng et al. 2022; Fang et al. 2026). These challenges highlight the value of assessing non-chemical approaches suitable for greenhouse production.

Insect-proof netting provides a physical barrier to insect immigration in protected cultivation. Its exclusion performance depends on mesh dimensions and geometry, material characteristics, and airflow resistance (Bell and Baker 2000). However, finer meshes may also restrict ventilation and light transmission, potentially changing temperature, humidity, radiation, evapotranspiration, and crop performance (Teitel 2007; Tanny 2013; Mahmood et al. 2018). In cowpea, *Vigna unguiculata* (L.) Walp., insect-proof netting reduced thrips abundance but also altered temperature and humidity (Fan et al. 2025). Therefore, evaluations of netting should consider both pest exclusion and crop responses within the protected environment.

Manipulating insect responses to light is another potential non-chemical strategy for noctuid pest management (Hirama et al. 2007; Yoon et al. 2012; Liu et al. 2018). Ultraviolet-, blue-, and long-wavelength-sensitive opsins have been identified in *S. exigua*, and its long-wavelength visual system contributes to light-mediated behaviour (Liu et al. 2018). Unlike ultraviolet or near-ultraviolet lamps designed to attract and kill insects, yellow-light illumination modifies the nocturnal light environment and may interfere with moth activity. Yellow LEDs have been reported to influence activity, flight, and mating-related behaviour in noctuid moths (Hirama et al. 2007; Yoon et al. 2012), while artificial light at night can disrupt pheromone communication and other reproductive processes (van Geffen et al. 2015; Owens and Lewis 2018). For *S. exigua*, exposure to yellow light at 10 and 100 lx reduced fecundity and shortened the oviposition period and female longevity, whereas 1 lx had little effect (Jiang et al. 2020a). Reduced moth-pest pressure under yellow-light illumination has also been reported in field studies (Jiang et al. 2023). Together, these findings provide a rationale for evaluating yellow light under greenhouse conditions.

Insect-proof netting and yellow-light illumination may provide complementary forms of pest suppression. Netting primarily restricts the entry of insects from outside the greenhouse, whereas yellow light may alter the behaviour and reproduction of adults present inside. Using both approaches together could therefore reduce pest pressure more consistently than either approach alone.

Although both methods have been investigated separately, evidence on their combined application against *S. exigua* in greenhouse asparagus remains limited, particularly where pest abundance, spear growth, and nutritional quality are assessed together. Accordingly, we compared four treatments—yellow-light illumination, insect-proof netting, their combination, and an untreated control—in independent replicate greenhouses. We monitored the number of trapped adults and larval abundance and measured spear growth and the contents of vitamin C, soluble sugar, soluble protein, and nitrate nitrogen to assess the potential agronomic value of combining the two physical control methods.

2. Materials and methods

2.1. Study site and materials

The experiment was conducted at the Fumin Asparagus Cooperative Base, Sunshe Village, Jiangyan District, Taizhou, Jiangsu Province, China (32°27'34"N, 120°13'16"E). Asparagus (*Asparagus officinalis* L.) was cultivated in plastic greenhouses, each measuring approximately 80 m × 6 m. Twelve greenhouses were used in the experiment, with three separate greenhouses assigned to each treatment.

Yellow-light lamps had a peak wavelength of 589 nm and were fitted with automatic photosensitive switches that turned the lights on at dusk and off at dawn (Hirama et al. 2007; Yoon et al. 2012). Illuminance was measured using a TES illuminance meter. *Spodoptera exigua* sex-pheromone lures and traps were purchased from Beijing Zhongjie Sifang Biotechnology Co., Ltd. The 40-mesh insect-proof netting was obtained from Henan Hekang Agricultural Materials, and the biochemical assay kits from Suzhou Comin Biotechnology Co., Ltd.

2.2. Experimental design

Twelve greenhouses were assigned to four treatments, with three independent greenhouses per treatment (n = 3): (1) yellow-light illumination, (2) insect-proof netting, (3) insect-proof netting combined with yellow-light illumination, and (4) an untreated control. Thus, an individual greenhouse—not a survey plot, trap, or plant—constituted the experimental unit. Yellow-light illumination was initiated when baseline moth abundance was close to zero, following the timing rationale of Jiang et al. (2020a). In treatments receiving yellow light, lamps were installed at 6-m intervals along the greenhouse roof and operated from dusk to dawn. Illuminance at the top of the asparagus canopy was 10–20 lx, a range previously associated with reduced *S. exigua* fecundity and longevity (Jiang et al. 2020a). Routine crop-management practices were kept consistent among greenhouses. Larval surveys were conducted at treatment initiation and 15 d after lamp installation, followed by surveys at 3-d intervals. Within each greenhouse, three fixed survey plots were examined by parallel-line sampling, with 25 asparagus plants inspected in each sampled row. Larvae observed in the subsamples were used to obtain a single greenhouse-level abundance estimate at each sampling date; greenhouse estimates were expressed as larvae per 100 plants for comparison among treatments.

