Economics of Anaerobic Soil Disinfestation in Strawberry Production

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Abstract

Growers face increasingly stringent regulatory restrictions on the use of pre-plant soil fumigation, a crucial input in many fruit and vegetable farming systems, driving a search for effective non-chemical alternatives. Anaerobic soil disinfestation (ASD) has emerged as a promising strategy for managing soilborne pests and pathogens in strawberry production. This study evaluates the economic viability of ASD in strawberry farming using partial budget analysis and data from field trials conducted in California during the 2021–2022 and 2022–2023 seasons. Our analysis compares net returns (gross revenues minus analyzed costs) across ASD treatments and control plots, with and without chemical fumigation. Results from the 2021–2022 trial reveal no meaningful difference in yields from ASD-treated plots compared to control plots. Findings from the 2022–2023 trial show that ASD treatments significantly increased strawberry yields relative to non-fumigated control plots but yields from ASD with fumigation plots did not significantly differ from fumigated control plots. High ASD material, labor, and fumigation costs and low yields in the 2021–2022 trial resulted in negative and significantly smaller net returns from ASD treatments relative to the control. In the 2022–2023 trial, high yields among ASD plots resulted in positive net returns, but ASD treatment costs remained impractically high, leading to meaningfully smaller net returns from ASD treatments compared to the controls.

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1 Introduction

Growers face increasing restrictions on the chemical tools available to control soilborne pests and pathogens before planting, threatening crop yields, quality, and farm profitability. Amidst this changing regulatory landscape, anaerobic soil disinfestation (ASD) has emerged as a promising alternative to chemical soil fumigation in strawberry production. Results of strawberry field experiments reveal that ASD treatments reduce the incidence of weeds, nematodes, and disease (Hoffmann et al., 2016; Song et al., 2020; Giovannini et al., 2021). However, evidence of the economic benefits of ASD treatments is lacking in the existing literature. Economic analysis provides practitioners with a more complete picture of the relative benefits of ASD treatments.

We use a partial budget analysis to compare the economic returns of ASD treatment and control plots with and without fumigation from a California strawberry experimental field site. The field trials, conducted at the USDA Spence Experimental Station in Salinas, California, included four replicates of four ASD and fumigation treatment combinations and two control groups harvested in 2022, and six ASD and fumigation treatment combinations and two control groups harvested in 2023. The carbon sources used for ASD treatments included rice bran, wheat, and a mix of rice bran and wheat, while control plots lay fallow. Fumigated plots were treated with TriClor (containing 99% chloropicrin) and PicClor 60 (containing 39% 1,3-dichloropropene (1,3-D) and 59.6% chloropicrin), chemical soil fumigants commonly used in conventional strawberry production.

Results indicate that control plots with and without fumigation generated higher net returns (calculated as revenue from marketable strawberries minus harvest and treatment costs) than ASD treatments with or without fumigation. Notably, ASD treatments resulted in negative net returns during the 2021–2022 trial. While prior studies demonstrate the potential for ASD to match or exceed the net returns of chemical fumigation under certain conditions (Shennan et al., 2018; Michuda et al., 2019; Zavatta et al., 2021), our findings highlight the challenges posed by high ASD input costs, particularly labor costs. Our analysis illustrates the inherent difficulties in replicating commercial production conditions in experimental settings. Specifically, the labor hours recorded for wheat cultivation and ASD activities and rice bran costs for the field trial were substantially higher than those typically expected in commercial operations. Furthermore, the relative benefit of ASD treatments depends on unobserved environmental factors, like the disease status of the soil and weather during ASD treatments, which may vary from field to field.

Since the 1960s, growers have utilized the soil fumigant methyl bromide to control weeds, nematodes, insects, and plant-disease-causing bacteria and fungi. However, due to its ozone-depleting effects, United States (U.S.) regulators banned methyl bromide in 2005 under the Montreal Protocol (Carter et al., 2005), with Critical Use Exemptions extending applications in California strawberry production through 2015 (Rosskopf et al., 2024). Growers have adapted to the methyl bromide ban by adopting alternative pre-plant soil fumigants, like chloropicrin and 1,3-D.[1] However, these alternatives face increasingly strict regulations (Xu et al., 2014). For instance, on January 1st, 2024, the California Department of Pesticide Regulation implemented regulations establishing minimum buffer zone distances from occupied buildings, maximum application rates, and block sizes to minimize human exposure to 1,3-D emissions from agricultural applications (Mace et al., 2024). By November 2024, the Department of Pesticide Regulation proposed new regulations that will change buffer zone distances and duration periods based on the fumigation method and crops to address cancer risks to bystanders, placing additional stringent restrictions on 1,3-D users (CDPR, 2024). ASD offers a non-chemical alternative to heavily regulated fumigants, providing a pest management solution that can be used inside buffer zones. Additionally, ASD treatments comply with organic standards, thereby introducing a new pest management practice suitable for organic growers.

Strawberries are a key crop in California agriculture, ranked in terms of farm receipts, and a major market for soil fumigants (Carter et al., 2005). California leads the U.S. in

[1] Like methyl bromide, chloropicrin and 1,3-D target a broad range of pests and diseases and are registered for use in California.

strawberry production, accounting for 2.46 billion pounds in 2023, valued at $2.97 billion. These figures represent approximately 89% of total U.S. strawberry production and 87% of production value (USDA NASS, 2024). Florida accounts for almost all of the remainder.

Methyl bromide was pivotal in establishing California as the dominant strawberry-producing region in the U.S. by enabling high-yield, high-quality varieties otherwise vulnerable to disease (Olver and Zilberman, 2022). Since the methyl bromide ban, the strawberry industry has adapted, primarily by the use of alternative fumigants, and strawberry acres and production have remained close to record highs. From 2006 through 2018, the harvested acreage of strawberries in California fluctuated between 35,300 and 41,500 acres (CDFA, 2016; CDFA, 2023). More recently, the harvested area expanded from 34,100 acres in 2019 to 42,000 acres in 2022, underscoring the continued relevance of strawberries and associated soil fumigants in the California agricultural landscape. In 2022, organic strawberry acres accounted for 16% (6,741 acres) of total California strawberry acreage (CDFA, 2022).

In the remainder of this paper, we outline ASD practices and review key results from the ASD literature. Next, we detail the experimental design, data, and economic analysis. Subsequently, we present our main findings of the partial budget analysis supported by sensitivity and breakeven analyses. Later, we discuss our results and the last section concludes.

2 Anaerobic Soil Disinfestation and Other Non-Fumigant Alternatives

ASD is a pre-plant procedure, meaning growers treat soils in the weeks preceding crop planting. It involves incorporating carbon-rich amendments into the topsoil, covering the soil in impermeable plastic, and saturating the soil with water. About three to six weeks later, growers remove or cut the plastic to allow planting. The combination of carbon source, water saturation, and impermeable plastic creates anaerobic conditions, promotes anaerobic soil microbes, and suppresses soilborne plant pathogenic bacteria, fungi, nematodes, and weeds (Rosskopf et al., 2020). The mechanisms by which ASD achieves pest suppression are an ongoing area of research and likely vary by local environmental characteristics. However, researchers posit that the production of organic acids and volatile compounds and the alteration of the soil microbiome and chemistry play a role (Momma et al., 2013).

Carbon-rich amendments are a focus of ongoing research as growers seek effective, low-cost materials. The amendment must provide a labile carbon source, meaning anaerobic microbes easily break down the carbon, and be cost-effective. Reflecting this economic consideration, researchers and early adopters of ASD typically utilize local crop residues and by-products of crop processing. For instance, rice bran, molasses, cover crops, and ethanol have been utilized in California, Florida, the Netherlands, and Japan, respectively (Shrestha, Augé, and Butler, 2016). In addition to their role in ASD, these amendments are associated with enhanced soil fertility, further contributing to their agronomic and economic appeal.

