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Performance-Economy-Environment multi-criteria assessment on an IPM package involving fertilization manipulation and biological pest control: a semi-field case study on tomato

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With 3 figures

Abstract: Soil organic fertilization and biological control – key components of the Multidimensional Management of Multiple Pests (3MP) theoretical framework – are known to influence insect pest populations. To evaluate their combined impact, we employed the Performance-Economy-Environment (PEE) multi-criteria assessment, which considers pest control efficacy, crop yield and quality, and environmental outcomes, to develop innovative IPM packages. However, such an integrated assessment of packages involving both organic fertilization and biological control has been lacking. We conducted a semi-field experiment using the *Solanum lycopersicum – Bemisia tabaci – Encarsia formosa* system under two fertilization regimes: full chemical fertilization (CF) and partial replacement with organic manure (COF). We found that *B. tabaci* adult and nymph abundance was significantly lower under the COF regime when *E. formosa* was present, although parasitism rates remained similar across both fertilization treatments – suggesting comparable top-down control. This implies that the COF regime exerted negative bottom-up effects on *B. tabaci* populations. In addition to improved pest suppression, the COF regime enhanced tomato yield and fruit quality, as evidenced by higher lycopene and soluble solids content and lower nitrate accumulation. Environmentally, the COF regime improved soil fertility – indicated by increased soil organic matter and organic carbon – and reduced nitrous oxide (N_2O) emissions by 16.25%, a key greenhouse gas. This first application of the PEE assessment framework to an IPM package integrating organic fertilization and biocontrol highlights the ecological, agronomic, and economic benefits of such sustainable pest management strategies.

Keywords: biological control; multidimensional management of multiple pests; top-down effects; bottom-up effects; *Bemisia tabaci*; *Encarsia formosa*

1 Introduction

In the Multidimensional Management of Multiple Pests (3MP) theoretical framework proposed by Han et al. (2024), bottom-up and top-down forces interact to shape insect pest populations through their effects on multitrophic interactions within the plant–pest–natural enemy system (Chen et al. 2010; Han et al. 2015, 2019, 2022). Among the key drivers of bottom-up effects, soil fertilization – particularly the use of organic versus chemical inputs – has been shown to influence both herbivores and their natural enemies, thereby affecting the second and third trophic levels in agroecosystems (Garratt et al. 2011, 2018; Blundell et al. 2020; Gu et al. 2021). To evaluate and optimize such complex interactions

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within integrated pest management (IPM), the Performance-Economy-Environment (PEE) multi-criteria assessment framework – comprising pest control efficacy, crop yield and quality, and environmental impacts – has been employed (Han et al. 2024). However, a comprehensive PEE assessment of IPM packages that integrate organic fertilization and biological control remains lacking.

In conventional agriculture, the long-term overuse of chemical fertilizers has been linked to an increased risk of insect pest outbreaks (Zhao et al. 2015; Fallahpour et al. 2020; Han et al. 2022). In addition to pest proliferation, conventional fertilization practices contribute to several environmental issues, including elevated greenhouse gas emissions and declining soil fertility (Yang et al. 2020; Han et al. 2023; Hou et al. 2024). In contrast, organic agriculture offers several ecological advantages: it can suppress pest populations, enhance resilience to pest damage, and improve soil quality through increased organic matter content (Garratt et al. 2018; Blundell et al. 2020; Gu et al. 2021; Rani et al. 2023). For instance, organically fertilized tomato fields have been shown to host fewer leafhoppers (*Circulifer tenellus*) (Blundell et al. 2020) and contain higher levels of soil organic matter (Garratt et al. 2018) compared to conventionally managed fields. While organic fertilization contributes to sustainable pest management and delivers various co-benefits – including improved soil health and reduced environmental impacts (Muller et al. 2012; Yang et al. 2020; Rani et al. 2023), a major limitation of fully organic fertilization systems is their often lower crop yield relative to conventional systems (Ponisio et al. 2015; Rani et al. 2023). This trade-off underscores the need to explore integrated fertilization strategies that balance productivity with sustainability.