Adults were monitored with sex-pheromone traps. Three traps, each comprising a pheromone lure, trap, and collection bag, were positioned along the central area of each greenhouse. Traps were inspected every 3 d, and captured *S. exigua* adults were counted and removed. For analysis, counts from the three traps within a greenhouse were averaged to give one estimate of the number of trapped adults per trap per 3-d interval for that greenhouse. The three greenhouses, rather than individual traps, were treated as independent replicates of each treatment.

For spear-growth assessment, five newly emerged spears measuring 30–50 mm were selected and marked in each fixed survey plot. Spear height was measured with a ruler to the nearest 1 mm at approximately the same time each day until the mean height approached the 370-mm harvest threshold. Measurements from spears within the same greenhouse were averaged to generate one greenhouse-level value per date; between-treatment comparisons were based on the three replicate greenhouse values.

Vitamin C, soluble sugar, soluble protein, and nitrate nitrogen contents of asparagus spears were measured using commercial assay kits according to the manufacturer's instructions. Nutritional-quality results were summarized at the greenhouse level before treatment comparisons so that each greenhouse contributed one independent replicate. Vitamin C and nitrate nitrogen contents are reported in μg/g fresh weight (FW), consistent with the fresh-weight-based assay calculations.

Relative reduction in larval abundance (%) was calculated for each sampling date as:

$$\text{Relativelarvalreduction}\,(\varrvec{\%}) = \frac{\varrvec{N}_{\varrvec{c}} - \varrvec{N}_{\varrvec{t}}}{\varrvec{N}_{\varrvec{c}}} \times 100$$

where Nc and Nt represent, respectively, the mean larval abundance per 100 plants across the three control greenhouses and the three greenhouses receiving the treatment on the same date. Relative reduction was not calculated when Nc equalled zero because the denominator would be zero.

2.3. Data analysis

Data were organized using Microsoft Excel 2019 and analyzed using GraphPad Prism 10.0. The number of trapped adults and larval abundance were log10(x + 1)-transformed prior to analysis. The effects of treatment, sampling time, and their interaction on the number of trapped adults and larval abundance were evaluated using two-way repeated-measures analysis of variance (ANOVA), with sampling time as the repeated-measures factor. The Geisser–Greenhouse correction was applied when the assumption of sphericity was not met. Dunnett's multiple-comparison test was used to compare each treatment with the untreated control at individual sampling dates. Spear growth was analyzed using two-way repeated-measures ANOVA, whereas nutritional-quality variables were analyzed using one-way ANOVA followed by Tukey's multiple-comparison test. Data are presented as means ± standard errors (SE), and differences were considered statistically significant at $P < 0.05$.

3. Results

3.1. Number of trapped adults under different treatments

The number of trapped adults varied over time among treatments (Fig. 1). In greenhouses receiving yellow light alone, the number of trapped adults increased rapidly early in the monitoring period, peaked in mid-July, and then declined sharply. The number of trapped adults was relatively low in all four treatments from late July to mid-August. Between mid-August and early September, several increases were observed in the untreated control, whereas the number of trapped adults generally remained low in the insect-proof netting and combined treatments. The number of trapped adults decreased across treatments after mid-September. The repeated-measures analysis indicated significant effects of treatment, sampling time, and their interaction (Table 1). Dunnett's comparisons identified significantly fewer trapped adults than in the untreated control on several mid- and late-season dates in the netting

and combined treatments. In contrast, the number of trapped adults under yellow-light illumination alone did not differ significantly from the control on individual sampling dates.

3.2. *Spodoptera exigua* larval abundance under different treatments

Larval abundance varied considerably over the monitoring period (Fig. 2). The largest peak occurred in late July, followed by a rapid decline. From August onward, abundance in the untreated control fluctuated markedly, with further increases in mid- to late August and early September. Larval abundance was lower in the three intervention treatments than in the control on many sampling dates, and the combined treatment generally showed smaller fluctuations. The repeated-measures analysis detected significant treatment, time, and treatment × time effects (Table 1). Dunnett's comparisons indicated lower larval abundance than in the control on multiple dates for each intervention. These differences occurred on more sampling dates under the combined treatment than under either single treatment and extended through much of the middle and late monitoring period.