Before widespread methyl bromide adoption in the 1960s, growers relied on crop rotations for managing soil-borne pests and diseases. However, profitable rotations often involve crops susceptible to similar diseases, such as lettuce in strawberry-lettuce production systems in the Central Coast region of California (Michuda et al., 2019). In recent decades, industry and researchers have explored alternative pre-plant systems for soil-borne pest and disease suppression, including ASD, organic amendments, suppressive crop rotations with non-host crops, biofumigation, biosolarization, and steam injection.

Organic amendments, like compost, decompose to release compounds toxic to several pests, contributing to disease suppression (Rosskopf et al., 2020). ASD and biofumigation are variations of organic amendments that refine treatment variables to enhance pest and disease control. For instance, *Brassicaceae* plant residues biofumigate soils when the glucosinolate-rich biomass—like mustard seed meal—breakdown, releasing isothiocyanate and other volatile compounds toxic to many soil-borne pests (Henderson et al., 2009). Researchers have also experimented with introducing *Brassicaceae* crops, such as broccoli, into strawberry rotations (Michuda et al., 2019). These crops act as non-hosts for pathogens like *Verticillium dahliae*, lowering the pathogen population before strawberry planting.

Other alternative methods, such as biosolarization and steam treatments, suppress pests by elevating soil temperatures. Biosolarization utilizes transparent polyethylene mulch to trap solar heat for six to eight weeks, raising soil temperatures and killing many pests and pathogens (Rosskopf et al., 2020). Steam treatments, on the other hand, use tractor-mounted equipment to inject steam, heating the soil to approximately 70 degrees Celsius at a depth of 20 centimeters for 20 minutes (Samtani et al., 2012). Additionally, pathogen-resistant crop varieties and grafting plants onto resistant rootstocks have shown promise in improving yields in infested soils (Rosskopf et al., 2024).

In lieu of synthetic fumigants, profitable farming systems will likely integrate several complementary alternative practices tailored to specific cropping systems and local environmental conditions.

3 Literature Review

A small but growing body of literature indicates that ASD offers a viable alternative to chemical fumigation in conventional strawberry systems (Shennan et al., 2018) and can enhance yields in organic systems (Zavatta et al., 2021). In the following paragraphs, we review partial budget analysis studies from the strawberry ASD literature. Later, we review papers that report ASD impacts on strawberry yields.

In a series of California field trails conducted in Castroville, Watsonville, and Santa Maria in 2010 through 2012, Shennan et al. (2018) find that ASD with 20 metric tons of rice bran per hectare provides equivalent marketable strawberry yields to treatment with fumigant PicClor 60 in three out of four trials, resulting in net returns 4–8% lower than fumigated plots. On one trial site, fumigation results in higher marketable yields and net returns about 20% greater than ASD treatment. The researchers also vary the treatment length and month and find that 3- and 6-week ASD treatments in September and October provide similar yields. Furthermore, the authors observe increased early-season strawberry yields in ASD treatment plots, which they attribute to improved soil fertility from incorporating rice bran. Replacing some pre-plant fertilizer with soil amendments may represent further savings associated with ASD treatments.

Michuda et al. (2019) examine the impact of ASD treatments with rice bran and molasses as carbon sources on the profitability of organic strawberry production in Santa Cruz, California. Researchers also vary the crop rotations, cover cropping, and mustard seed meal amendments—a biofumigant. Their analysis reveals that crop rotations coupled with soil fertility and disease management treatments are important factors in determining profitability. For instance, ASD treatments resulted in the highest net present value of net returns in two-year strawberry rotations with broccoli. They find a similar result in two-year lettuce rotations. However, mustard seed meal produced the highest net present value of net returns in four-year strawberry–broccoli and strawberry–lettuce rotations. Furthermore, they find that treatment and control groups produced negative net returns from the first strawberry harvest in the two-year strawberry rotations and positive net returns from the second strawberry harvest in year four.

In an eight-year organic strawberry trial conducted at an experimental station in Santa Cruz, California, Zavatta et al. (2021) examined the effect of ASD, mustard seed meal, and crop rotations on yields. They established four soil treatment groups: 1) ASD and winter cover crop, 2) ASD, compost and fertilizer, and winter cover crop, 3) mustard seed meal and winter cover crop, and 4) fertigation and winter fallow. ASD treatments included rice bran plus broccoli or lettuce residues as soil amendments. Their results reveal that ASD treatments significantly increased yields relative to control plots across all crop rotation systems and by 40% relative to mustard seed meal treatments in two- and four-year strawberry–lettuce rotations. In two- and four-year broccoli rotations, they find no statistical difference in yields between ASD and mustard seed meal plots but statistically higher yields from ASD treatments compared to control plots. Shrestha et al. (2024) also experiment with crop rotations and ASD treatment. Using a molasses–soybean hull–wheat bran mix as a carbon source, they find that ASD treatments increase strawberry yields by about 25% across three crop rotations tested. Results from Zavatta et al. (2021) and Shrestha et al. (2024) broadly support the yield effects observed by Shennan et al. (2018) and Michuda et al. (2019) and indicate that systems integrating ASD and crop rotations are potentially economically feasible systems for production.

To address the high cost of rice bran soil amendments compared to other prospective amendment materials, Daugovish et al. (2023) compare ASD treatments using wheat middlings and distillers dried grains to untreated control plots and measure strawberry yields during the following 2022 and 2023 harvest seasons at an experiment station in Santa Paula, Ventura County in southern California. Plots were treated with ASD in 2021 and again in 2022. They find that the 2022 marketable yields per strawberry plant were 28% higher in those grown in ASD with wheat middlings treated soils and 39% higher in ASD with distiller dried grains treated soil compared to the untreated control. Researchers find smaller treatment effects during the second harvest, with wheat middling amended ASD increasing yields by 11% higher compared to the untreated control and no significant yield improvement from ASD with distiller dried grains treated soil. The authors attribute the yield increase to the release of nutrients from the amendments, as the researchers failed to detect any common strawberry pathogens in the soil that ASD might otherwise suppress.

Giovannini et al. (2021) examine ASD, biofumigation, and chloropicrin and 1,3-D fumigation treatments in a two-year strawberry field trial in Southern Italy using a proprietary amendment product as an ASD carbon source. In the first year of the trial, they found that ASD results in yields 24% greater than an untreated control, 30% greater than biofumigation, and 20% lower than chemical fumigation. In the second year of the trial, they found that ASD results in yields 19% greater than an untreated control, 5% greater than biofumigation, and 5% lower than chemical fumigation. Individual strawberry weights follow a similar pattern in response to treatment, with the highest mean fruit weight observed in fumigated treatments, followed by ASD, biofumigation, and untreated control.

In a series of trials conducted at two experiment stations in Salinas and Watsonville, California, conducted over two growing seasons beginning in fall 2021, Hoffmann et al. (2016) evaluate strawberry yields grown in plots treated with ASD (with a rice bran carbon source), mustard seed meal, or steam. Results from the 2012–2013 trial in Watsonville reveal that ASD increased yields by 27% relative to the control plots but results in yields 40% lower than steam treatment. Results from the 2013–2014 McFadden field trial at the Spence experimental station in Salinas show that ASD increased yields by 9% relative to mustard seed meal, 13% relative to steam treatment, and 29% relative to the control, and did not significantly increase yields relative to steam treatment with mustard seed meal amendment. Results from the 2014–2015 Fuji field trial at the Spence experiment station in Salinas show that ASD increased yields by 22% relative to an untreated control plot, and steam treatment with mustard seed meal amendments increased yields by 44%.

In field trials conducted in China, Song et al. (2020) find no statistically significant difference in disease suppression and yields between strawberries grown in plots treated by ASD with maltose as a carbon source and chemical fumigation with chloropicrin. However, they find that ASD maltose applications of 9 tons per hectare increase yield by 63% and 140% relative to soil solarization and no treatment, respectively.

Song et al. (2023) find that ASD with 5 (resp. 10) tons per hectare of biochar as amendment increases strawberry yields by 50% (resp. 132%) relative to an untreated control. ASD with 5 (resp. 10) tons per hectare increases yields by 50% (resp. 120%) relative to the control. ASD treatments effectively control several pathogenic organisms, including *Fusarium* and *Phytophthora* species, present in the experimental soils. The authors attribute these large yield improvements from ASD treatments to effective disease suppression and improved soil fertility.