Given the significant influence of fertilization practices on pest dynamics, crop productivity, and environmental outcomes, integrated soil fertility management approaches that support sustainable agriculture warrant greater attention. One promising strategy is the partial replacement of chemical fertilizers with organic manure. Previous studies have demonstrated that such combined applications can enhance pest control – such as in the case of wheat aphid (*Sitobion avenae*) (Gu et al. 2021) – increase crop yield and quality (Ye et al. 2020; Yang et al. 2023; Li et al. 2023a; Li et al. 2023b), and improve soil fertility (Yang et al. 2020; Han et al. 2023; Li et al. 2023a; Hou et al. 2024) across various cropping systems, including wheat, maize, rice, tomato, and apple. Despite these promising findings, comprehensive evaluations of the integrated bottom-up effects of such fertilization strategies – specifically their simultaneous impact on pest suppression, fruit yield and quality, and environmental performance – remain scarce, particularly under semi-field conditions. Addressing this gap is essential for developing robust, ecologically grounded IPM packages.

Tomato (*Solanum lycopersicum*) is one of the most widely traded vegetables globally. In 2023, China had the largest area dedicated to tomato cultivation – over 1.16 million hectares – accounting for 36.51% of global production (FAO 2025). Among the major pests threatening tomato crops are the tomato leaf miner *Tuta absoluta* (Lepidoptera: Gelechiidae) (Desneux et al. 2022; Wang et al. 2024) and the whitefly *Bemisia tabaci* (Hemiptera: Aleyrodidae) (Gennadius), a pervasive and economically significant pest worldwide (Horowitz et al. 2020). One effective method for managing *B. tabaci* is the augmentative release of its parasitic natural enemy *Encarsia formosa* (Hymenoptera: Aphelinidae), which is mass-produced and commercially available for use in greenhouse and field crops (Wang et al. 2015). In China, however, tomato farmers frequently apply excessive amounts of chemical fertilizers in pursuit of higher yields (Qu et al. 2020). This short-sighted and unsustainable practice degrades soil ecosystem health and undermines the long-term productivity of tomato cropping systems.

In this study, we address the following three questions: (i) Does the partial replacement of chemical fertilizer with organic manure (COF) influence *B. tabaci* abundance through bottom-up effects, compared to full conventional chemical fertilization (CF), when a natural enemy is present? (ii) How does the COF regime affect tomato yield and fruit quality in the presence of both the pest and its natural enemy? (iii) What are the effects of the COF regime on soil fertility and greenhouse gas emissions? To answer these questions, we established a semi-field experimental system involving *S. lycopersicum, B. tabaci*, and *E. formosa*. The findings enable a comprehensive PEE multi-criteria assessment of an IPM package integrating organic fertilization manipulation with biological control.

2 Materials and methods

2.1 Study organisms

Bemisia tabaci colonies were maintained on tomato plants in climate-controlled chambers (25 ± 1 °C, 65 ± 5% RH, 16:8 h L:D photoperiod). The parasitoid *E. formosa* was obtained from the Institute of Plant Protection, Shandong Academy of Agricultural Sciences (Shandong, China). Tomato seedlings (cv. Charlotte No. 2) were provided by Shandong Weifang Pinyu Agricultural Technology Co., Ltd., and 45-day-old plants were used for the experiments.

