Economic Evaluation of Anaerobic Soil Disinfestation with Varying Carbon and Nitrogen Application Rates in Open-field Organic Strawberry Production

Dinglin Duan[1], Yefan Nian[2,3], Nan Xu[4], Xin Zhao[4], Jason Hong[5], Erin Rosskopf[5], and Zhifeng Gao[1]

KEYWORDS. biological soil disinfestation, economic analysis, *Fragaria* ×*ananassa*, partial budget analysis, sensitivity analysis, soilborne diseases

ABSTRACT. **The phaseout of methyl bromide in agricultural production due to its adverse environmental impact has prompted specialty crop industry stakeholders to seek alternative soilborne disease management practices in the United States. Anaerobic soil disinfestation (ASD), recognized as a biological and environmentally friendly alternative, is considered a promising practice for managing soilborne pathogens, nematodes, and weeds. However, the economic feasibility of ASD in strawberry (*Fragaria* ×*ananassa*) production remains underinvestigated. This study evaluated the economic viability of ASD using various application rates of carbon and nitrogen fertilizer sources in open-field organic strawberry production. Using field experiment data from production seasons 2022–23 and 2023–24 in Citra, FL, USA, the economic analysis demonstrated that although ASD treatments incur higher costs, the additional returns from increased yields of some treatments can offset these costs. Using 1486.0 gal/acre of molasses as the carbon source and 4.2 tons/acre of Everlizer (a heat-processed chicken litter product) as the nitrogen source in season 2022–23 produced the highest yield compared with the control group that did not use ASD in production. The same treatment in season 2023–24 produced the fifth-highest yield. When averaging the yields from both seasons, the same treatment still generated the highest added profit compared with the control group. Sensitivity analysis identified yield as the primary determinant of profit. Meanwhile, the profitability of strawberry production in treatment groups was highly sensitive to fluctuations in both strawberry selling price and molasses price. The findings of this study provide crucial information for strawberry producers to determine the economic viability of using ASD in organic crop production systems.**

Soilborne diseases pose significant risks to specialty crop production worldwide. Multiple pathogens, including fungi, nematodes, bacteria, viruses, and protozoans, can cause severe soilborne diseases and affect the roots, stems, and vascular systems of specialty crops (Abawi and Widmer 2000; Agrios 2005; Katan 2017). Soilborne diseases can bring substantial economic loss to crop production by decreasing yield and fruit quality (Blok et al. 2000; Koike et al. 2003; Lucas 2006). According to the US Department of Agriculture–Agricultural Research Service (USDA-ARS 2022). Soilborne diseases caused by fungal pathogens alone can result in 10% to 20% yield losses. In addition, soilborne fungi that may cause soilborne diseases can persist in the soil for an extended period because of their resistant structures, such as melanized mycelium, chlamydospores, oospores, and sclerotia. For example, chlamydospores may have thick walls to protect fungi from unfavorable conditions. As a result, managing soilborne diseases becomes exceptionally challenging (Baysal-Gurel et al. 2012; Lucas 2006).

For years, specialty crop producers in the United States have heavily relied on chemical fumigants such as methyl bromide to manage soilborne diseases in crop production (Kubota et al. 2008; Rosskopf et al. 2005, 2024). However, due to methyl bromide's negative impact on the ozone layer, it is no longer available for producers to use, in accordance with the Montreal Protocol signed by the United States and 182 other countries (Osteen 2003). While efforts continue to seek alternative chemical fumigants, developing viable nonchemical approaches to managing soilborne diseases toward long-term sustainability is also critical.

Among several emerging nonchemical alternatives to control soilborne pathogens in specialty crop production, ASD has been identified by researchers as a promising approach (Blok et al. 2000; Di Gioia et al. 2017; Lamers et al. 2010; Rosskopf et al. 2020). As a biologically based technology, ASD uses readily decomposable carbon sources, such as molasses, rice bran, wheat middlings, and cover crops, to provide reliable carbon and nutrients and to stimulate the growth of beneficial soil microbes (Guo et al. 2018; Hewavitharana et al. 2019; Ono-Raphel et al. 2025; Vincent et al. 2022). Before planting, plastic film coverage, combined with thorough irrigation to saturation, is applied to effectively restrict air exchange and sustain an anaerobic environment in the soil. Decreased available oxygen facilitates anaerobic microbes to break down carbon sources, producing organic acids, volatiles, and other by-products to suppress soilborne pathogens (Momma 2008; Panth et al. 2020; Rosskopf et al. 2015; van Agtmaal et al. 2015).

ASD has been proven effective in managing soilborne diseases in open-field and protected crop productions (Blok et al. 2000; Shinmura et al. 1999). Extensive research and field trials on ASD have been conducted in the United States (Butler et al. 2012, 2014; Di Gioia et al. 2016, 2017; Donahoo et al. 2021; Rosskopf et al. 2014, 2020; Shi et al. 2019; Vincent et al. 2024). For example, field trials conducted in Florida have demonstrated that ASD effectively controlled

Received for publication 18 Feb 2025. Accepted for publication 7 Jul 2025.

Published online 19 Aug 2025.

[1]Food and Resource Economics Department, University of Florida, Gainesville, FL 32611, USA

[2]Department of Agricultural Sciences, Clemson University, Clemson, SC 29631, USA

[3]Sandhill Research and Education Center, Clemson University, Columbia, SC 29229, USA

[4]Horticultural Sciences Department, University of Florida, Gainesville, FL 32611, USA

[5]US Horticultural Research Laboratory, USDA-ARS, Fort Pierce, FL 34945, USA

Current address for N.X.: Southern Oregon Research and Extension Center, Oregon State University, Central Point, OR 97502, USA

Z.G. is the corresponding author. E-mail: zfgao@ufl.edu.

https://doi.org/10.21273/HORTTECH05631-25

various soilborne diseases across multiple crops, including tomato (*Solanum lycopersicum*), cucumber (*Cucumis sativus*), bell pepper (*Capsicum annuum*), eggplant (*Solanum melongena*), and strawberry (*Fragaria* × *ananassa*) (Butler et al. 2012, 2014; Di Gioia et al. 2016, 2017; Guo et al. 2017; Rosskopf et al. 2014; Shennan et al. 2014). In addition to disease control, ASD is effective in promoting higher yields compared with chemical soil fumigation in tomato production (Di Gioia et al. 2016; Guo et al. 2017; Paudel et al. 2020). The same and additional research has shown that ASD can suppress plant-parasitic nematodes and weeds (Di Gioia et al. 2016; Guo et al. 2018; Singh et al. 2025; Vincent et al. 2024). As a nonchemical tool, ASD also brings benefits to organic production systems.

Many strawberry producers remain hesitant to adopt ASD because of concerns about the economic viability of implementing this relatively new technique. First, although ASD can increase crop production revenue by increasing yield, it also incurs additional labor and material costs and results in uncertainty about profitability. Second, the economic viability of ASD-based crop production may largely depend on factors such as production region, production system, and crop type. Because ASD requires a carbon source to initiate the process, the cost of locally available carbon sources can greatly affect the net returns of ASD-based crop production. Also, the variation of market conditions across crop types and regions can cause producers to receive different revenue gains from yield increases in ASD-based crop production. As a result, determining the economic impact of ASD on crop production is of critical importance.

To our knowledge, most economic analyses of ASD have focused on tomato production (e.g., Donahoo et al. 2021; Shi et al. 2019), and the economic implications of ASD in strawberry production are still unknown. To fill the gap in the literature, this study investigates the economic viability of ASD in organic strawberry production. Specifically, we analyzed the economics of ASD implemented with different application rates of carbon and nitrogen fertilizer inputs in organic strawberry production. Using 2-year field trial data generated on an agricultural research station in north central Florida (Citra, FL, USA), we examined the extent to which ASD treatments with five levels of carbon source rates and five levels of nitrogen source rates affected the economic outcomes of organic strawberry production compared with organic strawberry production without carbon and nitrogen sources.

Materials and methods

Experimental setup. Open-field experiments of organic strawberry production were established on USDA-certified organic land at the Plant Science Research and Education Unit of the University of Florida in Citra, FL, USA. The soil type at the research site was Gainesville loamy sand (hyperthermic, coated Typic Quartzipsamments) with 93.04% sand, 6.72% clay, 0.24% silt, and an average soil organic matter content of 0.7%. To ensure the robustness of the experimental results, the experiment was conducted during two strawberry production seasons, that is, 2022–23 and 2023–24. Each field trial followed a split-plot design with the whole plot factor being the carbon source (blackstrap molasses purchased from Double S Liquid Feed, Inc., Danville, IL, USA) and the subplot factor being the granular organic fertilizer (Everlizer®, heat-treated chicken litter, 3%N–3%P_2O_5–3%K_2O; Live Oak, FL, USA). Five rates of molasses were applied at 0, 371.5, 743.0, 1,114.5, and 1486.0 gal/acre and five rates of Everlizer were applied at 0, 2.1, 4.2, 6.4, and 8.5 tons/acre. The group that applied no molasses and no Everlizer (0 gal/acre molasses and 0 tons/acre Everlizer) will be referred to as the control group in later analysis. Although it did not apply any carbon and nitrogen sources, it received the same ASD setup as all other treatments, including sunn hemp (*Crotalaria juncea*) incorporation, soil preparation, totally impermeable film (TIF; black on top) application, and irrigation to saturation. Each treatment combination was replicated four times, resulting in 100 plots per experiment, with 25 treatment combinations per replicate, and each subplot measuring 48 ft^2 with 30 strawberry plants. Each bed (whole plot) was 110 ft in length and 3 ft in width, with 5 ft buffers between plots. The five beds in each replication were on 5 ft spacing (from center to center), and there was a 10 ft buffer between the four replications.