4 Methods and Data

Data come from a combination of experimental results and publicly available sources. The following subsections detail the experimental design and data, sources and calculations of price and cost data, partial budget analysis, sensitivity analysis, and breakeven analysis.

4.1 Experimental Design and Data

Yield data are from field experiments conducted at the USDA Spence Experimental Station in Salinas, California. The experimental data include yields and treatment costs from trials conducted in 2021–2022 and 2022–2023 using a split-plot block design, meaning the main treatments, like rice bran ASD, were randomly assigned to treatment plots, and half of each plot received the fumigation treatment, and half did not. There were four replicates per treatment.[2] All trials were subject to typical management practices unless stated in the paragraphs below.

In spring 2021, researchers established 24 0.01415-acre treatment plots (for example, the control with fumigation). Wheat was planted in assigned wheat treatment plots in April and mowed in July at the end of flowering. Next, researchers implemented ASD treatments in the assigned plots, including incorporating mowed wheat and rice bran into the soil using a tractor-driven rototiller, laying drip tape, covering the soil with a tarp, and saturating soils with irrigation water. This experiment employed broadcast ASD, meaning plots were treated before forming growing beds. Transparent tarps were used to raise soil temperatures higher than what might be achieved using opaque tarps. Tarps and drip tape were removed at the end of ASD treatments, and strawberry beds were formed before fumigation and planting. Assigned subplots were fumigated in October by bed fumigation, meaning only the beds were fumigated via the drip irrigation system.[3] Strawberries were planted in November.

[2]Data from four replicates were recorded from 2021-2022 control groups, while five replicates were recorded ASD treatments. We exclude block 1 data (the missing control block) to achieve an equal number of replicates across all treatments, allowing a balanced design for statistical analysis.

[3]Bed fumigation is common in strawberry production. Compared to field fumigation, bed fumigation

For the 2022-2023 trials, researchers established 32 0.0166-acre treatment plots in spring 2022. These trials followed a similar calendar of events as those described for the 2021-2022 trials above.

In the 2021-2022 and 2022-2023 trials, researchers planted 140 pounds of wheat seed (cultivar Summit 515) per acre, applied 300 pounds of a 6–20–20 fertilizer per acre, and irrigated throughout the growing season. Researchers transplanted Monterey—a commercial strawberry cultivar—seedlings into trial plots at densities of 14,522 plants per acre.

The 2021-2022 trial included six treatment groups, and the 2022-2023 trial included eight. We summarize the treatments in Table 1. Research staff harvested strawberries on 39 days in 2022, beginning on April 20th and ending on September 14th, and 38 days in 2023, beginning on June 3rd and ending on October 12th. Harvest intervals ranged from 2 to 6 days. The average number of days between harvests equaled 4 days in 2022 and 3.5 days in 2023.

4.2 Economic Data and Analysis

We employ a partial budget analysis comparing the net returns from the treatment and control groups. Net returns, in this case, equal the gross revenues minus the costs that vary over treatments, like harvest labor, ASD materials and installation, and fumigation costs.

We calculate gross revenues using the following formula:

$$Revenue = \sum_t Yield_t \times Price_t$$

where $Yield$ denotes the pounds of marketable strawberries, $Price$ denotes the price per pound of marketable strawberries, and subscript t denotes the harvest date.

We collected daily conventional strawberry prices for flats of eight one-pound containers with lids in Salinas-Watsonville, California, from the U.S. Department of Agriculture's Agri-

is less expensive and more convenient as beds are formed before treatment, plumbed with drip tape, and mulched in plastic, allowing planting to occur sooner after treatment. The downside to bed fumigation is that furrows remain untreated, and the fumigant is less evenly distributed through the soil (Strawberry Working Group, 2021).

Table 1: Summary of ASD and Fumigation Treatments

Treatment	Description
2021–2022 trials	
Control with fumigation	Fallow during ASD treatments followed by fumigation with 15 gallons per acre of TriClor (99% Chloropicrin)
Control without fumigation	Fallow during ASD and fumigation treatments
Rice bran ASD with fumigation	9 tons per acre of rice bran and 15 gallons per acre of TriClor
Rice bran ASD without fumigation	9 tons per acre of rice bran
Wheat and rice bran ASD with fumigation	4.5 tons per acre of dry wheat biomass, 4.5 tons per acre of rice bran, and 15 gallons per acre of TriClor
Wheat and rice bran ASD without fumigation	4.5 tons per acre of dry wheat biomass and 4.5 tons per acre of rice bran
2022–2023 trials	
Control with fumigation	Fallow during ASD treatments followed by fumigation with 25 gallons per acre of PicClor 60 (59.6% Chloropicrin and 39% 1,3-D)
Control without fumigation	Fallow during ASD and fumigation treatments
Rice bran ASD with fumigation	9 tons per acre of rice bran and 25 gallons per acre of PicClor 60
Rice bran ASD without fumigation	9 tons per acre of rice bran
Wheat and rice bran ASD with fumigation	4.5 tons per acre of dry wheat biomass, 4.5 tons per acre of rice bran, and 25 gallons per acre of PicClor 60
Wheat and rice bran ASD without fumigation	4.5 tons per acre of dry wheat biomass and 4.5 tons per acre of rice bran
Wheat ASD with fumigation	9 tons per acre of dry wheat biomass and 25 gallons per acre of PicClor 60
Wheat ASD without fumigation	9 tons per acre of dry wheat biomass

Note: Custom operator installed tarp and drip tape in all fumigated and ASD treatment plots.

cultural Marketing Service Market Reports (USDA AMS, 2024). When data were available, we used the mean of the mostly high and mostly low prices of strawberry flats on the harvest day. Otherwise, we used the mean of the low and high prices. Where available, we used market prices on the harvest date. Where no price data are available for the harvest date, we used prices from the next available date. Price data represent extra large berries in April and May and decrease in size to small/medium berries in September and October. We do not observe strawberry size from the experimental data, but the berry sizes reported in the price data follow a typical pattern of declining berry size throughout the season.

The pounds of strawberries ready for harvest change throughout the season, affecting harvest labor costs. We use harvest rates from Bolda et al. (2021) equal to 24 pounds harvested per hour in the early and late seasons and 52 pounds per hour during the peak season when yields per plant are higher. Bolda et al. (2021) assume peak season occurs in June and July. However, we observe peak yields from May 9th through June 15th, 2022, and June 3rd through August 28th, 2023, when mean yields correspond to more than 1,000 pounds per acre. Approximately 50% and 75% of strawberries were harvested during the peak harvest window in 2022 and 2023, respectively. We use the industry average wage rate, inclusive of the employer's payroll tax, workers' compensation insurance, and other benefit contributions, equal to $22.98 and $24.42 per hour for harvest labor in 2022 and 2023, respectively (Bolda et al., 2021, 2024). The higher wage rate in 2023 represents changes to California minimum wage and overtime laws.

We use marketing costs from Bolda et al. (2021), including fresh market strawberry selling costs equal to 8% of the strawberry price, refrigeration costs equal to 6.25 cents per pound, and California Strawberry Commission assessment fee equal to 0.28 cents per pound.

ASD treatment cost data were recorded during the trials. Rice bran was purchased in ton totes and delivered to the field site at a cost of $597.4 per ton in 2021. In 2022, researchers purchased rice bran packaged in 50-pound bags at a cost of $1,099 per ton. Wheat seed was free to the researchers. To assess the economics, we used a price of $0.75 per pound to reflect typical wheat seed costs (Mathesius et al., 2016). Fertilizer was purchased in 50-pound bags at a cost of $800 per ton. Irrigation water for wheat and ASD treatments was from groundwater wells. While the water was free, the electricity used for pumping was calculated using a price of $0.24 per kilowatt hour. Drip irrigation supplies included lay flat poly tubing and connectors but did not include permanent drip irrigation supplies like pressure regulators, filters, or manifolds. Some irrigation equipment was installed for wheat production and later replaced ahead of strawberry production. A custom operator installed drip tape and tarped ASD treatment plots at a cost of $3,600 per acre. Appendix Table (A.1) summarizes the material, labor, and custom service costs by treatment.