2.2 Experimental Design

The study was conducted from March to July 2024 in a semi-field environment at the Kunming Experiment for Sustainable Agriculture (KESA) base, Yunnan Province, China (24°52′32″N, 102°57′18″E). The semi-field setup included a roof to protect against rainstorms. During the experiment, the average daily temperature was 22 ± 1 °C, and relative humidity averaged 77 ± 2 %. The experiment included 18 separate plots, each measuring 2 m × 3 m and enclosed by nylon mesh to prevent insect escape (2 m in height) (Fig. S1). Additionally, 1-mm-thick double-layer waterproof polyethylene (PE) barriers were installed around the base of each plot at 1-meter depth to minimize lateral nutrient and water movement. Each plot was planted with 10 healthy tomato seedlings, arranged in two rows of five plants each. Two fertilization regimes were tested: chemical fertilizer alone (CF), and a combination of chemical fertilizer and organic manure (COF), with the latter consisting of a 1:1 ratio of chemical fertilizer and sheep manure (Li et al. 2023b). Nine plots were assigned to each treatment. Following local recommendations, nitrogen was applied at an optimal rate of 450 kg/ha for a planting density of 36,000 tomato plants. In both treatments, the quantities of urea, superphosphate, and potassium sulfate were adjusted to achieve a uniform nutrient ratio of 16.9:9:30.3 for N:P:K (Table S1). Sheep manure, provided by Junfa Agricultural Science and Technology Co., Ltd., was incorporated into the soil one week prior to transplanting. Chemical fertilizers were applied as a basal dose at the seedling stage, with additional applications during the flowering and fruiting stages. Plots were artificially infested with *B. tabaci*, and the parasitoid *E. formosa* was subsequently released. To establish overlapping generations of *B. tabaci*, adults were released twice: 50 individuals per plot were introduced seven days after transplanting, followed by a second release of the same number seven days later. *Encarsia formosa* was released 20 days after the first *B. tabaci* release, at a density of two adults per plant.

2.3 Insect sampling

The population dynamics of *B. tabaci* were monitored at 10-day intervals, beginning one week after the release of *E. formosa*. Sampling was conducted using a systematic zigzag approach within each plot, with five tomato plants selected from the ten available per plot. To reduce sampling bias, different plants were selected in successive sampling events. Nymph and adult stages of *B. tabaci* were assessed separately. On each selected plant, three leaves – one each from the upper, middle, and lower canopy – were randomly chosen, and insects were counted on both sides of each leaf. The abundance of *E. formosa* was evaluated by counting the number of *B. tabaci* pupae parasitized by the wasp. Parasitized pupae, which turn black, served as a reliable indicator of successful parasitism (Wang et al. 2015).

2.4 Tomato yield and quality

Undamaged (marketable) fruits were harvested when their color changed from green to pink. For yield monitoring, three tomato plants were randomly selected and tagged in each plot. All the 18 plots were sampled. For fruit quality analysis, three fruits of similar size and color were collected from each of four plots per treatment and pooled as a single sample. All fruit samples were homogenized and stored at –80 °C prior to analysis of quality parameters, including soluble solids, soluble sugars, soluble proteins, lycopene, and nitrate content (Li et al. 2023a; Li et al. 2023b; Yang et al. 2023).

Soluble solids were measured using the constant weight method. Briefly, 40 g of fruit homogenate was mixed with 100 mL of distilled water, boiled for 2–3 min, cooled to room temperature, and left to stand for 20 min. The sample was then weighed, filtered, and 1 g of the filtrate was dried at 105 °C and reweighed. Soluble sugars were quantified using a commercial biochemical kit (Chongqing Bonoheng Biotechnology Co., Ltd.) based on the anthrone colorimetric method. Soluble proteins were measured with the same supplier's kit using the bicinchoninic acid (BCA) method.

Lycopene content was determined by high-performance liquid chromatography (HPLC; Agilent 1200). Two grams of homogenized fruit sample were mixed with 5 mL of methylene chloride in a 15 mL brown centrifuge tube, homogenized for 1 min, and shaken at room temperature for 4 h. The mixture was centrifuged at 4,000 rpm for 10 min. The supernatant was collected, and the residue was re-extracted. Both extracts were combined, filtered through a 0.22 μm membrane, and used for HPLC analysis.

Nitrate content was measured by ultraviolet spectrophotometry. Briefly, 0.1 g of fruit sample was placed in a 100 mL volumetric flask with 20 mL of distilled water. One drop of *n*-octanol was added to eliminate foam, followed by 3 mL of ammonia buffer solution and 0.5 g of activated carbon. The mixture was shaken for 30 min at 200 oscillations/min. Afterward, 1 mL each of potassium ferrocyanide and zinc sulfate solutions was added. The volume was adjusted to 100 mL with distilled water, shaken, allowed to stand for 5 min, and filtered. The optical density (OD) was measured at 219 nm.