As a common practice, sunn hemp (*Crotalaria juncea*) was seeded in July as a cover crop in rotation with strawberry production and was ended ~60 d after planting. Termination involved chopping the aboveground biomass into ~5 cm pieces using a flail chopper (Model 5700; Hiniker Company, Mankato, MN, USA), followed by incorporating the sunn hemp residues into the soil to a depth of 10 cm using a rototiller. Soil preparation and ASD treatment initiation occurred within 7 to 8 d after sunn hemp residue incorporation. In mid-September, all ASD inputs (molasses and Everlizer) were applied manually and incorporated into the raised beds using a rototiller before laying the TIF (black on top) and installing two drip irrigation lines. Two acre-inches of water was delivered through the drip lines to saturate the soil and initiate the ASD treatment. The ASD treatment lasted for 21 d and was ended by punching planting holes through the TIF, allowing for gas exchange before strawberry transplanting. The TIF film remained in place and continued to be used for strawberry production, with the drip lines serving as in-season irrigation and fertigation lines. Upon completion of the ASD treatment, bare-root strawberry 'Florida Brilliance' plants were transplanted in double rows on each raised bed (30 plants per subplot) in early October of both years. Strawberry harvests started in early December and ended in late April. Ripe fruits were harvested twice a week in each plot. After harvesting, the fruits were evaluated and weighed based on the USDA strawberry grade standards [US Department of Agriculture–Agricultural Marketing Service (USDA-AMS), 2006]. Fruits were considered marketable if they were not overripe or underdeveloped; free from decay, disease, or damage; and met minimum size (10 g) and shape requirements, making them suitable for sale in fresh markets.

Partial budget analysis. We used partial budget analysis to examine the impact of ASD on the overall economic performance of organic strawberry production. Partial budget analysis is a valuable tool to assess the effects of farm management practice changes on crop production's economic outcomes (Alimi and Manyong 2000; Sydorovych et al. 2008). This method focuses exclusively on resources that will be changed by implementing a specific practice, which leads to incremental costs and benefits in farm management. By comparing these added costs and returns, producers can evaluate the potential economic advantages of adopting new technologies (Nian et al. 2022; Shi et al. 2019).

In the case of ASD-based crop production, added costs incurred by additional materials and labor required by ASD are considered negative effects. Added economic returns associated with yield increases are positive effects. With the identified and aggregated positive and negative effects, producers can determine the net benefits of adopting ASD by subtracting the total costs from the total benefits. The principal formulas used in partial budget analysis are listed as follows. First, the formation of the total cost is

$$TC = Preproduction\ cost + Production\ cost + Harvesting\ cost + Marketing\ cost, \quad [1]$$

where TC represents the total cost, which is the combined cost from different stages of strawberry production. To calculate the total revenue of strawberry production, we used the following formula:

$$TR = \Sigma_t \bar{P}_t \times Q_t, \quad [2]$$

where TR (\$/acre) is the total revenue, t denotes the week number in the harvesting season, P_t (\$/lb) is the average weekly shipping point price for strawberries from 2019 to 2023 in week t, and Q_t (lb/acre) is the total marketable yield in week t.

We used the weekly shipping point price to calculate the strawberry production revenue because the selling price of strawberry fluctuates over the production season. The ASD treatments may influence the strawberry yields at different harvest dates and, thus, affect the production revenue. In our experiment, we recorded harvesting dates and the corresponding marketable yield in each experimental plot. For strawberry prices, we collected Florida organic strawberry daily shipping point prices from the USDA-AMS (2023). To ensure our analysis matched the actual market scenario and considering strawberry price fluctuations over the years, we aggregated and calculated the average weekly organic strawberry price in the past 5 years (2019–23). We then matched the weekly organic strawberry price with the harvesting dates recorded from field production. The average organic strawberry price for week t was calculated using the following formula:

$$\bar{P}_t = \frac{P_{t,y-4} + P_{t,y-3} + P_{t,y-2} + P_{t,y-1} + P_{t,y}}{5}, \quad [3]$$

where $P_{t,y}$ denotes the organic strawberry selling price in week t at year y. Then, the net return of strawberry production was derived by subtracting total cost from total revenue:

$$Net\ return = TR - TC. \quad [4]$$

To better assess the distribution of economic returns, we calculated the mean and standard deviations (SDs) of

Table 1. Two-year average costs of anaerobic soil disinfestation treatments in organic strawberry production in Citra, FL (2022–23 and 2023–24 seasons).

Treatments			Cost (\$/acre)						
	Molasses	Everlizer							
Treatment ID	(gal/acre)	(tons/acre)	Molasses	Everlizer	Labor	Container box	Selling and marketing	Organic certification fee	Total cost
M1F1[i]	0	0	0	0	2,562.68	1,804.13	820.06	46.13	5,232.99
M1F2[i]	0	2.1	0	847.59	3,172.40	2,036.25	925.57	52.06	7,033.88
M1F3[i]	0	4.2	0	1,695.18	3,697.30	2,405.78	1,093.54	61.51	8,953.30
M1F4[i]	0	6.4	0	2,542.77	3,632.42	2,360.11	1,072.78	60.34	9,668.42
M1F5[i]	0	8.4	0	3,390.36	3,511.50	2,274.98	1,034.08	58.17	10,269.09
M2F1[i]	371.5	0	323.21	0	3,481.16	2,209.97	1,004.53	56.50	7,075.37
M2F2[i]	371.5	2.1	323.21	847.59	4,096.02	2,445.71	1,111.69	62.53	8,886.74
M2F3[i]	371.5	4.2	323.21	1,695.18	3,907.60	2,313.06	1,051.39	59.14	9,349.57
M2F4[i]	371.5	6.4	323.21	2,542.77	3,964.16	2,352.88	1,069.49	60.16	10,312.66
M2F5[i]	371.5	8.4	323.21	3,390.36	3,840.69	2,265.96	1,029.98	57.94	10,908.13
M3F1[i]	743	0	646.41	0	3,605.67	2,297.62	1,044.37	58.75	7,652.82
M3F2[i]	743	2.1	646.41	847.59	3,964.56	2,353.16	1,069.62	60.17	8,941.50
M3F3[i]	743	4.2	646.41	1,695.18	3,397.22	1,953.76	888.07	49.95	8,630.60
M3F4[i]	743	6.4	646.41	2,542.77	3,533.70	2,049.83	931.74	52.41	9,756.87
M3F5[i]	743	8.4	646.41	3,390.36	3,871.69	2,287.78	1,039.90	58.49	11,294.64
M4F1[i]	1,114.5	0	969.62	0	3,741.06	2,392.94	1,087.70	61.18	8,252.49
M4F2[i]	1,114.5	2.1	969.62	847.59	3,677.42	2,151.01	977.73	55.00	8,678.37
M4F3[i]	1,114.5	4.2	969.62	1,695.18	4,001.19	2,378.95	1,081.34	60.83	10,187.11
M4F4[i]	1,114.5	6.4	969.62	2,542.77	3,571.50	2,076.45	943.84	53.09	10,157.26
M4F5[i]	1,114.5	8.4	969.62	3,390.36	3,828.16	2,257.13	1,025.97	57.71	11,528.95
M5F1[i]	1,486	0	1,292.82	0	3,124.99	1,959.23	890.56	50.09	7,317.69
M5F2[i]	1,486	2.1	1,292.82	847.59	3,931.57	2,329.93	1,059.06	59.57	9,520.54
M5F3[i]	1,486	4.2	1,292.82	1,695.18	4,636.97	2,826.54	1,284.79	72.27	11,808.57
M5F4[i]	1,486	6.4	1,292.82	2,542.77	4,074.08	2,430.26	1,104.67	62.14	11,506.73
M5F5[i]	1,486	8.4	1,292.82	3,390.36	4,121.93	2,463.95	1,119.98	63.00	12,452.03

[i] Treatment codes combine molasses application rates (M1–M5 representing 0, 371.5, 743.0, 1114.5, and 1486.0 gal/acre, respectively) and Everlizer application rates (F1–F5 representing 0, 2.1, 4.2, 6.4, and 8.5 tons/acre, respectively). M1F1 represents the control group that received the same anaerobic soil disinfestation setup but without molasses or Everlizer application.

the added net returns for each treatment relative to the control groups (with the same ASD setup but no molasses or Everlizer sources) using data from both experiments. Given the variation of the net returns observed over the two production seasons, we calculated the coefficient of variation (*CV*) of the added net returns for each treatment relative to the control groups to better understand the stability of economic returns of ASD strawberry production. The *CV* was calculated as the ratio of the *SD* of the added net returns to the mean of the added net returns. It is commonly used as a measurement of the relative dispersion of the data.

Sensitivity analysis. Following studies such as Nian et al. (2022) and Shi et al. (2019), we used sensitivity analysis to examine how sensitive the net return is to various underlying factors. The analysis is an essential method to quantify the extent to which changes in each factor can affect the overall profitability of business operations (Frey and Patil 2002; Rafiee et al. 2010; Wei et al. 2020). In our study, we used yield, strawberry price, and molasses price as three key factors in strawberry production that can lead to net return variation. Strawberry yields are susceptible to changes in various production factors, such as water availability, temperature, and soil quality (Ariza et al. 2021; Madhavi et al. 2023; Natsheh et al. 2015; Zareei et al. 2021). In addition, fresh-market strawberry prices fluctuate constantly based on supply and demand dynamics, seasonality, and market competition (Samtani et al. 2019; Suh et al. 2017). As an important input in ASD, molasses price is a significant factor in the cost of strawberry production. Molasses prices can fluctuate based on factors such as the choice of supplier, market conditions, and the quantity ordered. It is important for producers to monitor and manage input expenses effectively.