The custom operator also installed drip tape and tarped fumigated control plots at a cost of $3,600 per acre. In 2021, they fumigated assigned plots with 15 gallons per acre of TriClor at a cost of $2,351 per acre. In 2022, they fumigated assigned plots with 25 gallons per acre of PicClor 60 at a cost of $2,392 per acre, while the cost of drip tape and tarp installation equaled $3,600 per acre.

Researchers recorded staff hours on ASD treatments like wheat cultivation and rice bran applications. We used experiment station staff costs for treatment labor, which on average equaled $29 per hour, close to the machine operator wage rates faced by strawberry growers (Bolda et al., 2021).

4.3 Sensitivity Analysis

We perform a series of sensitivity analyses to assess the extent to which net returns respond to shifts in input costs, strawberry yields, and prices. These analyses highlight the relative importance of prices and yields in shaping net returns. Specifically, our analysis focuses on key variables: the price of rice bran, the cost of wheat production, harvest labor costs, and the price and yield of strawberries.

The components of wheat production costs considered in the analysis include seeds, fertilizers, electricity for groundwater pumping, and labor. To model changes in wheat production costs, we scale these input costs by a common factor, enabling an assessment of the corresponding impact on net returns. Harvest labor costs, the largest strawberry production cost, are determined by the wage rate and the number of strawberries harvested per hour. The productivity of harvest labor is highly variable, influenced by factors such as strawberry yield per plant, weather, worker experience, and the distance between the picking area and the collection table. Rice bran material costs comprise the price of rice bran delivered to the field station multiplied by the quantity used.

We also examine the effects of variations in strawberry price and yield. Yield fluctuations impact harvest costs and associated cooling and assessment fees, whereas price changes directly affect revenues without altering production costs. To capture a range of possible outcomes, we test scenarios involving a 25% increase and a 25% decrease in each of the selected variables.

4.4 Breakeven Analysis

The breakeven price for an input is the price at which the treatment using the input generates the same net return as the control method that does not use the input, holding all other variables constant. The breakeven input price represents the maximum a producer would be willing to pay to adopt the treatment method that uses the input given the cost of other inputs and holding gross revenues constant. We calculate the breakeven price or cost of four variables, including: (1) the price of rice bran delivered to the field site, (2) the cost to produce a ton of dry wheat biomass, (3) the wage rate for labor used in wheat production and ASD treatments, and (4) the total cost of ASD treatments including materials, labor, electricity, and tarp and drip tape installation custom services. We compare ASD treatments with fumigation to control plots with fumigation and ASD treatments without fumigation to control plots without fumigation.

5 Results

The following sections detail the results of the partial budget, sensitivity, and breakeven analyses.

5.1 Partial Budget Analysis

Control groups resulted in higher mean net returns than ASD treatments, despite some ASD treatments achieving higher strawberry yields. ASD treatments without fumigation increased strawberry yields relative to the untreated control groups, and ASD treatments with fumigation increased yields relative to the fumigated control groups, except for rice bran ASD with fumigation. However, high material and labor costs led to net returns from ASD being lower than those from control groups at realized yields and prices. Table 2 shows that the untreated control—control plots without fumigation—yielded the highest net return in the 2021–2022 trial, with a value of $9,368 per acre. In contrast, ASD treatments resulted in negative net returns. In the 2022–2023 trial, control plots with fumigation provided the highest mean net return, equal to $24,231 per acre, followed by control plots without fumigation, which achieved $19,144 per acre. Below, we provide a detailed discussion of these findings supported by statistical tests.

In the 2021–2022 trial, control plots without fumigation provided the highest mean net return despite having the lowest mean yield of 24,731 pounds per acre. Wheat and rice bran ASD with fumigation achieved the highest mean yield, equal to 30,464 pounds per acre. However, results from the Tukey test for differences in means, shown in Table 3, indicate no statistically significant differences in yields between ASD treatments and untreated control plots. However, fumigation significantly increased yields in the control plots, but only at the 10% significance level.

Despite higher yields than the control group, ASD treatments incurred negative net returns due to high treatment costs and low strawberry yields at realized market prices. Net returns ranged from -$7,000 per acre for rice bran ASD with fumigation to -$15,308 per acre for wheat and rice bran ASD with fumigation. Panel B of Table 3 confirms that ASD treatments had significantly lower net returns than control plots with and without fumigation.

ASD performed better in the 2022–2023 trial. Table 2 shows that mean yields ranged from 30,979 pounds per acre for the untreated control to 52,499 pounds per acre for wheat and rice bran ASD with fumigation. All treatments achieved positive net returns during this trial. Tukey test results reported in Panel A of Table 4 indicate that ASD treatments significantly increased yields compared to the untreated control, except for wheat ASD without fumigation, which had a mean yield statistically indistinguishable from the control and significantly lower than the control with fumigation.

In the 2022–2023 trial, control plots with fumigation provided the highest net return, equal to \$24,231 per acre. This value was statistically different at the 10% significance level from rice bran ASD with fumigation, which had the lowest net return equal to \$7,466 per acre. Panel B of Table 4 reveals no other statistically significant differences in mean net returns between treatments and the control.

Across both trials, rice bran ASD treatments with fumigation achieved higher mean yields than rice bran ASD without fumigation, but this difference was not statistically significant. We found a similar relationship for wheat and rice bran ASD. Statistically significant yield improvements were realized in the fumigated control (in both trials) and wheat ASD (in the 2022–2023 trial) plots compared to the non-fumigated control and wheat ASD plots, respectively. However, yield improvements from fumigation did not consistently translate into higher net returns.

In the 2021–2022 trial, the additional fumigation costs, totaling \$5,951 per acre (including tarp, drip tape, fumigant materials, and application costs), combined with modest yield improvements, resulted in lower net returns for fumigated groups compared to non-fumigated groups. However, these differences in net returns were not statistically significant.

In the 2022–2023 trial, fumigated control and wheat ASD plots resulted in net returns 27% and 84% higher than their non-fumigated counterparts, respectively. By contrast, high fumigation costs and limited yield improvements from fumigation in rice bran ASD and wheat and rice bran ASD treatments resulted in lower net returns. However, these differences in net returns were not significant.

Table 2: Treatment and Harvest Costs, Yield, Revenue, and Net Returns Above Harvest and Treatment Costs

Treatment	Yield	Treatment costs	Harvest costs	Gross revenue	Net returns
	lbs/acre	$/acre			
2021–2022 trials					
Control & fum.	29,809	5,951	26,209	36,815	4,656
Control & no fum.	24,731	0	22,147	31,514	9,368
Rice bran ASD & fum.	29,105	17,627	24,675	35,295	-7,006
Rice bran ASD & no fum.	27,156	15,276	23,745	33,058	-5,963
Wheat, rice bran ASD & fum.	30,464	26,324	25,740	36,756	-15,308
Wheat, rice bran ASD & no fum.	27,179	23,973	24,256	34,293	-13,937
2022–2023 trials					
Control & fum.	50,158	5,992	38,446	68,669	24,231
Control & no fum.	30,979	0	23,617	42,760	19,144
Rice bran ASD & fum.	47,042	20,776	36,037	64,279	7,466
Rice bran ASD & no fum.	46,939	18,384	36,019	63,493	9,090
Wheat & fum.	51,136	15,946	38,913	69,905	15,046
Wheat & no fum.	35,928	13,554	27,240	48,973	8,179
Wheat, rice bran ASD & fum.	52,499	20,890	41,164	70,685	8,631
Wheat, rice bran ASD & no fum.	51,107	18,498	38,836	68,491	11,157

Note: Treatment costs equal mean treatment costs over four replicates for each treatment. We follow similar calculations for harvest costs, yields, gross revenues, and net returns.