2.5 Soil sample and soil-surface greenhouse gas emission measurement

At the late growth stage of tomatoes, soil samples were collected from three locations within each plot, combined into a composite sample, and stored in sealed bags. Samples were air-dried, ground, and sieved through a 2 mm mesh prior to analysis. Soil organic matter (SOM) was determined following the Chinese Agricultural Industry Standard for Soil Testing (Part 6: Determination of Soil Organic Matter, NY/T 1121.6-2006). Soil organic carbon (SOC) was quantified using the potassium dichromate-sulfate colorimetric method (Li et al. 2023a). Four plots per fertilization regime were sampled.

Soil surface emissions of the greenhouse gas nitrous oxide (N_2O) were measured using the static closed chamber–gas chromatography method. Four experimental units were randomly selected per treatment, and one transparent glass gas sampling chamber (30 cm in diameter, 25 cm in height) was installed in each plot. Gas sampling was performed three times per week immediately following each fertilization event, and once per week thereafter. Gas samples were collected between 8:00 and 11:00 AM at 0, 15, 30, and 45 minutes after chamber closure. During sampling, the chamber valve was opened and the internal gas was mixed by pumping a syringe back and forth three times. A 50 mL gas sample was then extracted and injected into a pre-evacuated 12 mL gas vial. At least 40 mL of gas was introduced to maintain sufficient internal pressure for accurate analysis. The chamber temperature was recorded during each sampling event.

All gas samples were analyzed within seven days using gas chromatography to determine N_2O concentrations. The N_2O emission flux from soil was calculated using the linear least squares regression method, following Metcalfe et al. (2007), using the equation:

$$F=\frac{dc}{dt}\times\frac{273}{273+T}\times\frac{M}{22.4}\times\frac{V}{A}$$

where F is soil greenhouse gas emissions, dc/dt is the rate of change in gas concentration inside the chamber, T is the air temperature in the chamber, M is the molecular weight of the gas (N_2O: 44 g mol^{-1}), 22.4 is the standard molar volume (1 mol^{-1}), V is the chamber volume (m^3), and A is the bottom area of the chamber (m^2).

The cumulative soil greenhouse gas emissions during the sampling period were calculated using the formula (Yuan et al. 2019):

$$E=\sum_{i=1}^{n}\frac{f_i+f_{i+1}}{2}\times(t_{i+1}-t_i)\times24\times10^{-2}$$

where E is the cumulative emissions of N_2O (kg N_2O ha^{-1}) during the sampling period, f represents the emission rate of N_2O (mg N_2O m^{-2} h^{-1}), i refers to the ith measurement, $(t_{i+1} - t_i)$ is the number of days between two measurements, and 24×10^{-2} is used for unit conversion.

3 Statistical analyses

To assess the population dynamics of *B. tabaci*, data on adult and nymph abundances were analyzed using generalized linear mixed models (GLMMs) with a negative binomial error distribution to account for overdispersion (R function 'glmer.nb', R package 'lme4'). In the model, "fertilization regime" (CF vs. COF) was treated as a fixed factor, "survey date" as a covariate, and "plot" as a random factor. Parasitism rates of *E. formosa* were analyzed using GLMMs with a Beta distribution and a logit link function, with the same fixed and random effects structure as above.

Tomato yield and fruit quality variables (soluble solids, soluble sugars, soluble proteins, lycopene, and nitrates) were analyzed using generalized linear models (GLMs) with a Gamma distribution and a log link function. Similarly, soil fertility indicators (soil organic matter and soil organic carbon) and cumulative N_2O emissions were analyzed using GLMs with Gamma distributions and log link functions.