We conducted two sensitivity analyses to understand the effect of variations in each factor on strawberry production profitability. The first sensitivity analysis focused on the strawberry selling price and strawberry yield on the net return of strawberry production, whereas the second examined the effect of strawberry selling price and molasses price on the profitability of strawberry production. We focused the sensitivity analysis on the treatment that resulted in the highest average yield in season 2022–23 and season 2023–24. The study used the average organic strawberry shipping point price (the price farmers received) from 2019 to 2023 as the base price. The base yield was the 2-year average yield from our harvesting record for

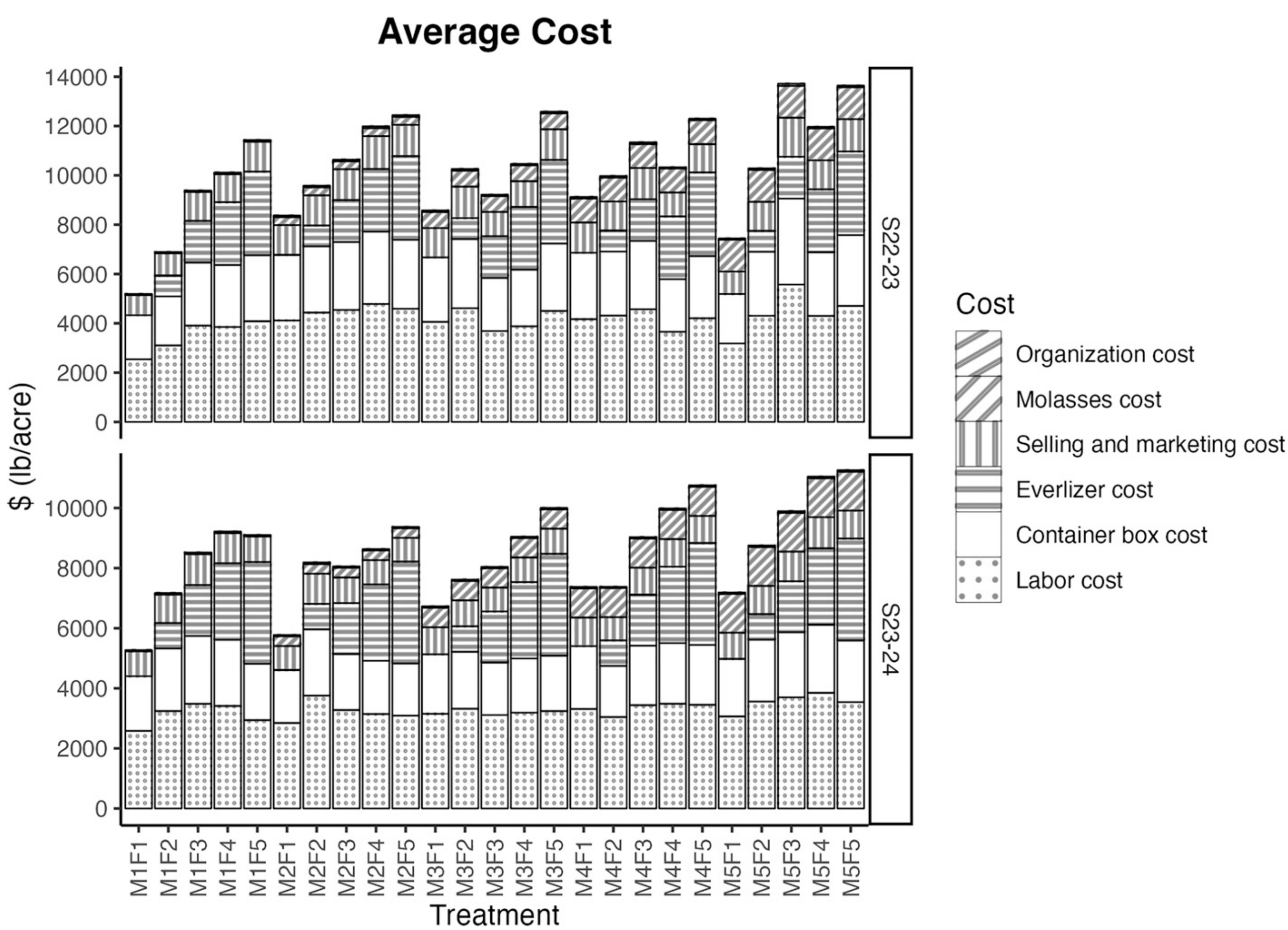

Fig. 1. Two-year average cost breakdown of anaerobic soil disinfestation treatments in organic strawberry production in Citra, FL (2022–23 and 2023–24 seasons). Treatment codes combine molasses application rates (M1–M5 representing 0, 371.5, 743.0, 1114.5, and 1486.0 gal/acre, respectively) and Everlizer application rates (F1–F5 representing 0, 2.1, 4.2, 6.4, and 8.5 tons/acre, respectively). M1F1 represents the control group that received the same anaerobic soil disinfestation setup but without molasses or Everlizer application.

each treatment. The base molasses price was the market price. The fluctuation was simulated by a 20% increase or decrease based on the base value of each factor (Donahoo et al. 2021; Shi et al. 2019).

Results and discussion

Production costs, yields, and added net returns. Table 1 summarizes the factors and associated average costs of key materials for each treatment in the production years 2022–23 and 2023–24. For simplicity, we only included the costs directly related to the ASD treatments, as our goal is to determine whether the additional costs of ASD can be offset by the added gross returns from the increased yield when using different application rates of carbon source (i.e., molasses) and nitrogen fertilizer source (i.e., Everlizer) in ASD-based strawberry production. All other costs remained the same across the control (i.e., 0 gal/acre molasses and 0 tons/acre Everlizer) and treatment groups (i.e., ASD-based production with various application rates of carbon and nitrogen fertilizer sources). The costs of molasses and Everlizer were associated with the ASD setup and varied based on differences in application rates. Labor, container boxes, selling and marketing expenses, and organic certification fees were incurred during the crop harvesting stage. These costs varied across treatments because each treatment resulted in different yields. Changes in yield affected the amount of labor and materials required for harvesting, packing, marketing, and selling, leading to variations in total costs across treatment groups. When calculating the labor cost, we used the wage of $15/h according to the field's local labor rate at Citra, FL. This rate is slightly higher but closely aligns with Florida's Adverse Effect Wage Rate at $14.77/h (US Department of Labor 2024).

High application rates of molasses and Everlizer significantly increased production costs due to greater material and labor requirements during the ASD application process. Meanwhile, these rates also required higher harvesting and marketing expenses. This cost increase was primarily attributed to the additional labor needed to handle and process the larger strawberry harvest volumes.

Figure 1 shows the year-by-year production, harvesting, and marketing costs measured in $/acre directly related to different ASD treatments in the 2022–23 and 2023–24 strawberry production seasons. Production costs can vary between years despite