Table 3: Difference in Mean Yields and Net Returns from 2021-2022 Trials

	Control & fum.	Control & no fum.	Rice bran ASD & fum.	Rice bran ASD & no fum.	Wheat, rice bran ASD & fum.
Panel A. Difference in yields					
Control & no fumigation	5,079*				
Rice bran ASD & fumigation	1,604	-3,475			
Rice bran ASD & no fumigation	3,085	-1,994	1,481		
Wheat, rice bran ASD & fumigation	439	-4,639	-1,164	-2,645	
Wheat, rice bran ASD & no fumigation	3,179	-1,899	1,576	94	2,740
Panel B. Difference in net returns					
Control & no fumigation	-4,712				
Rice bran ASD & fumigation	12,781**	17,493**			
Rice bran ASD & no fumigation	11,219**	15,931**	-1,561		
Wheat, rice bran ASD & fumigation	21,555**	26,267**	8,774**	10,335**	
Wheat, rice bran ASD & no fumigation	19,985**	24,697**	7,204*	8,766**	-1,570

Note: Values represent mean yields for treatments defined in the columns minus mean yields for treatments defined in the rows. We follow similar calculations for net returns. We used the Tukey test to test for the difference in means.
* $p < 0.10$, ** $p < 0.05$.

Table 4: Difference in Mean Yields and Net Returns from 2022-2023 Trials

	Control & fum.	Control & no fum.	Rice bran ASD & fum.	Rice bran ASD & no fum.	Wheat ASD & fum.	Wheat ASD & no fum.	Wheat, rice bran ASD & fum.
Panel A. Difference in yields							
Control & no fum.	19,179**						
Rice bran ASD & fum.	3,116	-16,063**					
Rice bran ASD & no fum.	3,219	-15,960**	103				
Wheat & fum.	-978	-20,158**	-4,095	-4,197			
Wheat & no fum.	14,230**	-4,949	11,114	11,011	15,209**		
Wheat, rice bran ASD & fum.	-2,341	-21,520**	-5,457	-5,560	-1,363	-16,572**	
Wheat, rice bran ASD & no fum.	-948	-20,128**	-4,065	-4,167	30	-15,179**	1,393
Panel B. Difference in net returns							
Control & no fum.	5,087						
Rice bran ASD & fum.	16,765*	11,678					
Rice bran ASD & no fum.	15,141	10,054	-1,624				
Wheat & fum.	9,185	4,098	-7,580	-5,956			
Wheat & no fum.	16,052	10,965	-713	911	6,867		
Wheat, rice bran ASD & fum.	15,599	10,512	-1,166	459	6,414	-452	
Wheat, rice bran ASD & no fum.	13,074	7,987	-3,691	-2,067	3,889	-2,978	-2,525

Note: Values represent mean yields for treatments defined in the columns minus mean yields for treatments defined in the rows. We follow similar calculations for net returns. We used the Tukey test to test for the difference in means.
* $p < 0.10$, ** $p < 0.05$.

5.2 Sensitivity Analysis

Table 5 presents the results of the sensitivity analysis evaluating the extent to which net returns respond to changes in rice bran, wheat, and harvest labor costs, as well as strawberry yields and prices. A 25% increase or decrease in each variable was tested to represent meaningful variation.

ASD treatment and harvest costs were substantial relative to revenues, with rice bran, wheat production, and harvest labor constituting significant shares of total costs. Consequently, a 25% change in rice bran material costs produced notable shifts in net returns. Similar effects were observed for wheat production and harvest costs. However, in the 2021–2022 trial, net returns for ASD treatments remained negative even under a 25% reduction in input costs. A 25% improvement in yields also failed to result in positive net returns for ASD treatments, although a 25% increase in strawberry prices produced modest positive net returns for rice bran ASD. Conversely, higher harvest labor costs and lower strawberry prices led to negative net returns for the control with fumigation group.

For the 2022–2023 trial, sensitivity analysis revealed positive net returns across all scenarios except for ASD treatments under a 25% reduction in strawberry prices. In this scenario, control plots without fumigation generated the highest net return.

Table 5: Sensitivity of Net Returns to Changes in Input Costs, Strawberry Yield, and Price

	Cost of:						Strawberry:			
	rice bran materials		wheat production		harvest labor		yield		price	
	-25%	+25%	-25%	+25%	-25%	+25%	-25%	+25%	-25%	+25%
Treatment	$/acre									
2021–2022 trials										
Control & fum.	4,656	4,656	4,656	4,656	9,985	-673	2,004	7,307	-3,812	13,123
Control & no fum.	9,368	9,368	9,368	9,368	13,870	4,865	7,026	11,709	2,119	16,616
Rice bran ASD & fum.	-5,662	-8,350	-7,006	-7,006	-2,019	-11,994	-9,661	-4,351	-15,124	1,112
Rice bran ASD & no fum.	-4,619	-7,307	-5,963	-5,963	-1,131	-10,795	-8,291	-3,635	-13,566	1,640
Wheat, rice bran ASD & fum.	-14,636	-15,980	-12,992	-17,624	-10,106	-20,511	-18,062	-12,554	-23,762	-6,854
Wheat, rice bran ASD & no fum.	-13,265	-14,609	-11,621	-16,253	-9,003	-18,872	-16,446	-11,428	-21,824	-6,050
2022–2023 trials										
Control & fum.	24,231	24,231	24,231	24,231	31,650	16,812	16,675	31,787	8,437	40,025
Control & no fum.	19,144	19,144	19,144	19,144	23,687	14,601	14,358	23,930	9,309	28,979
Rice bran ASD & fum.	9,938	4,994	7,466	7,466	14,422	510	405	14,526	-7,318	22,250
Rice bran ASD & no fum.	11,562	6,618	9,090	9,090	16,059	2,122	2,222	15,959	-5,513	23,694
Wheat & fum.	15,046	15,046	16,310	13,781	22,541	7,551	7,298	22,794	-1,032	31,124
Wheat & no fum.	8,179	8,179	9,444	6,915	13,423	2,935	2,746	13,612	-3,085	19,443
Wheat, rice bran ASD & fum.	9,867	7,395	9,896	7,367	16,651	611	1,251	16,012	-7,626	24,889
Wheat, rice bran ASD & no fum.	12,393	9,921	12,421	9,892	18,662	3,652	3,743	18,570	-4,596	26,910

Note: Net returns equal gross revenues from marketable strawberries minus the ASD, fumigation, and harvest costs. Rice bran materials equal the cost of rice bran delivered to the experiment station. Wheat production costs include seeds, fertilizer, electricity used for groundwater pumping, and labor.

5.3 Breakeven Prices and Treatment Costs

Table 6 shows the breakeven prices and costs. The results reveal negative breakeven prices of rice bran, wheat, and labor, indicating that ASD treatments lead to lower net returns than the control groups at positive rice bran prices, wheat production costs, and labor wage rates. For instance, in the 2021–2022 trial, a grower would have to pay -$698 per ton for rice bran in the rice bran ASD treatment with fumigation to achieve net returns equal to the net returns from the control with fumigation. In other words, a grower would require a subsidy of at least $698 per ton for rice bran to incentivize the adoption of rice bran ASD over a fumigation-only treatment at realized strawberry yields and prices. The negative breakeven rice bran, wheat, and labor prices across all ASD treatments shown in Table 6 have a similar interpretation.

Table 6 reveals positive ASD breakeven costs apart from rice bran ASD without fumigation in the 2021–2022 trial, which has a breakeven cost of -$55 per acre. While positive ASD costs appear promising, they are, in most cases, a small fraction of the realized treatment costs. For instance, in the 2021–2022 trial, the breakeven ASD cost in the rice bran ASD with fumigation treatment ($3,614 per acre) is 24% of analyzed ASD costs, and in the wheat and rice bran ASD without fumigation ($669 per acre) is 2% of analyzed ASD costs. In the 2022–2023 trial, the breakeven cost of ASD in the rice bran ASD without fumigation and wheat and rice bran ASD without fumigation are each a large share of analyzed costs (45% and 57%, respectively). In these cases, it is feasible that commercial growers could achieve ASD treatment costs less than the calculated breakeven ASD costs from a combination of lower material costs and labor hours.