3.3. Repeated-measures analysis of the number of trapped adults and larval abundance

Table 1
Two-way repeated-measures ANOVA for the number of trapped adults and larval abundance, with greenhouse as the independent experimental unit (three greenhouses per treatment).

Response variable	Effect	*F*	*P*
Number of trapped adults	Treatment	F(3, 8) = 12.23	0.0023
	Time	F(4.63, 37.04) = 12.34	< 0.0001
	Treatment × Time	F(84, 224) = 2.18	< 0.0001
Larval abundance	Treatment	F(3, 8) = 59.28	< 0.0001
	Time	F(5.21, 41.71) = 329.70	< 0.0001
	Treatment × Time	F(84, 224) = 9.25	< 0.0001

Note: Each greenhouse contributed one observation at each sampling date. The number of trapped adults and larval abundance were transformed using log10(x + 1) before analysis. The Geisser–Greenhouse correction was applied to the reported sampling-time degrees of freedom; the treatment × time degrees of freedom are retained as reported in the original analysis.

The repeated-measures ANOVA indicated significant effects of treatment, sampling time, and their interaction on both response variables (Table 1). For the number of trapped adults, the treatment effect was significant (F(3, 8) = 12.23, $P = 0.0023$), as were the sampling-time effect (F(4.63, 37.04) = 12.34, $P < 0.0001$) and the treatment × time interaction (F(84, 224) = 2.18, $P < 0.0001$). Similarly, larval abundance was associated with significant effects of treatment (F(3, 8) = 59.28, $P < 0.0001$), sampling time (F(5.21, 41.71) = 329.70, $P < 0.0001$), and their interaction (F(84, 224) = 9.25, $P < 0.0001$). The denominator

degrees of freedom of eight for the treatment effects are consistent with four treatment groups containing three independent greenhouse replicates each.

Relative reductions in larval abundance varied with treatment and sampling date (Fig. 3). The combined treatment generally maintained comparatively high reductions and reached 100% in early September. Netting alone also showed relatively high reductions during much of the observation period. The yellow-light-only treatment was more variable; negative values occurred on several early dates when its mean larval abundance exceeded that of the untreated control. Relative reduction under yellow light subsequently increased from mid- to late August into early September. After mid-September, reductions declined across the three intervention treatments, although the combined treatment generally retained higher values. These relative reductions describe differences between treatment means and are not, by themselves, tests of statistical significance.

3.5. Effects of treatments on asparagus spear height

Spear height increased steadily from 8 to 11 September in all treatments, with broadly similar growth patterns (Fig. 4). Mean heights were approximately 40–50 mm on 8 September, 100–130 mm on 9 September, and 180–270 mm on 10 September. By 11 September, mean spear height in each treatment had reached or exceeded the 370-mm harvest threshold. Although the yellow-light-only and combined treatments had slightly greater mean heights than the netting-only and control treatments, the differences among treatments were not significant ($P > 0.05$). Thus, no detectable effect of the interventions on spear elongation was observed over the measurement period.

3.6. Effects of treatments on nutritional quality of asparagus spears

Nutritional-quality traits differed among treatments (Fig. 5). Vitamin C content was higher under yellow-light illumination alone and under the combined treatment than under the untreated control or netting alone ($P < 0.05$). Soluble protein content was highest in the combined treatment and exceeded that in the other three treatments; the yellow-light-only and netting-only treatments showed intermediate values. Nitrate nitrogen content was lowest in the combined treatment, followed by yellow light alone. Both were lower than the untreated control, whereas netting alone did not differ significantly from the control. Soluble sugar content was also higher in the two yellow-light treatments than in the control or netting-only treatment, with no significant difference between the two yellow-light treatments. These comparisons were based on the three independent greenhouse replicates assigned to each treatment.

4. Discussion

The number of trapped adults generally remained low in greenhouses protected by insect-proof netting, either alone or combined with yellow light. In contrast, yellow-light illumination alone did not significantly reduce the number of trapped adults relative to the control on any individual sampling date. These patterns are consistent with the established role of physical netting in restricting insect entry into

protected crops (Bell and Baker 2000; Böckmann 2022). Because the treatments were replicated across separate greenhouses, the comparison reflects among-greenhouse responses rather than repeated observations from a single greenhouse.