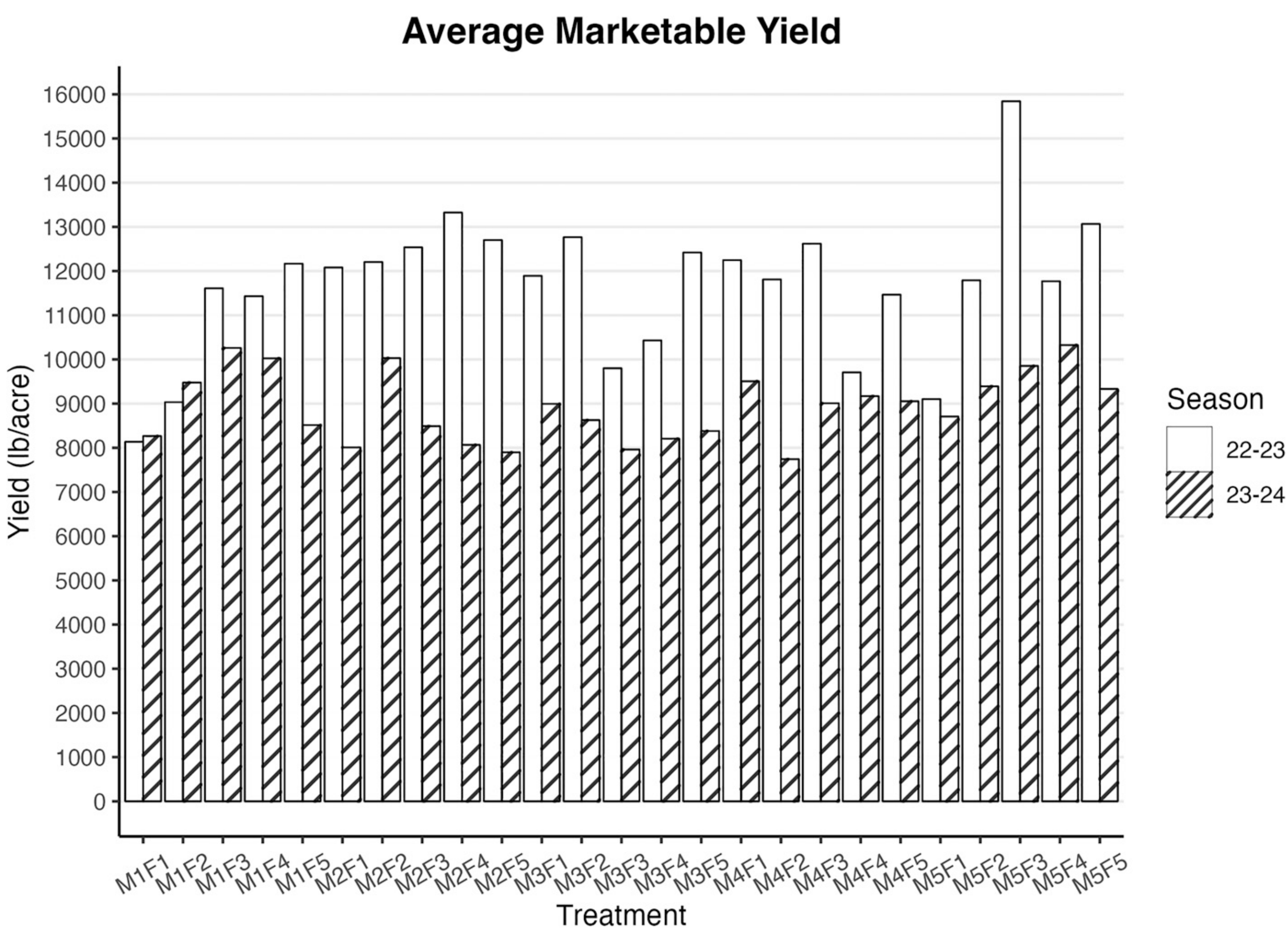

Fig. 2. Year-by-year marketable yield of organic strawberry production under anaerobic soil disinfestation treatments with varying carbon and nitrogen application rates in Citra, FL (2022–23 and 2023–24 seasons). Treatment codes combine molasses application rates (M1–M5 representing 0, 371.5, 743.0, 1114.5, and 1486.0 gal/acre, respectively) and Everlizer application rates (F1–F5 representing 0, 2.1, 4.2, 6.4, and 8.5 tons/acre, respectively). M1F1 represents the control group that received the same anaerobic soil disinfestation setup but without molasses or Everlizer application.

using identical methods and treatments, as some of the costs are yield-dependent. For example, container box costs scale directly with production volume. In general, the results from the 2022–23 and 2023–24 seasons indicated similar trends. Higher molasses and Everlizer application rates were associated with higher production costs in ASD treatments. Meanwhile, it also induced a higher cost for fruit harvesting and marketing because the crop yield tended to be higher when using a higher molasses and nitrogen fertilizer application rate in ASD. Producers need to use additional labor and resources to harvest and sell strawberries.

Figure 2 shows the year-by-year accumulated yield of each ASD treatment over the 2022–23 and 2023–24 production seasons. In the field trial conducted in the 2022–23 season, higher application rates of molasses and Everlizer generally resulted in higher yields. Treatment M5F3 (i.e., 1486.0 gal/acre of molasses and 4.2 tons/acre of Everlizer) resulted in the highest average marketable yield with 15,842.17 lb/acre. It almost doubled the yield of the control group M1F1 with 8135.31 lb/acre. This increase in yield can be attributed to the enhanced biological activity promoted by the carbon source in the soil, which can foster the growth of beneficial microbes that contribute to the decomposition of organic matter and the suppression of soil pathogens (Lamers et al. 2010; Meshram et al. 2024; Shennan et al. 2014). The combination of carbon and nitrogen inputs likely created a nutrient-rich environment that stimulated plant growth, leading to higher yields.

The results from the field trial conducted in the 2023–24 season showed treatment effects on yield, although the pattern differed from the previous season's results. As Fig. 2 illustrates, the overall yield for the second season for all treatments was lower than that in the first season. The difference can be partly attributed to the variations in environmental conditions and the difference in the accumulation of sunn hemp biomass between the two growing seasons. Several studies have demonstrated that the performance of ASD can vary significantly depending on environmental conditions such as soil temperature, moisture, and soil type. For example, Shennan et al. (2018) found that ASD was more effective at 25 °C than at 15 °C, highlighting the role of air temperature in both pathogen suppression and shifts in microbial communities. Rosskopf et al. (2015) similarly noted that ASD efficacy is

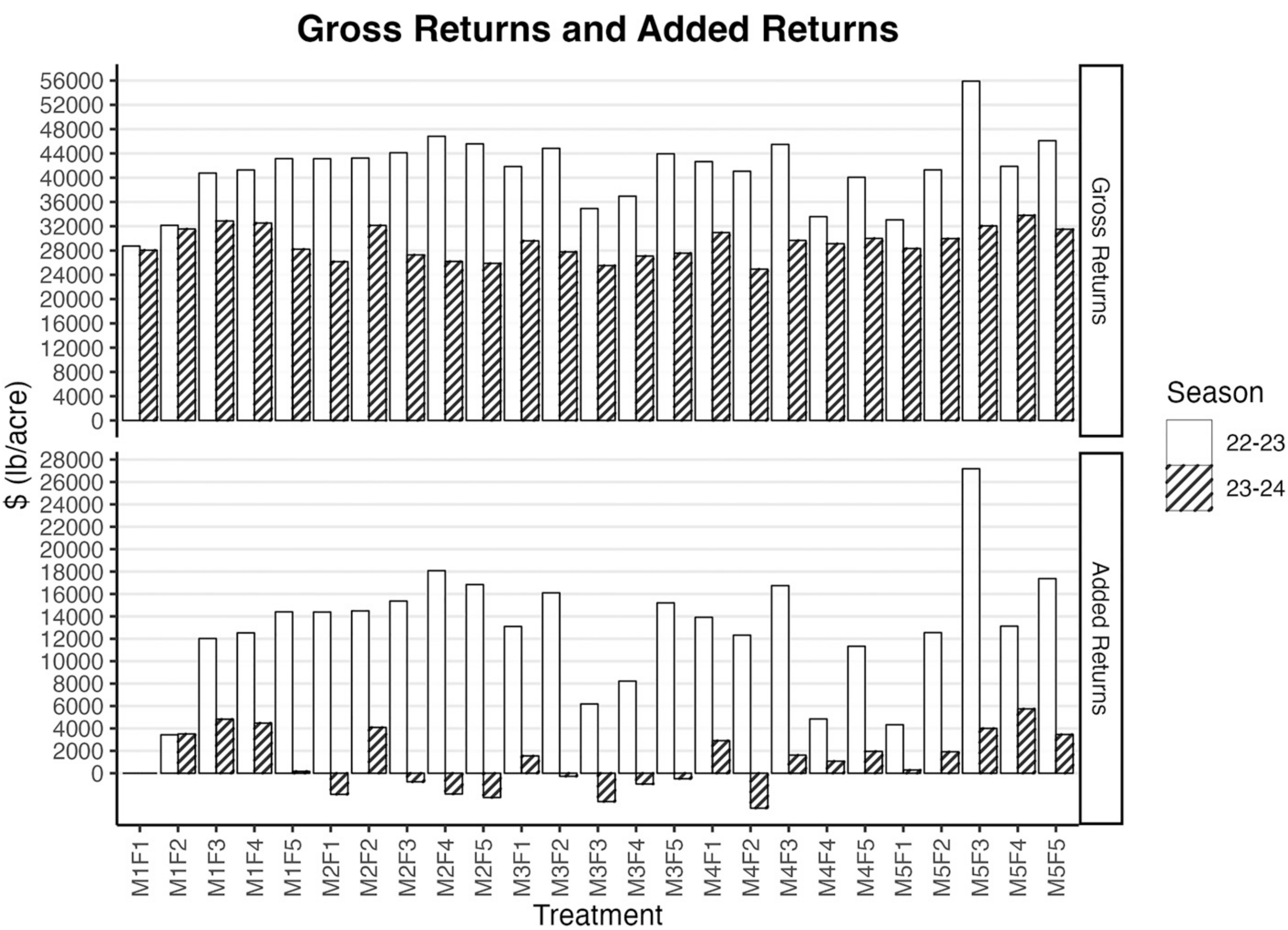

Fig. 3. Year-by-year gross returns and added returns of organic strawberry production under anaerobic soil disinfestation treatments with varying carbon and nitrogen application rates in Citra, FL (2022–23 and 2023–24 seasons). Treatment codes combine molasses application rates (M1–M5 representing 0, 371.5, 743.0, 1114.5, and 1486.0 gal/acre, respectively) and Everlizer application rates (F1–F5 representing 0, 2.1, 4.2, 6.4, and 8.5 tons/acre, respectively). M1F1 represents the control group that received the same anaerobic soil disinfestation setup but without molasses or Everlizer application.

influenced by soil type, with sandy soils, due to their low buffering capacity, more likely to exhibit strong pH responses to ASD treatment or organic matter additions. The 2023–24 field trial was conducted in an adjacent field to the 2022–23 trial to avoid residual effects from previous treatments. Both fields had similar soil physical and chemical properties, minimizing potential confounding effects related to soil type. However, seasonal variation in soil temperature and rainfall likely affected the extent of anaerobic conditions achieved, which may partly explain differences in treatment efficacy between years. This highlights the importance of external factors such as soil properties and temperature in the economic effectiveness of ASD in strawberry production. In the 2023–24 season, treatment M5F4 (i.e., 1486.0 gal/acre of molasses combined with 6.4 tons/acre of Everlizer) produced the highest average marketable yield of 10,323 lb/acre overall treatments. Treatment M5F3 (i.e., 1486.0 gal/acre of molasses combined with 4.2 tons/acre of Everlizer) that yielded the highest marketable yield in the 2022–23 season had the fifth-highest yield of 9853.59 lb/acre in the 2023–24 season. However, in the 2023–24 season, the average yields of the top five treatments were very close, showing relatively small differences in performance.

Figure 3 demonstrates the year-by-year total gross and added returns for the 2022–23 and 2023–24 strawberry production seasons. The gross return performance of each treatment followed a pattern similar to yield because gross returns were calculated as the product of price and total yield. In the 2022–23 season, the gross return of treatment M5F3 was the highest, at $55,908.02/acre, which was 95% more than the gross return of M1F1 with $28,733.21/acre. The added returns represent the gross return difference between each treatment and the control group M1F1, where no molasses or nitrogen fertilizer was applied. In the 2022–23 season, all treatments generated higher gross returns than the control group. In the 2023–24 season, the treatment M5F3 still performed relatively well compared with other treatments but did not reach its performance in the first season. Some treatment groups in the second season resulted in lower net returns than the control group, as indicated by the negative added returns in the figure.