6 Discussion

Our study highlights the relevance of treatment costs and relative yields in the economic evaluation of ASD as a non-chemical alternative to fumigation in strawberry production.

Table 6: Breakeven Prices and Treatment Costs

	Rice bran[a]	Wheat[b]	Labor[c]	Total ASD costs[d]
Treatment	$/ton		$/hour	$/acre
2021–2022 trials				
Rice bran ASD & fum.	-698		-47	3,614
Rice bran ASD & no fum.	-1,106		-70	-55
Wheat, rice bran ASD & fum.	-3,839	-2,378	-15	4,009
Wheat, rice bran ASD & no fum.	-4,581	-3,120	-22	669
2022–2023 trials				
Rice bran ASD & fum.	-764		-143	1,619
Rice bran ASD & no fum.	-18		-74	8,330
Wheat & fum.		-459	-8	4,369
Wheat & no fum.		-656	-15	2,589
Wheat, rice bran ASD & fum.	-2,368	-2,343	-35	2,898
Wheat, rice bran ASD & no fum.	-676	-651	-3	10,511

Note: Values in each column represent the cost per unit to achieve a net return equal to the control group holding all other variables constant. We compare ASD treatments with fumigation to the control group with fumigation and ASD treatments without fumigation to the control group without fumigation.
[a]Breakeven price of rice bran delivered to the experiment station.
[b]Breakeven cost to produce wheat, including seed, fertilizer, irrigation electricity, and labor.
[c]Breakeven wage rate for labor used to produce wheat and treat plots with ASD.
[d]Breakeven cost of ASD treatments, including materials, labor, and custom services.

While ASD treatments demonstrated some improvements in strawberry yields, especially when combined with fumigation, these yield gains did not consistently result in higher net returns due to considerable input costs. The divergence between agronomic performance and economic viability underscores the critical role of cost management and market conditions in determining the viability of ASD as a sustainable pest management practice. In the following paragraphs we discuss our results with reference to existing literature and government data.

In the 2021–2022 trials, mean yields ranged from 24,731 to 30,464 pounds per acre, far below the mean 2022 California strawberry yield of 59,000 pounds per acre (USDA NASS, 2024). Yields realized in the 2022–2023 trial were much higher than earlier trials, ranging from 30,979 to 52,499 pounds per acre and closer to commercial yields. Environmental factors like weather and disease status of the soils might explain the low yields from the

2021–2022 trials, but researchers did not note any issues that can help explain these results. We inspected the raw yield data for outliers that might explain the low yields, but we found no examples.

Compared to the untreated control, rice bran ASD and wheat and rice bran ASD without fumigation in the 2021–2022 trial increased mean yields by 10%. Compared to the control with fumigation, rice bran with fumigation decreased yields by 2.4%, and wheat and rice bran ASD with fumigation increased yields by 2.472%. In the 2022-2023 trial, fumigated rice bran ASD, wheat ASD, and wheat and rice bran ASD were 6% lower and 2% and 5% higher than control with fumigation plots, respectively. Rice bran ASD, wheat ASD, and wheat and rice bran ASD without fumigation increased yields by 52%, 16%, and 65% relative to the control without fumigation, respectively. Lower yields from rice bran ASD treatments compared to their control counterparts are unexpected and inconsistent with previous findings (Shennan et al., 2018; Michuda et al., 2019; Hoffmann et al., 2016). Even without the disease-suppressive effects of ASD, we expect the rice bran amendments to improve soil fertility and, consequently, strawberry yields. We can not find any discussion of rice bran ASD interacting with chemical fumigants to decrease yield, and this result likely warrants further experimentation. Yield improvements from ASD relative to their control counterparts are within the range reported across similar studies (Shennan et al., 2018; Michuda et al., 2019; Hoffmann et al., 2016).

ASD treatment and control plots from 2021–2022 trials follow similar marketable strawberry yields throughout the harvest, as shown in appendix Figure A.1a, peaking in mid-May and decreasing through June, where they remained relatively stable until the harvest concluded in September. The pattern of yields through the harvest has implications for revenues as strawberry prices change over time. However, we find that the weighted average price of strawberries harvested in 2022 was similar across treatments, ranging from $1.21 per pound for berries sold from wheat and rice bran ASD with fumigation plots, which produced a higher share of strawberries in May and June when the price for extra large strawberries was around \$1.07 per pound, to \$1.27 per pound for berries sold from untreated control plots, which produced a high share of strawberries in July and August when the price for medium strawberries averaged \$1.60 per pound. The effect of high late-season yields and corresponding prices can be seen in appendix Figure A.2a where the revenue from the untreated control converges towards revenues from the treatment groups from about August 3rd onward.

The pattern of yields over the harvest season, shown in appendix Figure A.1a, also has implications for harvest costs. A higher proportion of strawberries harvested during peak harvest weeks–defined as May 9th through June 15th, 2022, in our analysis–translates to lower harvest costs per pound of strawberries. Indeed, we find that average harvest costs per pound of strawberries are highest in control plots without fumigation and lowest in wheat and rice bran ASD with fumigation because of the distribution of yields over time.

In the 2022–2023 trial, yields over the harvest season, shown in Figure A.1b follow a different pattern. We find that the mean yields from most treatments peak in early July and again in early August. The sawtooth pattern in Figure A.1b is explained by the inconsistent number of days between harvests, ranging from 2 to 6. Longer periods between harvests yield more strawberries picked on the harvest day, but do not affect the cumulative yield of strawberries at the end of the harvest season.

Carbon amendment costs are frequently discussed as the largest cost of ASD treatments in the existing literature (Shrestha, Augé, and Butler, 2016; Shennan et al., 2018). We find that rice bran and wheat (wheat seed, fertilizer, irrigation electricity, and labor) account for the highest share of costs in this experiment, as shown in appendix Table A.1. However, these costs are not representative of those expected in commercial settings. In particular, rice bran was delivered in ton totes to the experiment station in 2021 at a cost of \$615 per ton and in 50-pound bags in 2022 at a cost of \$1,248 per ton. Packaging and transport contribute to these high prices. Field-scale ASD would require bulk delivery of rice bran, further lowering the cost. U.S. Department of Agriculture, Agricultural Marketing Service (2024) report rice bran prices equal to \$260 per ton in the Central Valley of California in

2022. Transport costs to Salinas might add a further $20 per ton to the price,[4] resulting in a delivered price of $280 per ton, equivalent to 47% and 25% of the price paid for rice bran in the experiment in 2021 and 2022, respectively.

Furthermore, wheat costs totaled $9,265 per acre in the 2021–2022 trial and $5,058 per acre in the 2022–2023 trial, primarily because of high labor hours attributed to wheat production. In contrast, Mathesius et al. (2016) report it cost $534 per acre to grow, harvest, and market irrigated wheat in California in 2016 using 2.2 hours of labor. Our experimental wheat production required approximately 291 hours per acre in 2021 and 145 hours per acre in 2022. The lower hours of wheat labor used in 2022 resulted from an increase in the experimental area without any meaningful change in total labor hours. The high cost of labor for ASD similarly results from high hours per acre, specifically 146 hours per acre in 2021 and 97 hours per acre in 2022.

Results of the sensitivity and breakeven analyses further illustrate the economic challenges associated with ASD adoption. Reduced input costs, including rice bran and labor, or increases in strawberry prices and yields significantly improve net returns. However, even with a 25% decrease in the cost of rice bran, wheat production, or harvest labor, ASD treatments in the 2021–2022 trial failed to achieve positive net returns, reinforcing the need for cost-effective carbon amendments and labor. Moreover, negative breakeven prices for rice bran, wheat, and ASD labor imply that control plots result in higher net returns when analyzed prices are positive, holding other input costs and revenues constant.