Yellow-light illumination may act through mechanisms different from those of physical exclusion. Rather than attracting and killing insects, it changes the nocturnal light environment and can influence moth behaviour (Cieraad et al. 2022; Shimoda and Honda 2013). Light exposure may alter visual adaptation and interfere with flight, activity, and mating (Shimoda and Honda 2013). However, responses depend on insect species, light intensity, lamp arrangement, and environmental conditions. Green and yellow wavelengths (500–590 nm) have been associated with behavioural and reproductive changes in several noctuid species (Jiang et al. 2018). Yellow-light exposure reduced fecundity and male longevity in *Spodoptera frugiperda* (J.E. Smith) (Jiang et al. 2020b), and yellow light can accelerate light adaptation of the compound eye, potentially changing normal nocturnal activity (Jiang et al. 2021). Thus, the larval patterns observed here are compatible with an indirect effect of yellow light on adult behaviour or reproduction, although these mechanisms were not measured in the present field experiment.

Larval abundance was lower than in the untreated control on many sampling dates under each intervention, particularly when netting and yellow light were combined. The lower larval counts in greenhouses receiving yellow light are compatible with behavioural interference affecting adult activity and reproduction (Cieraad et al. 2022; Shimoda and Honda 2013). However, the wide fluctuations and occasional negative relative reductions under yellow light alone indicate that this approach did not consistently prevent short-term increases in larval abundance. Continued immigration in the absence of a physical barrier may have contributed to this pattern (Bell and Baker 2000; Teitel 2007). Moreover, pheromone traps measure the subset of adults responding to the lure rather than total adult abundance inside a greenhouse (Onufrieva et al. 2026). If yellow light affects flight, courtship, or mating (Tanino-Springsteen et al. 2025), changes in reproductive activity may not be reflected directly in the number of trapped adults. The lower larval abundance under the combined treatment is therefore consistent with complementary effects of netting on immigration and yellow light on adult behaviour, but the underlying causal mechanisms require separate testing (Shimoda and Honda 2013; Bell and Baker 2000).

Across the three replicate greenhouses per treatment, the combined approach was associated with relatively stable larval suppression compared with the single interventions. Physical exclusion may limit the arrival of new moths, while nocturnal yellow light may affect adults already present in the greenhouse (Bell and Baker 2000; Teitel 2007; Shimoda and Honda 2013; Jiang et al. 2018). This interpretation agrees with previous work on light-based pest management (Jiang et al. 2023), but the present study did not independently quantify immigration, mating behaviour, or egg production. Accordingly, the evidence supports an association between the combined treatment and reduced larval pressure rather than definitive attribution to a particular behavioural pathway.

Spear growth was similar among treatments during the four-day observation period. Mean spear height in every treatment reached or exceeded the 370-mm harvest threshold by 11 September, and treatment

differences were not statistically significant. These observations suggest that the tested interventions did not measurably impair spear elongation under the conditions of this trial. Because growth was monitored over a short interval at one production site, longer-term effects on spear yield and marketability remain to be evaluated.

Insect-proof netting can modify the greenhouse microclimate in addition to excluding pests. Changes in daytime temperature and relative humidity under screened conditions have been documented and may influence crop development (Mahmood et al. 2018). Ventilation, light transmission, and evapotranspiration can also be affected by screen properties (Teitel 2007; Tanny 2013; Mahmood et al. 2018). In cowpea, *V. unguiculata*, netting reduced thrips abundance while changing the local microclimate (Fan et al. 2025). Consequently, plant responses to netting are likely to vary with mesh size, installation, crop species, and greenhouse conditions (Böckmann 2022). Microclimatic variables were not evaluated here, so their contribution to the observed growth and quality patterns cannot be determined.

The nutritional-quality measurements showed clearer treatment-associated differences than spear height. Vitamin C and soluble sugar contents were higher in the yellow-light-only and combined treatments, whereas the combined treatment had the highest soluble protein content and the lowest nitrate nitrogen content. Most values under netting alone were comparable to those in the untreated control. This pattern suggests that yellow-light exposure may have contributed to the observed quality differences, although the study did not directly identify the responsible physiological processes (Jiang et al. 2020c; Chen et al. 2017).