Partial budget analysis of 2022–23 and 2023–24 trials. Partial budget analysis outlines the costs and gross returns associated with alternative inputs and outputs. In this study, the increased or added costs of

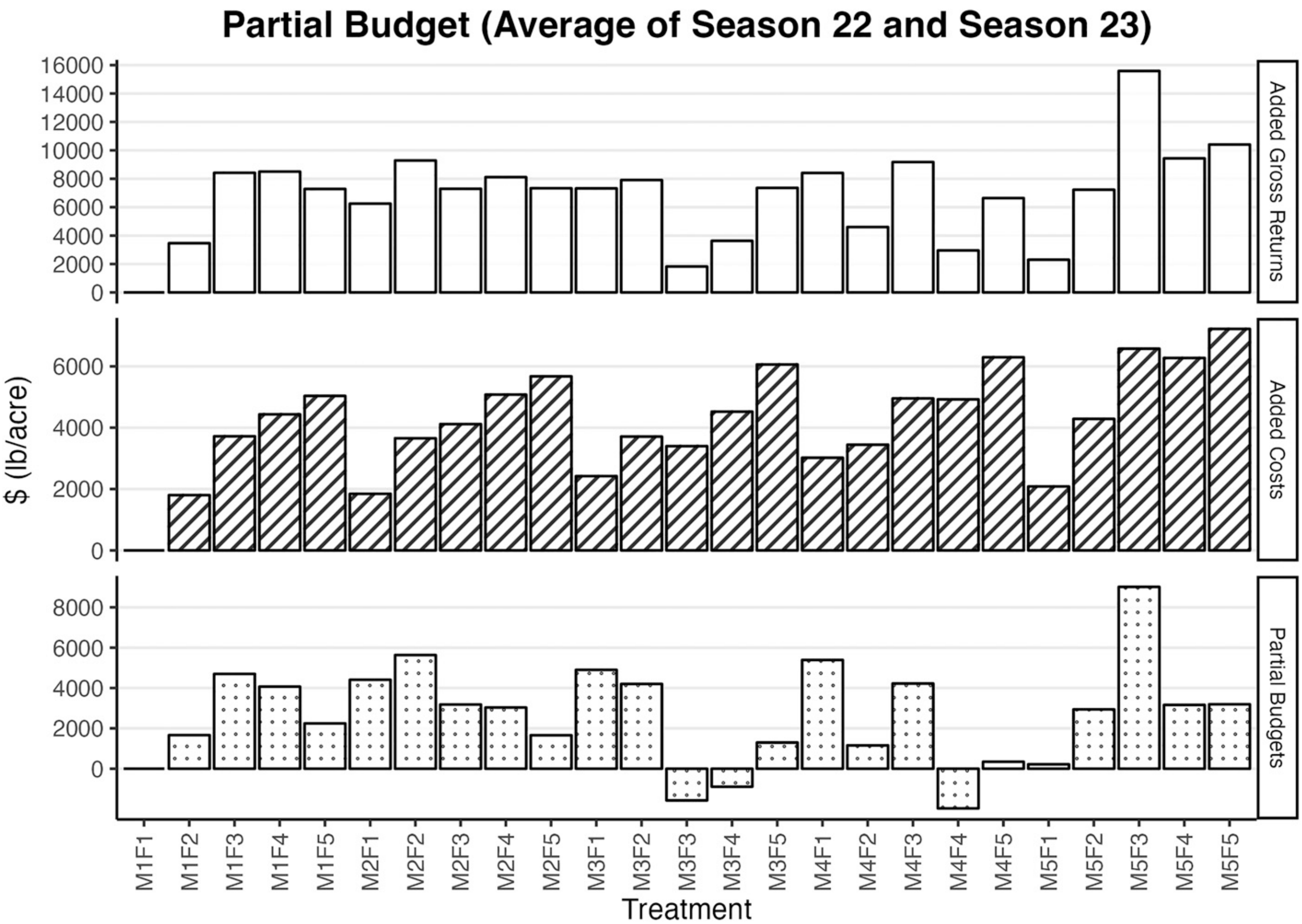

Fig. 4. Two-year average added gross returns, added costs, and partial budgets from anaerobic soil disinfestation treatments compared with the control group in organic strawberry production in Citra, FL (2022–23 and 2023–24 seasons). Treatment codes combine molasses application rates (M1–M5 representing 0, 371.5, 743.0, 1114.5, and 1486.0 gal/acre, respectively) and Everlizer application rates (F1–F5 representing 0, 2.1, 4.2, 6.4, and 8.5 tons/acre, respectively). M1F1 represents the control group that received the same anaerobic soil disinfestation setup but without molasses or Everlizer application.

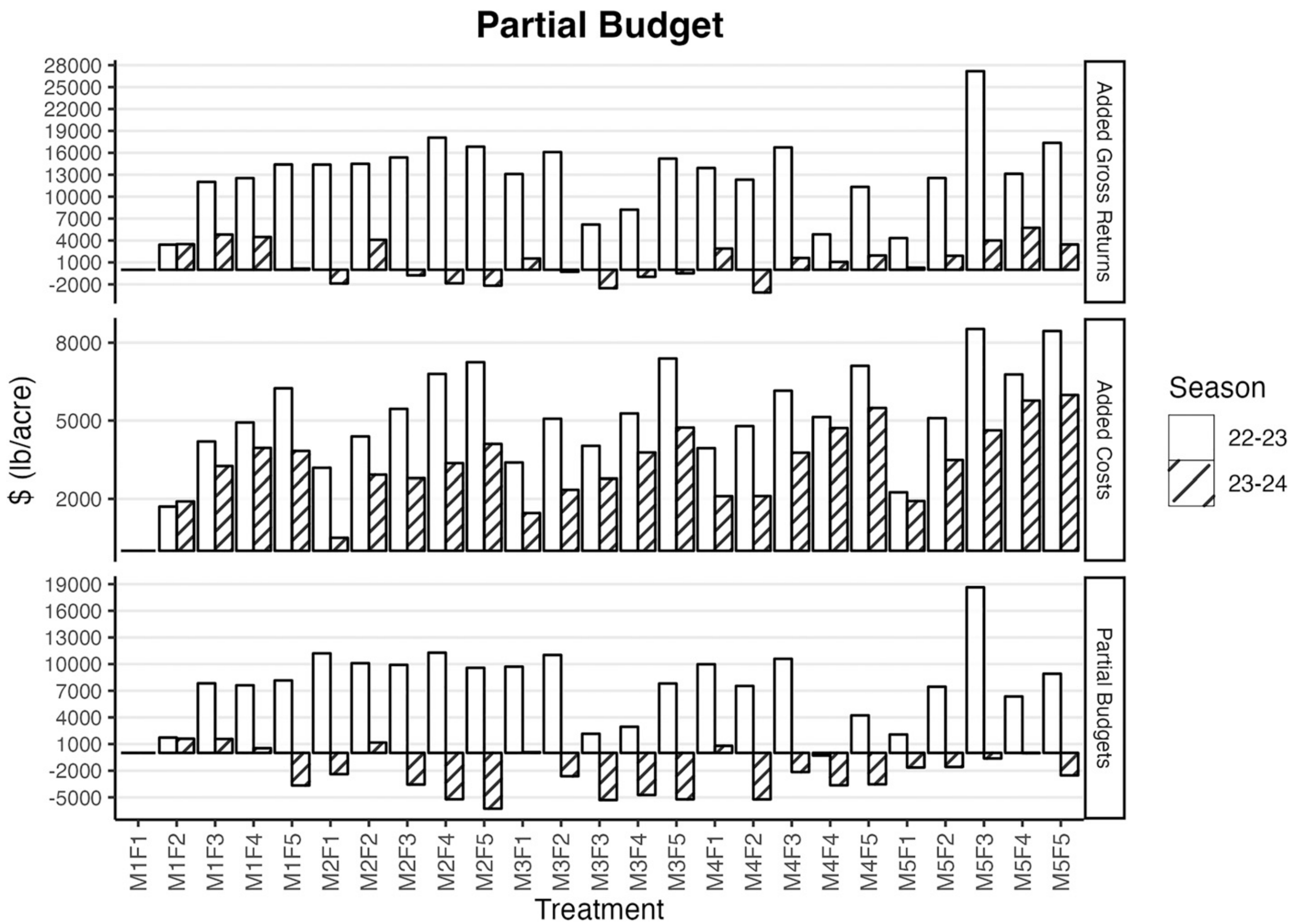

Fig. 5. Year-by-year added gross returns, added costs, and added net returns from anaerobic soil disinfestation treatments compared with the control group in organic strawberry production in Citra, FL (2022–23 and 2023–24 seasons). Treatment codes combine molasses application rates (M1–M5 representing 0, 371.5, 743.0, 1114.5, and 1486.0 gal/acre, respectively) and Everlizer application rates (F1–F5 representing 0, 2.1, 4.2, 6.4, and 8.5 tons/acre, respectively). M1F1 represents the control group that received the same anaerobic soil disinfestation setup but without molasses or Everlizer application.

ASD treatments were attributed to additional labor and the material cost from molasses and Everlizer. On the other hand, the extra gross return was gained from higher marketable yields and prices. Partial budget analysis allows the comparison between the added returns and added costs, which can help producers determine whether a treatment has the potential to generate higher profits than the other.