Breakeven prices and costs changed, in some cases markedly, between the 2021–2022 and 2022–2023 trials. For instance, the breakeven cost of rice bran ASD without fumigation equals -$55 per acre in the 2021–2022 trial and $8,330 in 2022–2023. In this case, the higher breakeven cost of ASD treatment is driven by the changes in strawberry yield relative to the control group over time. Specifically, rice bran ASD without fumigation increased yields relative to the control group by 10% in the 2021–2022 trial and 52% in 2022-2023. In contrast,

[4] Authors estimate based on trucking price of $3.29 per mile reported by Leslie and Murray (2023), a distance of 150 miles from Hanford to Salinas, and 25 tons per truck.

a decrease in the relative yield from rice bran ASD with fumigation relative to fumigated control plots over time is the driving factor behind the drop in breakeven ASD cost from $3,614 per acre in 2021–2022 to $1,619 in 2022–2023. Increased rice bran material costs in 2022 also play a role. It is also worth noting that the contrast between positive breakeven total ASD costs and negative analyzed input costs, while striking, is not unexpected given that the rice bran, wheat, and labor costs are each less than half of treatment costs.

7 Concluding Remarks

This study provides an economic assessment of anaerobic soil disinfestation (ASD) as an alternative to chemical fumigation in strawberry production. Results from two field trials reveal that while ASD treatments improve strawberry yields, particularly when combined with fumigation, these gains do not translate into higher net returns due to high material and labor costs in our experimental setting. In the 2021–2022 trial, ASD treatments resulted in negative net returns across all scenarios. However, the 2022–2023 trial demonstrated more favorable outcomes, with positive net returns for ASD treatments under most conditions, though fumigated control plots outperformed ASD treatments in profitability.

Sensitivity analyses highlight that net returns from ASD treatments are highly responsive to changes in input costs, yields, and market prices. Even under improved yield or reduced input cost scenarios, the profitability of ASD remains limited without favorable strawberry price conditions. These findings underscore the complexity of adopting ASD treatments in a commercial setting and suggest that its economic feasibility is highly contingent on site-specific factors and market conditions.

While ASD represents a viable non-chemical strategy for soilborne pathogen management, its adoption at scale will likely depend on further reductions in treatment costs, continued research into cost-effective carbon amendments, and market incentives for sustainably grown strawberries.

While this study provides much-needed insights into the economic performance of ASD, the results are context-dependent and highlight the variability of outcomes across different production environments. Future studies should prioritize assessing the cost-effectiveness of ASD treatments at commercial scales. Specifically, ASD trials conducted at typical California strawberry field acreage should provide ASD labor hours, wheat production labor hours, and rice bran material costs that more accurately reflect those faced by growers. Additionally, research should investigate the long-term effects of ASD on soil health, crop productivity, and overall profitability. Integrating ASD into broader sustainable farming systems, such as crop rotation practices, could generate synergistic benefits, including enhanced soil fertility and reduced reliance on chemical fertilizers.

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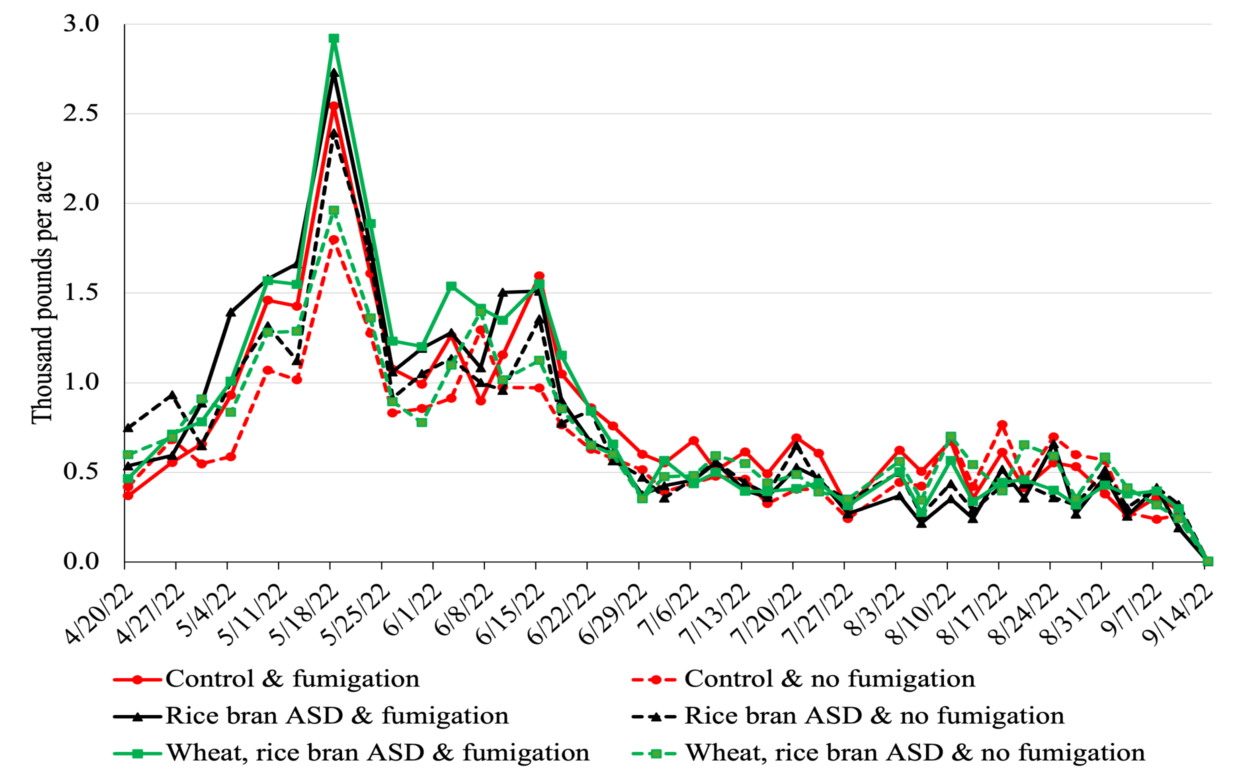
A Appendix