Previous work found that anti-moth lighting did not adversely affect the growth of Chinese cabbage, *Brassica rapa* L. subsp. pekinensis (Lour.) Hanelt, but altered aspects of its nutritional quality (Jiang et al. 2020c). Other studies have shown that supplemental lighting can influence sugars, proteins, vitamin C, and nitrate accumulation in leafy vegetables (Chen et al. 2017; Shen et al. 2024). The direction of several changes in asparagus was broadly consistent with these observations. Nevertheless, because irradiance responses and crop physiology may differ among species, mechanistic measurements and trials across seasons would be needed to establish how yellow light affects asparagus spear composition.

5. Conclusions

In this greenhouse-replicated field experiment, insect-proof netting combined with yellow-light illumination was associated with a comparatively low number of trapped adults and consistently reduced larval abundance during much of the monitoring period. The relative reduction in larvae reached 100% in early September, while netting alone also showed substantial reductions on many sampling dates. Yellow light alone produced more variable responses, indicating that illumination without a physical barrier may be insufficient for stable suppression under all field conditions.

Mean spear height reached the 370-mm harvest threshold in each treatment by 11 September, with no significant differences among treatments. Yellow-light illumination, alone or combined with netting, was

associated with higher vitamin C and soluble sugar contents, and the combined treatment showed the highest soluble protein and lowest nitrate nitrogen contents. These findings indicate that the physical control strategies tested did not measurably compromise short-term spear growth and were associated with differences in selected quality traits.

The findings are consistent with the possibility that physical exclusion and light-mediated interference operate in a complementary manner, although the underlying mechanisms were not directly measured. With three independent greenhouses per treatment at a single site and in one growing season, the results provide preliminary field evidence supporting combined netting and yellow-light illumination as a potential non-chemical management option for *S. exigua*. Further trials across sites and years, together with direct measurements of pest behaviour, greenhouse microclimate, and marketable yield, are needed to assess its robustness and practical applicability.

Declarations

CRediT authorship contribution statement

Deqing Xu: Methodology, Investigation, Data curation, Formal analysis, Writing – original draft. Kang Jiao: Investigation. Changshuai Wang: Investigation. Honghua Su: Conceptualization, Methodology, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contribution

Author ContributionsD.X. contributed to the methodology, field investigation, data collection, data analysis, and preparation of the original manuscript. K.J. and C.W. participated in field investigations and data collection. H.S. contributed to the study conception and experimental design, provided resources and supervision, and reviewed and edited the manuscript. All authors read and approved the final manuscript.