Prior to analysis, data normality was tested using the Shapiro–Wilk test, and homogeneity of variances was assessed using Levene's test. All statistical analyses were performed using R software (R Development Core Team, R4.4.1)

4 Results

4.1 Population dynamics of *B. tabaci* and *E. Formosa*

The abundances of *B. tabaci* adults and nymphs increased significantly over the survey period (adults: $\chi^2 = 29.78$, $df = 1$, $P < 0.001$; nymphs: $\chi^2 = 150.19$, $df = 1$, $P < 0.001$) (Fig. 1A, 1B). The COF regime resulted in significantly lower abundances of both adults and nymphs compared to the CF regime (adults: $\chi^2 = 4.75$, $df = 1$, $P = 0.029$; nymphs: $\chi^2 = 5.14$, $df = 1$, $P = 0.023$) (Fig. 1A, 1B). No significant interaction was detected between fertilization regime and survey time (adults: $\chi^2 = 0.10$, $df = 1$, $P = 0.749$; nymphs: $\chi^2 = 0.16$, $df = 1$, $P = 0.694$) (Fig. 1A, 1B).

The parasitism rate of *E. formosa* on *B. tabaci* populations increased significantly over the survey period ($\chi^2 = 61.83$, $df = 1$, $P < 0.001$) (Fig. 1C). However, fertilization regime had no significant effect on the parasitism rate ($\chi^2 = 0.05$, $df = 1$, $P = 0.817$) (Fig. 1C). No significant interaction was observed between fertilization regime and survey time ($\chi^2 = 0.22$, $df = 1$, $P = 0.639$) (Fig. 1C).

4.2 Tomato yield and quality

Fertilization regime had a significant effect on tomato yield, with COF regime resulting in a significantly higher yield compared to CF regime ($\chi^2 = 21.74$, $df = 1$, $P < 0.001$) (Fig. 2A). Additionally, the COF regime significantly improved tomato quality by increasing lycopene content ($\chi^2 = 9.65$, $df = 1$, $P = 0.002$) (Fig. 2B) and soluble solids content ($\chi^2 = 6.53$, $df = 1$, $P = 0.011$) (Fig. 2C), while reducing nitrate levels ($\chi^2 = 13.34$, $df = 1$, $P < 0.001$) (Fig. 2D) compared to the CF regime. However, no significant effects of the COF regime were observed on fruit soluble sugar ($\chi^2 = 1.09$, $df = 1$, $P = 0.296$) (Fig. 2E) or soluble protein content ($\chi^2 = 1.88$, $df = 1$, $P = 0.170$) (Fig. 2F).

4.3 Soil fertility and N_2O emissions

The COF regime significantly increased soil organic matter ($\chi^2 = 15.99$, $df = 1$, $P < 0.001$) (Fig. 3A) and soil organic carbon contents ($\chi^2 = 15.90$, $df = 1$, $P < 0.001$) (Fig. 3B) compared to the CF regime. Although the COF regime did not have a statistically significant effect on soil N_2O emissions ($\chi^2 = 2.74$, $df = 1$, $P = 0.098$), it reduced N_2O emissions by 16.25% relative to the CF regime (Fig. 3C).