To examine the overall economic viability of ASD in organic strawberry production, we took the average yield across both seasons for each treatment and used it to conduct the partial budget analysis. Figure 4 shows the result of partial budget analysis using the average yield over two seasons. All treatment groups achieved higher values for added returns than the control group. Added costs increased as the treatment application rate increased. The 2-year trial data showed that despite the underperformance of some ASD treatments in the 2023–24 season, most of the ASD treatments resulted in higher net returns than the control treatment. The top three treatments were M5F3 (i.e., 1486.0 gal/acre molasses and 4.2 tons/acre Everlizer), with $9012.35/acre additional net return compared with the control group; M2F2 (i.e., 371.5 gal/acre molasses and 2.1 tons/acre Everlizer), with $5635.02/acre additional net return compared with the control group; and M4F1 (i.e., 1114.5 gal/acre of molasses combined with 0 tons/acre of Everlizer), with $5392.17/acre additional net return compared with the control group.

Figure 5 presents the result of the year-by-year partial budget analysis for the two seasons. The added returns of each treatment followed a pattern similar to the yield. When a treatment generates a higher yield than the control group, it creates higher gross returns than the control group. For added costs, all treatments required additional labor and materials in preplanting because of the inclusion of applying molasses and Everlizer in the field as part of the ASD process. In addition, higher yields from treatments that performed better than those of the control group require additional labor in the harvesting and packing stage.

The economic viability of ASD strawberry production showed considerable variation between the two seasons. For partial budget analysis in the 2022–23 season, treatment M5F3 showed promising economic viability, with $18,646.87/acre higher net returns than the control group. Although most combinations of molasses and Everlizer gained higher profit than the

Table 2. Mean, standard deviation (*SD*), and coefficient of variation (*CV*) of the 2-year average added net returns of anaerobic soil disinfestation treatments relative to the control group in organic strawberry production in Citra, FL (2022–23 and 2023–24 seasons).

	Added Net Returns		
Treatment ID	Mean	*SD*	*CV*
M1F2[i]	1,664.14	5,182.14	3.11
M1F3[i]	4,700.66	11,529.09	2.45
M1F4[i]	4,069.17	9,707.28	2.39
M1F5[i]	2,246.47	10,570.6	4.71
M2F1[i]	4,408.93	13,183.93	2.99
M2F2[i]	5,635.02	7,782.88	1.38
M2F3[i]	3,181.04	10,326.91	3.25
M2F4[i]	3,034.92	15,485.09	5.1
M2F5[i]	1,659.45	11,154.71	6.72
M3F1[i]	4,902.39	8,773.15	1.79
M3F2[i]	4,204.3	9,836.05	2.34
M3F3[i]	−1,573.06	8,457.32	NA[ii]
M3F4[i]	−892.14	12,287.91	NA[ii]
M3F5[i]	1,296.18	12,092.09	9.33
M4F1[i]	5,392.17	8,301.07	1.54
M4F2[i]	1,158.02	8,848.03	7.64
M4F3[i]	4,223.09	9,515.66	2.25
M4F4[i]	−1,966.43	10,259.69	NA[ii]
M4F5[i]	345.77	9,363.11	27.08
M5F1[i]	219.63	8,460.13	38.52
M5F2[i]	2,942.25	9,164.88	3.11
M5F3[i]	9,012.36	12,472.48	1.38
M5F4[i]	3,162.17	9,757.93	3.09
M5F5[i]	3,192.9	10,283.36	3.22

[i] Treatment codes combine molasses application rates (M1–M5 representing 0, 371.5, 743.0, 1114.5, and 1486.0 gal/acre, respectively) and Everlizer application rates (F1–F5 representing 0, 2.1, 4.2, 6.4, and 8.5 tons/acre, respectively). M1F1 represents the control group that received the same anaerobic soil disinfestation setup but without molasses or Everlizer application.

[ii] NA indicates that the *CV* was not calculated for treatments with negative mean added net returns.

control group, one treatment M4F4 failed to achieve this. Treatments that generated yields close to the control group could not cover the additional costs incurred by the treatment through added gross returns, leading to a negative net return difference. In the 2022–23 season, treatment M4F4 (i.e., 1114.5 gal/acre molasses and 6.4 tons/acre Everlizer) resulted in a net loss due to insufficient added returns.

However, in the 2023–24 season, the ASD treatments performed worse than those in the 2022–23 season because of the overall lower yield. The low yields of ASD treatments in the second season made it difficult for the increased yield to generate enough revenue to offset the additional costs, leading to adverse partial budget outcomes. In the 2023–24 season, almost all ASD treatments resulted in lower net income than the control, which indicates significant economic uncertainty associated with using ASD applications.

Table 2 presents the mean, *SD*, and *CV* of added net returns from strawberry production in ASD treatment groups compared with the control group for both trials conducted in the 2022–23 and 2023–24 seasons. Organic strawberry production tends to be susceptible to a variation in added net return, which can incur potential risks. Hence, assessing the stability of the added net return from the four replications in the field trial is essential. For treatments with negative added net returns, evaluating their stability is not very meaningful, so we excluded the *CV* for those that failed to produce positive added net returns. As Table 2 indicates, under the two two-season average yield, treatment M5F3 had the highest average added net return at $9012.36 with an *SD* of 12,472.48 and a *CV* of 1.38. A *CV* above one generally indicates high variability. This suggests that the average profits from two seasons' yield data were volatile with extreme fluctuations, highlighting the significant impact that potential changes in agricultural variables could have on crop profitability. Although treatment M5F3 exhibited a *CV* above one, it was still more reliable than other treatments with even higher *CV*s. For instance, treatment M5F1 had a mean added net return of 219.63 but a *CV* of 38.52, indicating a significantly high uncertainty in its net return. Considering the mean and *CV* of net return for different ASD treatments, treatment M5F3 seemed to be the best choice. Other ASD treatments with low *CV*s were M2F2 (*CV* = 1.38), M4F1 (*CV* = 1.54), and M3F1 (*CV* = 1.79). The three treatments with the

Table 3. Estimated 2-year average net return differences ($/acre) between anaerobic soil disinfestation treatment M5F3[i] and the control group[ii] in organic strawberry production in Citra, FL, under varying molasses and strawberry price scenarios (2022–23 and 2023–24 seasons).

Molasses price ($/gal)	Strawberry price ($/lb)				
	2.05	2.73	3.42	4.1	4.79
0.52	3,472.83	6,649.93	9,827.02	13,004.12	16,181.20
0.70	3,214.27	6,391.37	9,568.46	12,745.56	15,922.64
0.87	2,955.70	6,132.80	9,309.89	12,486.99	15,664.07
1.04	2,697.14	5,874.24	9,051.33	12,228.43	15,405.51
1.22	2,438.57	5,615.67	8,792.76	11,969.86	15,146.94

[i] M5F3 = 1486.0 gal/acre of molasses and 4.2 tons/acre of Everlizer.

[ii] The control group received the same anaerobic soil disinfestation setup but without molasses or Everlizer application.

Table 4. Estimated 2-year average net return differences ($/acre) between anaerobic soil disinfestation treatment M4F1[i] and the control group[ii] in organic strawberry production in Citra, FL, under varying strawberry yield and strawberry price scenarios (2022–23 and 2023–24 seasons).

	Strawberry price ($/lb)				
Yield (lb/acre)	2.05	2.73	3.42	4.1	4.79
7,708.75	−4,304.86	−4,641.10	−4,977.33	−5,313.56	−5,649.81
10,278.33	−674.58	745.85	2,166.29	3,586.72	5,007.14
12,847.91	2,955.70	6,132.80	9,309.89	12,486.99	15,664.08
15,417.49	6,585.99	11,519.75	16,453.51	21,387.27	26,321.02
17,987.07	10,216.26	16,906.69	23,597.12	30,287.54	36,977.96

[i] M5F3 = 1486.0 gal/acre of molasses and 4.2 tons/acre of Everlizer.
[ii] The control group received the same anaerobic soil disinfestation setup but without molasses or Everlizer application.

highest *CV*s were M5F1 (*CV* = 38.52), M4F5 (*CV* = 27.08), and M3F5 (*CV* = 9.33).

In general, the profitability of the treatments was subject to significant variations across four replications over 2 years, indicating potential production risk. Although treatment M5F3 demonstrated promising added net returns with lower variability than other treatments, it was still subject to fluctuations influenced by external factors. As a result, producers need to carefully evaluate potential risks associated with high-performing ASD treatments before implementation, even when such treatments demonstrate promising results in increasing strawberry yield on average.

Sensitivity analysis. We conducted the sensitivity analysis using the average yield from both years of treatment M5F3 because it generated the highest 2-year average net return. Table 3 presents the sensitivity analysis of the net return based on the average yield under variations in molasses and strawberry prices. The base organic strawberry price was $3.42/lb, and the molasses price was $0.87/gal. We adjusted prices by a 20% or 40% increase or decrease to mimic potential market price fluctuation. Treatment M5F3 created a positive relative profit at base strawberry and molasses prices compared with M1F1. Strawberry production using ASD generated more economic benefits when the selling price of strawberries increased. However, if the strawberry selling price dropped to $2.05/lb, the difference in net returns dramatically decreased to $2955.70 from $9309.89, even with a constant molasses price. This result shows that, at the current yield level, the applicability of the ASD treatment is highly susceptible to extreme changes in strawberry selling price, regardless of molasses price. The results are consistent with previous findings, such as Djidonou et al. (2013), Nian et al. (2022), and Shi et al. (2019), who showed that crop selling price is a significant factor influencing profitability in crop production.