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Figures

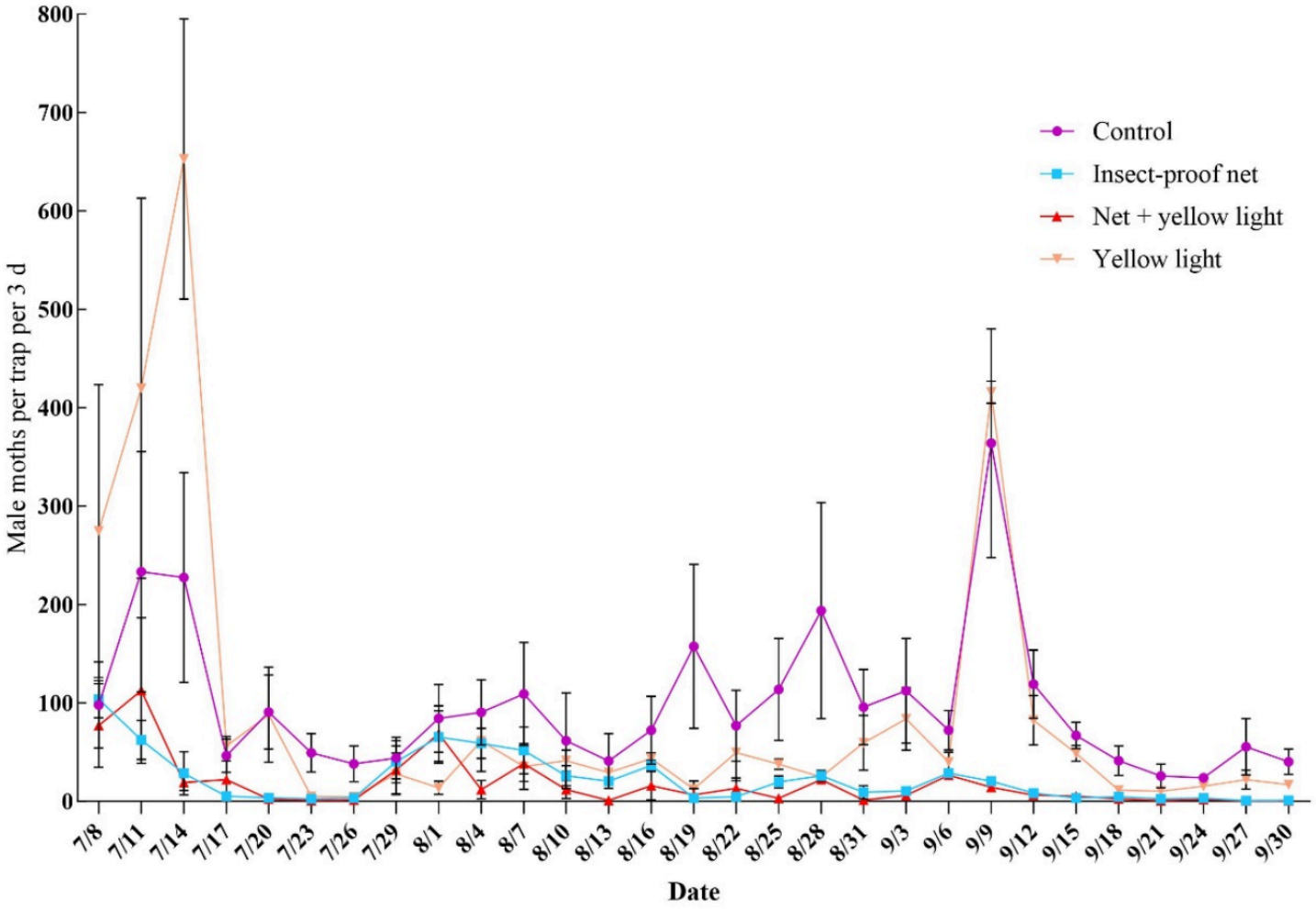
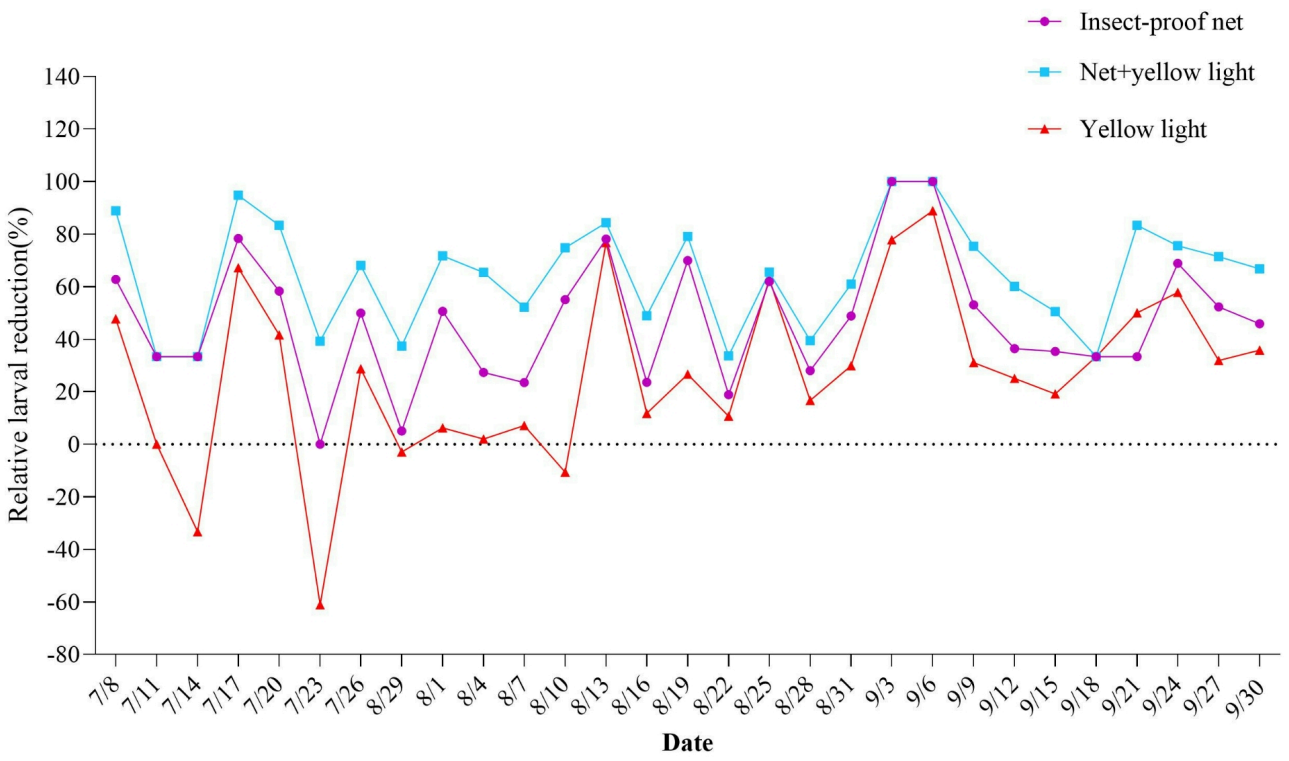