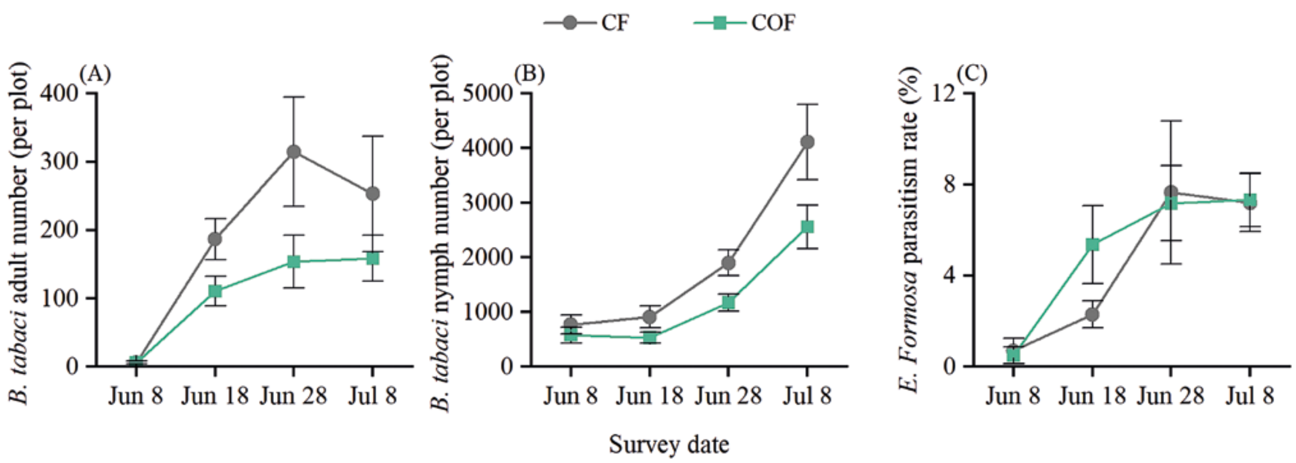

Fig. 1. Population dynamics of *B. tabaci* and *E. formosa* under different fertilization regimes. CF and COF represent chemical fertilizer and partial replacement of chemical fertilizer by organic manure, respectively. (A), (B), and (C) show the number of *B. tabaci* adults, the number of *B. tabaci* nymphs, and the parasitism rate of *E. formosa*, respectively. The abundance of *B. tabaci* adults and nymphs per plot corresponds to the total number counted on five plants sampled within each plot.