Table 4 shows the sensitivity analysis of the net return based on the average yield under changes in yield and strawberry selling price. At the current yield (15,842.17 lb/acre), the net return of treatment M5F3 was $9309.89 higher than that of M1F1 at a strawberry selling price of $3.42/lb. However, this additional net return decreased significantly as the strawberry selling price dropped. If the price fell to $2.05/lb, the added net return was reduced to $2955.70. In addition, when the yield decreased by 20% to 10,278.33 lb/acre, the net income of the ASD treatment was lower than that of the control if the strawberry selling price dropped to $2.05/lb. Our results suggest that increased yield from ASD can offset the profit loss caused by extreme strawberry price changes. However, the decrease in the yield of ASD production in the second year significantly affected its economic feasibility. Our findings are consistent with the conclusions from Shi et al. (2019), who stated that higher crop prices enhance the potential of ASD. However, the yield from the ASD treatment must reach a threshold to ensure its added profitability compared with other potential practices.

Conclusions

Examining the economic viability of organic strawberry production using ASD is critical to determining whether ASD can be a cost-effective alternative soilborne disease management strategy in crop production. In this study, we conducted an economic analysis of 25 different combinations of the application rates of molasses and nitrogen sources in organic strawberry production in two seasons in north central Florida. This study provides a critical foundation for the continued exploration of ASD as a viable tool in organic strawberry production, offering producers a practical solution for improving yields and profitability while reducing reliance on synthetic inputs. In addition to pathogen suppression, ASD also may be effective in controlling weeds during the strawberry production season. With Everlizer applied at 4.2 tons/acre, regardless of molasses application rate, the numbers of nutsedge and broadleaf weeds were significantly reduced in the 2022–23 season (Xu et al. 2023) compared with other rates, further enhancing the value of ASD as a chemical-free alternative for soilborne disease and weed management. However, it needs to be pointed out that the costs of weed removal were not considered in this study.

The results from these two growing seasons suggest that organic strawberry production yield using ASD depends on the amount of molasses and nitrogen fertilizer used in the ASD process. Aligning with previous research on the economic feasibility of ASD in different crops, our partial budget analysis results suggest that the additional gross return of crop production using ASD can offset the extra costs when the appropriate amount of carbon and nitrogen inputs are used. Moreover, our sensitivity analysis highlights the importance of considering market condition variabilities when assessing the profitability of ASD. Yield is a critical factor affecting the economic feasibility of ASD. Also, the economic outcomes of the treatments with higher yields are susceptible to price changes in strawberries and molasses. When ASD leads to higher yield than control treatments, and strawberry selling prices are high, the difference in profit between the treatment and control groups is more substantial.

Because of the potential impacts of weather and soil conditions, our field experiment on ASD treatments showed inconsistencies across the two production seasons, with the 2023–24 season experiencing overall lower yields. Future research can focus on further refining the optimal rates of molasses and nitrogen for different regions and growing conditions and identifying the key factors impacting crop yield performance and ASD benefits. Meanwhile, the effectiveness of ASD is highly dependent on the availability of local carbon sources. In Florida, we focused economic analysis on molasses as the primary carbon source in ASD because the state's sugarcane industry can provide a reliable carbon source. Studies in other regions may evaluate the economic feasibility of ASD using alternative carbon sources from the area, such as grape pomace or wheat middlings. In addition, long-term studies in strawberry should be considered to assess the robustness of ASD performance across multiple growing seasons and locations, especially under different external production factors, such as field soil and weather conditions.

References cited

Abawi GS, Widmer TL. 2000. Impact of soil health management practices on soilborne pathogens, nematodes and root diseases of vegetable crops. Appl Soil Ecol. 15(1):37–47. https://doi.org/10.1016/S0929-1393(00)00070-6.

Agrios GN. 2005. Plant pathology (5th ed). Elsevier Academic Press, Burlington, MA, USA. https://doi.org/10.1016/C2009-0-02037-6.

Alimi T, Manyong VM. 2000. Partial budget analysis for on-farm research. (IITA Research Guide No. 65). International Institute of Tropical Agriculture. https://hdl.handle.net/10568/92688.

Ariza MT, Miranda L, Gómez-Mora JA, Medina JJ, Lozano D, Gavilán P, Soria C, Martínez-Ferri E. 2021. Yield and fruit quality of strawberry cultivars under different irrigation regimes. Agronomy. 11(2): Article 2. https://doi.org/10.3390/agronomy11020261.

Baysal-Gurel F, Gardener BM, Miller SA. 2012. Soil borne disease management in organic vegetable production. https://eorganic.org/node/7581. [accessed 7 Dec 2024].

Blok WJ, Lamers JG, Termorshuizen AJ, Bollen GJ. 2000. Control of soilborne plant pathogens by incorporating fresh organic amendments followed by tarping. Phytopathology. 90(3):253–259. https://doi.org/10.1094/PHYTO.2000.90.3.253.

Butler DM, Kokalis-Burelle N, Albano JP, McCollum TG, Muramoto J, Shennan C, Rosskopf EN. 2014. Anaerobic soil disinfestation (ASD) combined with soil solarization as a methyl bromide alternative: Vegetable crop performance and soil nutrient dynamics. Plant Soil. 378(1–2):365–381. https://doi.org/10.1007/s11104-014-2030-z.

Butler DM, Rosskopf EN, Kokalis-Burelle N, Albano JP, Muramoto J, Shennan C. 2012. Exploring warm-season cover crops as carbon sources for anaerobic soil disinfestation (ASD). Plant Soil. 355(1–2):149–165. https://doi.org/10.1007/s11104-011-1088-0.

Di Gioia F, Ozores-Hampton M, Hong J, Kokalis-Burelle N, Albano J, Zhao X, Black Z, Gao Z, Wilson C, Thomas J, Moore K, Swisher M, Guo H, Rosskopf EN. 2016. The effects of anaerobic soil disinfestation on weed and nematode control, fruit yield, and quality of Florida fresh-market tomato. HortScience. 51(6): 703–711. https://doi.org/10.21273/HORTSCI.51.6.703.

Di Gioia F, Ozores-Hampton M, Zhao X, Thomas J, Wilson P, Li Z, Hong J, Albano J, Swisher M, Rosskopf E. 2017. Anaerobic soil disinfestation impact on soil nutrients dynamics and nitrous oxide emissions in fresh-market tomato. Agriculture, Ecosystems & Environment. 240:194–205. https://doi.org/10.1016/j.agee.2017.02.025.

Djidonou D, Gao Z, Zhao X. 2013. Economic analysis of grafted tomato production in sandy soils in northern Florida. HortTechnology. 23(5):613–621. https://doi.org/10.21273/HORTTECH.23.5.613.

Donahoo T, Zhang L, Cutulle M, Hajihassani A. 2021. Economic analysis of grafting and anaerobic soil disinfestation for tomato production in South Carolina. HortTechnology. 31(5):615–624. https://doi.org/10.21273/HORTTECH04858-21.

Frey HC, Patil SR. 2002. Identification and review of sensitivity analysis methods. Risk Anal. 22(3):553–578. https://doi.org/10.1111/0272-4332.00039.

Guo H, Di Gioia F, Zhao X, Ozores-Hampton M, Swisher ME, Hong J, Kokalis-Burelle N, DeLong AN, Rosskopf EN. 2017. Optimizing anaerobic soil disinfestation for fresh market tomato production: Nematode and weed control, yield, and fruit quality. Sci Hortic. 218:105–116. https://doi.org/10.1016/j.scienta.2017.01.054.

Guo H, Zhao X, Rosskopf EN, Di Gioia F, Hong JC, McNear DH. 2018. Impacts of anaerobic soil disinfestation and chemical fumigation on soil microbial communities in field tomato production system. Appl Soil Ecol. 126:165–173. https://doi.org/10.1016/j.apsoil.2017.12.018.

Hewavitharana SS, Klarer E, Reed AJ, Leisso R, Poirier B, Honaas L, Rudell DR, Mazzola M. 2019. Temporal dynamics of the soil metabolome and microbiome during simulated anaerobic soil disinfestation. Front Microbiol. 10:2365. https://doi.org/10.3389/fmicb.2019.02365.

Ono-Raphel JG, Custer GF, Arrington K, Morrison B, Kaye J, Rosskopf E, Dini-Andreote F, Di Gioia F. 2025. Effects of carbon sources on soil bacterial community dynamics during anaerobic soil disinfestation in an organic tomato production system. Agriculture, Ecosystems & Environment. 381:109448. https://doi.org/10.1016/j.agee.2024.109448.

Katan J. 2017. Diseases caused by soilborne pathogens: Biology, management and challenges. J Plant Pathol. 99(2): 305–315. https://doi.org/10.4454/jpp.v99i2.3862.

Koike ST, Subbarao KV, Davis RM, Turini TA. 2003. Vegetable Diseases Caused by Soilborne Pathogens. UCANR Publications, Riverside, CA, USA. https://doi.org/10.3733/ucanr.8099.

Kubota C, McClure MA, Kokalis-Burelle N, Bausher MG, Rosskopf EN. 2008. Vegetable grafting: History, use, and current technology status in North America. HortScience. 43(6):1664–1669. https://doi.org/10.21273/HORTSCI.43.6.1664.

Lamers JG, Runia WT, Molendijk LPG, Bleeker PO. 2010. Perspectives of anaerobic soil disinfestation. Acta Hortic. 883:277–283. https://doi.org/10.17660/ActaHortic.2010.883.34.

Lucas P. 2006. Diseases caused by soilborne pathogens, p 373–386. In: Cooke BM, Jones DG, Kaye B (eds). The Epidemiology of Plant Diseases. Springer, Dordrecht, Netherlands. https://doi.org/10.1007/1-4020-4581-6_14.