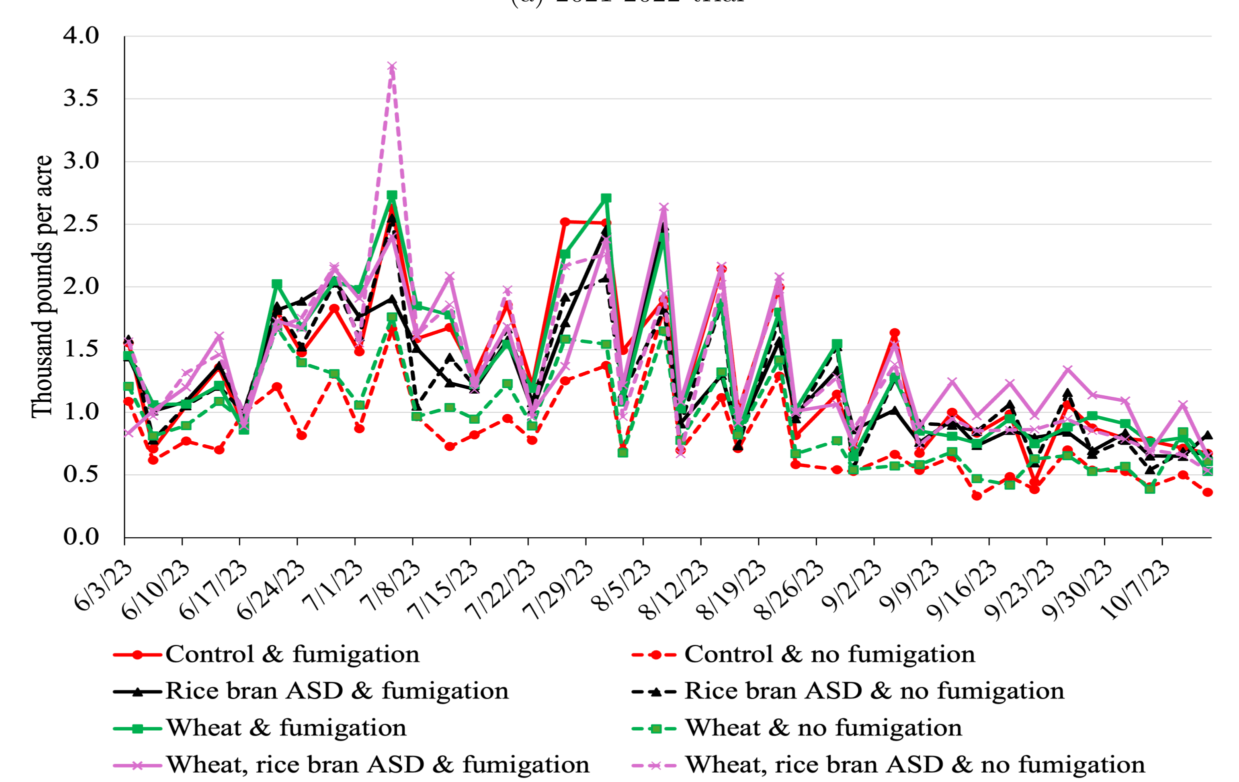
Table A.1: ASD Treatment Costs

	2021–2022 treatments		2022–2023 treatments		
	Rice bran	Wheat & rice bran	Rice bran	Wheat & rice bran	Wheat
Item	$/acre				
Seed	-	105	-	105	105
Fertilizer	-	283	-	242	242
Wheat irrigation electricity	-	143	-	363	363
ASD irrigation electricity	18	18	46	46	46
Wheat production labor	-	8,733	-	4,348	4,348
ASD labor	4,367	4,367	2,899	2,899	2,899
Rice bran	5,377	2,688	9,888	4,944	-
Irrigation supplies	1,915	4,036	1,951	1,951	1,951
Tarping and laying drip tape	3,600	3,600	3,600	3,600	3,600

Note: A custom operator supplied the tarp and drip tape materials and installation labor.

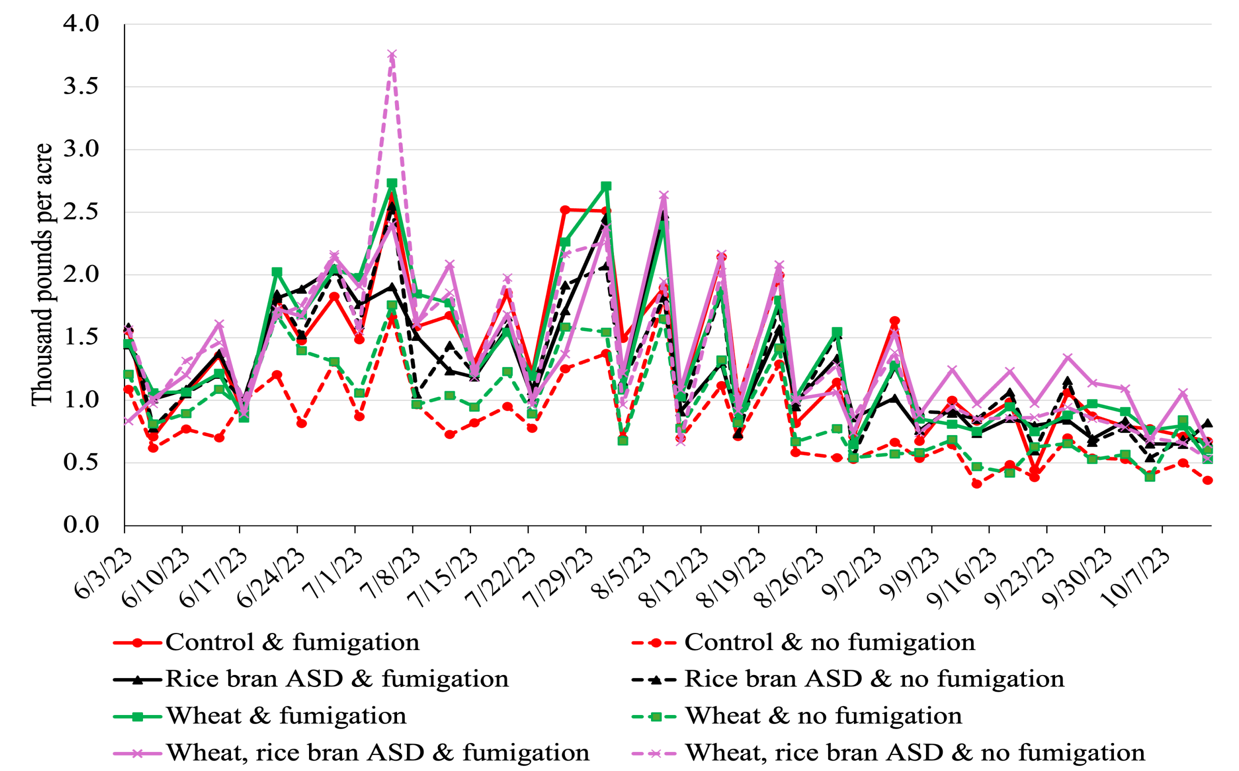


(a) 2021-2022 trial

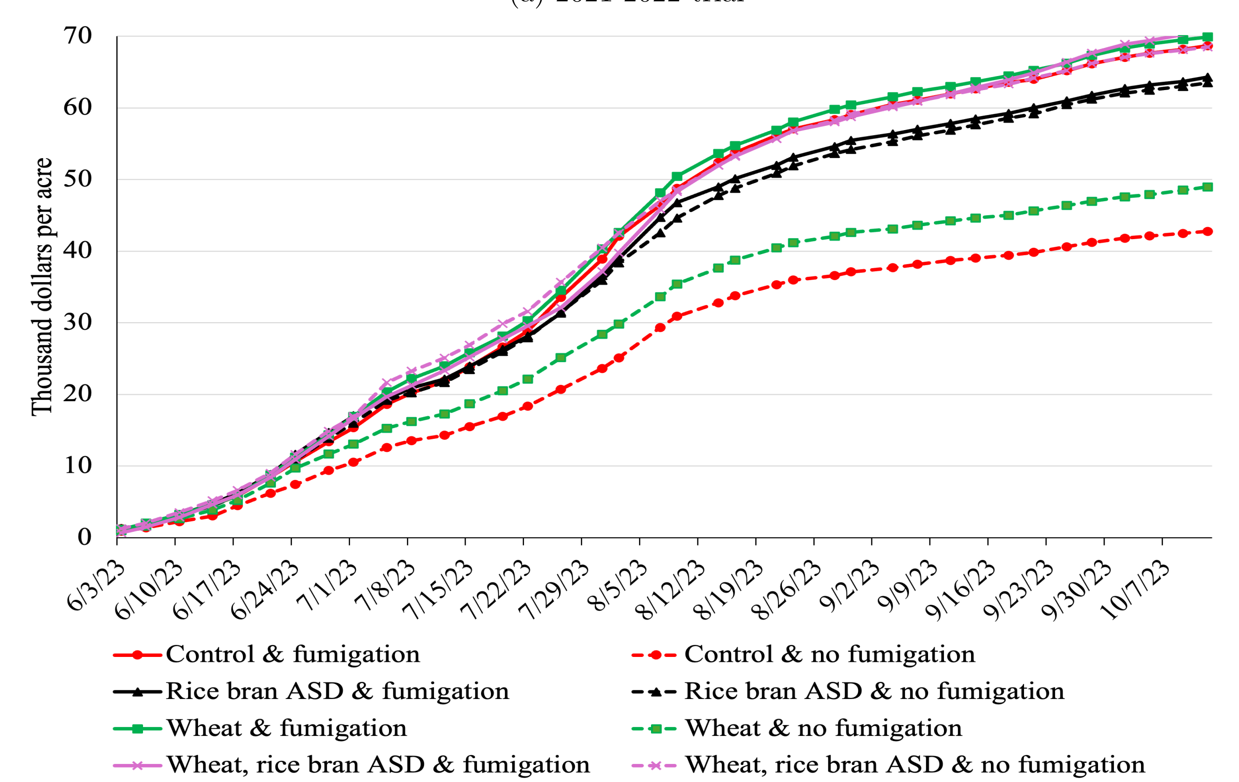


(b) 2022-2023 trial

Figure A.1: Marketable yield by harvest date.



(a) 2021-2022 trial



(b) 2022-2023 trial

Figure A.2: Cumulative gross revenues.