Figure 1

Temporal variation in the number of trapped adults under the four greenhouse treatments. Each point represents the mean number of trapped adults per trap per 3 d across three independent greenhouses (n = 3 per treatment); error bars indicate SE. Trap counts within a greenhouse were treated as subsamples.



3.4. Relative reduction in *Spodoptera exigua* larval abundance

Figure 3

Relative reduction in *Spodoptera exigua* larval abundance compared with the untreated control. Values were derived at each sampling date from treatment means based on three independent greenhouses per treatment; reductions were undefined when the control mean was zero.

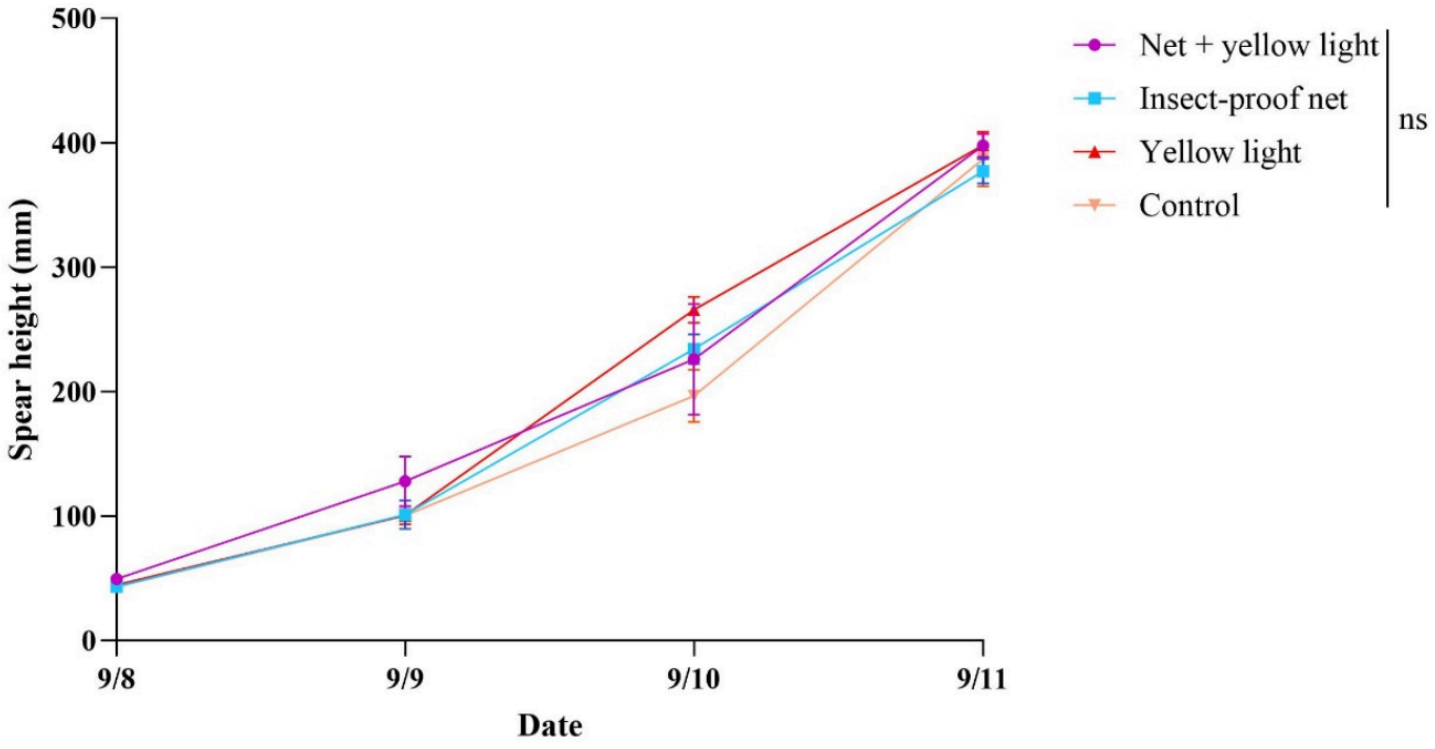


Figure 4

Changes in asparagus (*Asparagus officinalis*) spear height from 8 to 11 September under the four greenhouse treatments. Values are means across three independent greenhouses per treatment; spears within a greenhouse were subsamples. Error bars indicate SE. ns denotes a nonsignificant between-treatment difference ($P > 0.05$).