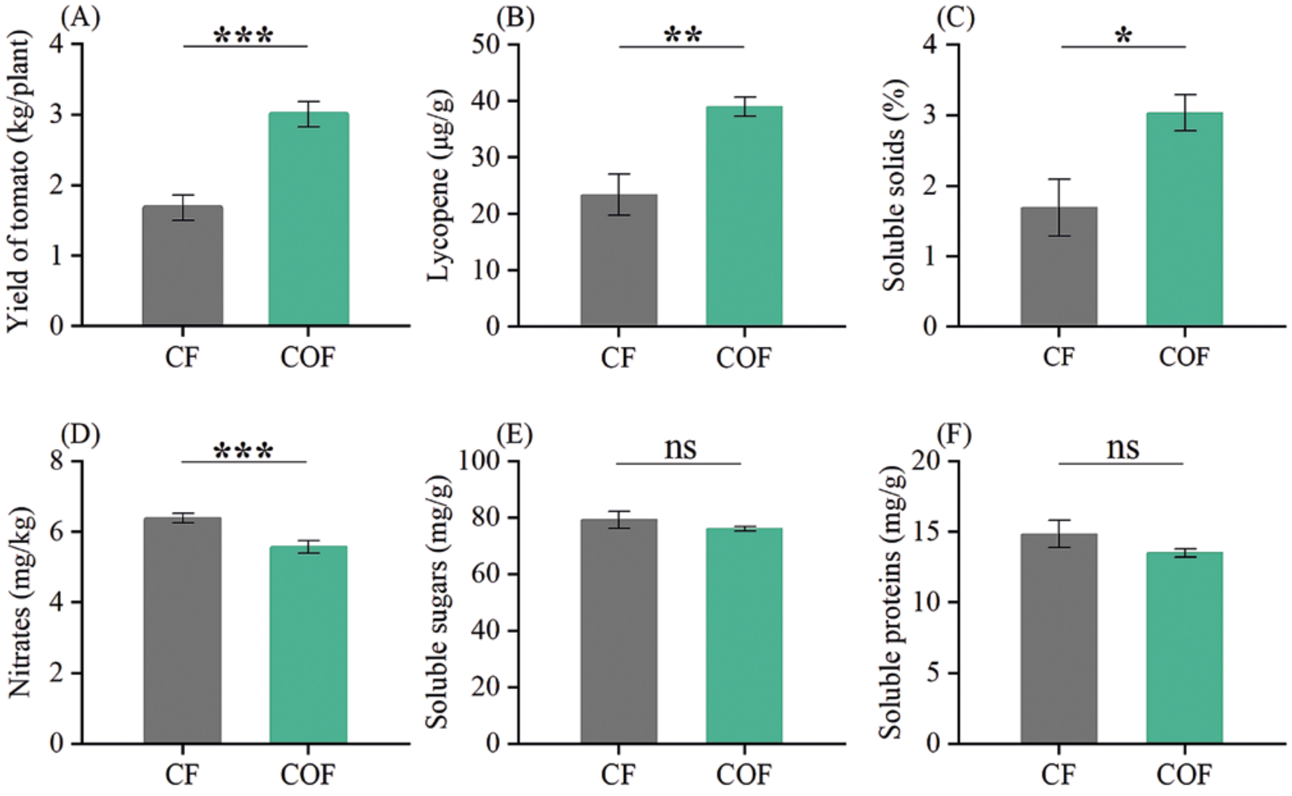

Fig. 2. Effects of different fertilization regimes on tomato yield and quality. CF and COF represent chemical fertilizer and partial replacement of chemical fertilizer by organic manure, respectively. Significance levels are indicated as follows: *** $P < 0.001$, ** $0.001 \le P < 0.01$, * $0.01 \le P < 0.05$, and ns (not significant) $P > 0.05$.

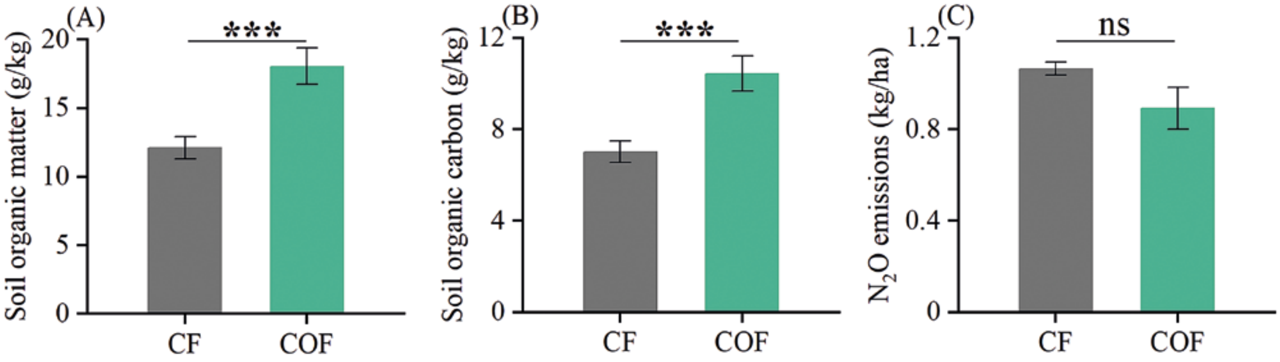

Fig. 3. Effects of fertilization regimes on soil fertility and greenhouse gas emissions. CF and COF represent chemical fertilizer and partial replacement of chemical fertilizer by organic manure, respectively. Significance levels are indicated as follows: *** $P < 0.001$, ns (not significant) $P > 0.05$.

5 Discussion

Our data demonstrated that *B. tabaci* populations – both adults and nymphs – were significantly lower under partial replacement of chemical fertilizer with organic manure (COF) compared to the chemical fertilizer (CF) regime when the parasitoid *E. formosa* was present. Notably, the parasitism rate of *E. formosa* on *B. tabaci* did not differ between fertilization regimes, indicating that biocontrol efficacy was retained. Compared to the CF regime, COF significantly enhanced tomato yield and quality. Furthermore, COF improved soil fertility and reduced emissions of the important greenhouse gas nitrous oxide (N_2O) by 16.25%.