Madhavi BGK, Kim NE, Basak JK, Choi GM, Kim HT. 2023. Comparative study of strawberry growth and fruit quality parameters in horizontal and vertical production systems. Hortic Environ Biotechnol. 64(3):409–419. https://doi.org/10.1007/s13580-022-00494-8.

Meshram S, Philbrick AN, Adhikari TB. 2024. Anaerobic soil disinfestation: A biologically-based solution for sustainable crop production. Front Hortic. 3:1436782. https://doi.org/10.3389/fhort.2024.1436782.

Momma N. 2008. Biological soil disinfestation (BSD) of soilborne pathogens and its possible mechanisms. JARQ. 42(1):7–12. https://doi.org/10.6090/jarq.42.7.

Natsheh B, Abu-Khalaf N, Mousa S. 2015. Strawberry (*Fragaria ananassa*

Duch.) plant productivity quality in relation to soil depth and water requirements. International Journal of Plant Research. 5(1):1–6. https://doi.org/10.5923/j.plant.20150501.01.

Nian Y, Zhao R, Tian S, Zhao X, Gao Z. 2022. Economic analysis of grafted organic tomato production in high tunnels. HortTechnology. 32(5):459–470. https://doi.org/10.21273/HORTTECH05101-22.

Osteen CD. 2003. Methyl bromide phaseout proceeds: Users request exemptions. Amber Waves. 1:23–27.

Panth M, Hassler SC, Baysal-Gurel F. 2020. Methods for management of soilborne diseases in crop production. Agriculture. 10(1):Article 1. https://doi.org/10.3390/agriculture10010016.

Paudel BR, Gioia FD, Zhao X, Ozores-Hampton M, Hong JC, Kokalis-Burelle N, Pisani C, Rosskopf EN. 2020. Evaluating anaerobic soil disinfestation and other biological soil management strategies for open-field tomato production in Florida. Renew Agric Food Syst. 35(3):274–285. https://doi.org/10.1017/S1742170518000571.

Rafiee S, Mousavi Avval SH, Mohammadi A. 2010. Modeling and sensitivity analysis of energy inputs for apple production in Iran. Energy. 35(8):3301–3306. https://doi.org/10.1016/j.energy.2010.04.015.

Rosskopf EN, Burelle N, Hong J, Butler DM, Noling JW, He Z, Booker B, Sances F. 2014. Comparison of anaerobic soil disinfestation and drip-applied organic acids for raised-bed specialty crop production in Florida. Acta Hortic. 1044:221–228. https://doi.org/10.17660/ActaHortic.2014.1044.26.

Rosskopf EN, Chellemi DO, Kokalis-Burelle N, Church GT, Pierce F. 2005. Alternatives to methyl bromide: A Florida perspective. Plant Health Prog. 6(1):19. https://doi.org/10.1094/PHP-2005-1027-01-RV.

Rosskopf EN, Di Gioia F, Hong JC, Ozores-Hampton M, Zhao X, Black Z, Gao Z, Wilson C, Thomas J, Jones JB, Butler DM, Shrestha U, Sattanno K, DeLong A, Swisher M, Kokalis-Burelle N, Wang J, Li Z, Shi L, Pisani C, Guo H, Zhu Q, Paudel B, Johns CW, Finley NL, Muramoto J, Albano J, Shennan C. 2020. Anaerobic soil disinfestation: Areawide project on obstacles and adoption. Acta Hortic. 1270:23–36. https://doi.org/10.17660/ActaHortic.2020.1270.3.

Rosskopf EN, Di Gioia F, Hong JC, Pisani C, Kokalis-Burelle N. 2020. Organic amendments for pathogen and nematode control. Annu Rev Phytopathol. 58(1):277–311. https://doi.org/10.1146/annurev-phyto-080516-035608.

Rosskopf EN, Gioia FD, Vincent I, Hong J, Zhao X. 2024. Impacts of the ban on the soil-applied fumigant methyl bromide. Phytopathology. 114(6):1161–1175. https://doi.org/10.1094/PHYTO-09-23-0345-IA.

Rosskopf EN, Serrano-Pérez P, Hong J, Shrestha U, Rodríguez-Molina M, del C, Martin K, Kokalis-Burelle N, Shennan C, Muramoto J, Butler D. 2015. Anaerobic soil disinfestation and soilborne pest management, p 277–305. In: Meghvansi MK, Varma A (eds). Organic amendments and soil suppressiveness in plant disease management. Springer International Publishing, Cham, Switzerland. https://doi.org/10.1007/978-3-319-23075-7_13.

Samtani JB, Rom CR, Friedrich H, Fennimore SA, Finn CE, Petran A, Wallace RW, Pritts MP, Fernandez G, Chase CA, Kubota C, Bergefurd B. 2019. The status and future of the strawberry industry in the United States. HortTechnology. 29(1):11–24. https://doi.org/10.21273/HORTTECH04135-18.

Shennan C, Muramoto J, Koike S, Baird G, Fennimore S, Samtani J, Bolda M, Dara S, Daugovish O, Lazarovits G, Butler D, Rosskopf E, Kokalis-Burelle N, Klonsky K, Mazzola M. 2018. Anaerobic soil disinfestation is an alternative to soil fumigation for control of some soilborne pathogens in strawberry production. Plant Pathol. 67(1):51–66. https://doi.org/10.1111/ppa.12721.

Shennan C, Muramoto J, Lamers J, Mazzola M, Rosskopf EN, Kokalis-Burelle N, Momma N, Butler DM, Kobara Y. 2014. Anaerobic soil disinfestation for soil borne disease control in strawberry and vegetable systems: Current knowledge and future directions. Acta Hortic. 1044:165–175. https://doi.org/10.17660/ActaHortic.2014.1044.20.

Shi L, Wang J, Gao Z, Zhao X, Di Gioia F, Guo H, Hong J, Ozores-Hampton M, Rosskopf E. 2019. Economic analysis of anaerobic soil disinfestation for open-field fresh-market tomato production in Southwest and North Florida. HortTechnology. 29(6):777–787. https://doi.org/10.21273/HORTTECH04332-19.

Shinmura A, Sakamoto N, Abe H. 1999. Control of *Fusarium* root rot of Welsh onion by soil reduction [abstract in Japanese]. Jpn J Phytopathol. 65:352–353.

Suh DH, Guan Z, Khachatryan H. 2017. The impact of Mexican competition on the U.S. strawberry industry. IFAM. 20(4):591–604. https://doi.org/10.22434/IFAMR2016.0075.

Sydorovych O, Safley CD, Welker RM, Ferguson LM, Monks DW, Jennings K, Driver J, Louws FJ. 2008. Economic evaluation of methyl bromide alternatives for the production of tomatoes in North Carolina. HortTechnology. 18(4):705–713. https://doi.org/10.21273/HORTTECH.18.4.705.

van Agtmaal M, van Os G, Hol G, Hundscheid M, Runia W, Hordijk C, De Boer W. 2015. Legacy effects of anaerobic soil disinfestation on soil bacterial community composition and production of pathogen-suppressing volatiles. Front Microbiol. 6:701. https://doi.org/10.3389/fmicb.2015.00701.

Singh S, Cutulle M, Rutter W, Wadl PA, Ward B, Khanal C. 2025. Anaerobic soil disinfestation as a tool for nematode and weed management in organic sweetpotato. Agronomy. 15(3):Article 3. https://doi.org/10.3390/agronomy15030548.

US Department of Agriculture, Agricultural Marketing Service. 2006. Strawberries grades and standards. https://www.ams.usda.gov/grades-standards/strawberries-grades-and-standards. [accessed 12 Dec 2024].

US Department of Agriculture, Agricultural Marketing Service. 2023. https://mymarketnews.ams.usda.gov/public_data. [accessed 12 Dec 2024].

US Department of Agriculture, Agricultural Research Service. 2022. Food security: How do crop plants combat pathogens? https://www.ars.usda.gov/oc/dof/food-security-how-do-crop-plants-combat-pathogens/. [accessed 3 Oct 2024].

US Department of Labor. 2024. H-2A Adverse Effect Wage Rates (AEWRs). https://flag.dol.gov/wage-data/adverse-effect-wage-rates. [accessed 1 Oct 2024].

Vincent IR, Paudel BR, Guo H, Rosskopf EN, Di Gioia F, Hong JC, McNear DH, Xu N, Anrecio L, Colee J, Zhao X. 2022. Spatial and temporal changes of soil microbial communities in field tomato production as affected by anaerobic soil disinfestation. Front Sustain Food Syst. 6:838635. https://doi.org/10.3389/fsufs.2022.838635.

Vincent IR, Rosskopf EN, Brecht JK, Dufault NS, Sandoya-Miranda G, Zhao X. 2024. Effects of anaerobic soil disinfestation for soilborne disease and weed management on baby leaf lettuce performance in a high tunnel organic production system. Agronomy. 14(4):764. https://doi.org/10.3390/agronomy14040764.

Wei X, Khachatryan H, Rihn A. 2020. Production costs and profitability for selected greenhouse grown annual and perennial crops: Partial enterprise budgeting and sensitivity analysis. HortScience. 55(5):637–646. https://doi.org/10.21273/HORTSCI14633-19.

Xu N, Zhao X, Hong J, Rosskopf EN. 2023. Assessing carbon and nitrogen inputs for applying anaerobic soil disinfestation to organic strawberry production in Florida. 2023 American Society for Horticultural Science Annual Conference, Orlando, Florida, 31 Jul–4 Aug, 2023.

Zareei E, Karami F, Gholami M, Ershadi A, Avestan S, Aryal R, Gohari G, Farooq M. 2021. Physiological and biochemical responses of strawberry crown and leaf tissues to freezing stress. BMC Plant Biol. 21(1):532. https://doi.org/10.1186/s12870-021-03300-2.