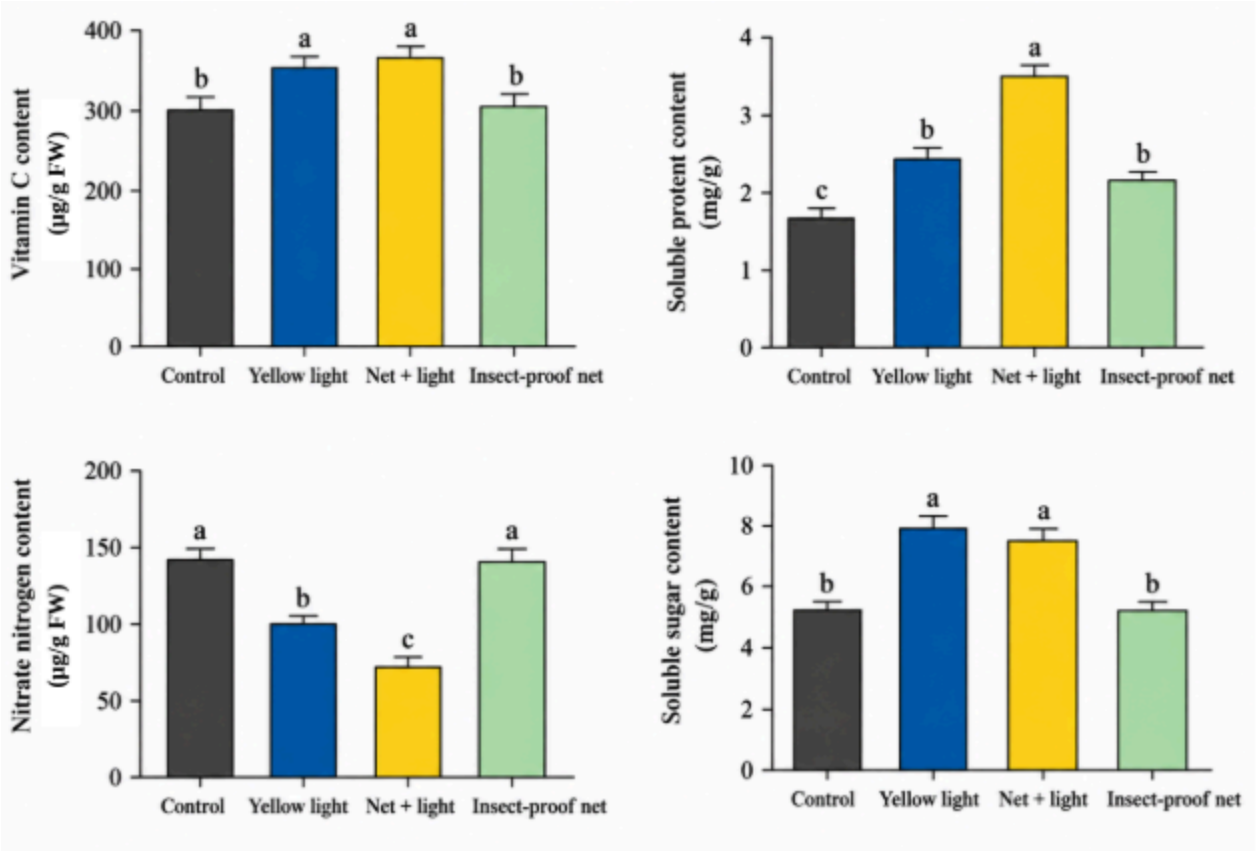


Figure 5

Nutritional-quality traits of asparagus (*Asparagus officinalis*) spears under the four greenhouse treatments: vitamin C, soluble protein, nitrate nitrogen, and soluble sugar contents. Bars represent means ± SE across three independent greenhouses per treatment. Different lowercase letters indicate significant differences among treatments ($P < 0.05$). Vitamin C and nitrate nitrogen are expressed in μg/g FW; 'Net + light' represents the combined insect-proof netting and yellow-light treatment.