Previous research has shown that soil fertilization can trigger tri-trophic nutritional cascades – affecting parasitoids and predators – by altering plant and herbivore nutritional quality (Chen et al. 2010; Hosseini et al. 2018; Han et al. 2022; Ma et al. 2024). For example, Hosseini et al. (2018) found that reduced nitrogen fertilization decreased the nutritional quality of cotton aphids (*Aphis gossypii*), which cascaded up to increase predation by *Hippodamia variegata*. However, other studies suggest these bottom-up effects on higher trophic levels depend on the functional guilds of natural enemies involved (Han et al. 2015; Becker et al. 2021; Ma et al. 2024). Ma et al. (2024) showed fertilization-driven bottom-up effects did not affect parasitoid pest control but modified carnivorous predator biocontrol efficacy. Our findings align with this, as the trophic cascade had no impact on *E. formosa* parasitism despite significant effects on *B. tabaci* abundance (Fig. 1). This supports the hypothesis of diluted bottom-up effects proposed by Becker et al. (2021), whereby parasitoids at the third trophic level are buffered by the herbivore (second trophic level). Moreover, COF likely reduced *B. tabaci* abundance by altering host plant chemistry and nutrient profiles, reducing host palatability and negatively affecting herbivores (Altieri & Nicholls 2003; Garratt et al. 2018; Blundell et al. 2020; Gu et al. 2021; Han et al. 2022). Overall, appropriate organic fertilizer management that does not disrupt parasitoid function offers promising routes for optimizing pest control in IPM.

It has been reported that partial replacement of chemical fertilizer with organic manure maintains and improves crop productivity and quality (Ye et al. 2020; Li et al. 2023a; Li et al. 2023b). Consistent with these findings, COF significantly improved tomato yield and fruit quality, evidenced by increased lycopene and soluble solids and reduced nitrate contents compared to CF (Fig. 2). These benefits likely arise from the complementary effects of organic and chemical fertilizers: while chemical fertilizer supplies nitrogen rapidly to promote early vegetative growth, organic manure provides a slow, sustained nutrient release and increases soil organic matter (Adekiya et al. 2020; Qu et al. 2020; Jin et al. 2023). This combination enhances soil nitrogen availability and improves nitrogen immobilization via increased soil microbial activity (Liao et al. 2018; Hou et al. 2024; Zhou et al. 2024), improving fertilizer use efficiency (Li et al. 2023a). Such mechanisms may explain the observed reductions in fruit nitrate and soil N_2O emissions under COF (Fig. 2D, 3C), as organic fertilizer promotes biological nitrogen fixation and inhibits ammoniacal nitrogen nitrification (Liao et al. 2018; Han et al. 2023).

Additionally, the combination fertilization regime increases soil organic matter and organic carbon (the main component of soil organic matter) that are both critical for soil fertility. (Adekiya et al. 2020; Yang et al. 2020; Li et al. 2023a). Our results confirm that COF significantly increased soil organic matter and organic carbon compared to CF (Fig. 3). Soil organic matter supports beneficial soil microorganisms by providing nutrients and energy, promoting microbial enrichment (Jin et al. 2023; Zhou et al. 2024). Microbial decomposition of organic matter releases nutrients available to crops, thereby improving fertility and crop performance (Ding et al. 2016; Du et al. 2022). The increased tomato fruit lycopene and soluble solids under COF (Fig. 2B, 2C) may be linked to enhanced soil organic matter and microbial activity. Organic fertilizer addition stimulates soil microbes that mineralize organic matter and alter soil physicochemical properties, thus improving fruit quality (Ding et al. 2016; Du et al. 2023; Gao et al. 2023).

In conclusion, partial replacement of chemical fertilizer with organic manure reduces *B. tabaci* abundance through bottom-up effects without diminishing the top-down parasitism by *E. formosa*, while simultaneously improving tomato yield, fruit quality, and soil health, and reducing environmental impacts such as N_2O emissions. These findings can inform optimized IPM strategies integrating fertilization regimes with biological control. Further research on interactions between fertilization and other pest management tactics, including companion planting, could promote synergistic pest suppression (Han et al. 2024). The Performance, Environment, and Economy (PEE) assessment framework offers a powerful approach to designing "multi-win" IPM packages that advance crop protection, environmental sustainability, and ecological health.

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The pdf version (Adobe JavaScript must be enabled) of this paper includes an electronic supplement: **Figure S1**