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Soil biosolarization for sustainable strawberry production

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Abstract Strawberry is a high value crop worth 315.6 million euros in 2013 in Spain. Strawberry diseases are commonly controlled by soil fumigation with toxic chemicals. However, since 2007, the methyl bromide fumigant is banned for strawberry cultivation. Moreover, European policies are progressively restricting the use of other toxic fumigants such as dichloropropene. Alternative control techniques are thus needed. Therefore, we have tested soil biosolarization, a new technique combining soil biofumigation and soil solarization, to cultivate the *Camarosa* strawberry in 2010–12 at Huelva in the southwestern coast of Spain. Soil was biofumigated by amendment of fresh chicken manure at 12,500 kg/ha with or without *Trichoderma* at 3.5 kg/ha; chicken manure at 25,000 kg/ha; *Brassica juncea* pellets at 2,000 kg/ha; sugar beet vinasse at 15,000 kg/ha; or dried olive pomace at 12,500 kg/ha. Soil was then solarized for 30 days by covering with a clear plastic mulch. A control that received fermented manure remained uncovered. Our results show that the highest yield averaging 70,543 kg/ha and the lowest percentage of 12.6 % of second-class fruits were obtained by amendment of fresh chicken manure. Yields were also similar to the higher yields previously reported for chemical fumigation with 1,3-dichloropropene and chloropicrin. In addition, biosolarization is about 20 % cheaper than treatment with 1,3-

dichloropropene and chloropicrin. Biosolarization with chicken manure is, therefore, a promising sustainable option for strawberry production.

Keywords Biosolarization · *Fragaria × ananassa* · Methyl bromide · Nonchemical alternatives · Organic amendment · Soil fumigation · Yield

1 Introduction

Strawberry (*Fragaria × ananassa* Duch.) is a high value crop (315.6 million euros were invoiced in 2013) grown in Spain. The fruit production is concentrated at Huelva, the major area of strawberry production in Europe and in the Mediterranean basin, and one of the most important strawberry production areas of the world (FAOSTAT agricultural data 2011). The conventional fruit production is based on annual planting of bare-root green plants of the short-day varieties from high-elevation nurseries in autumn. The plants are placed in two rows into beds protected by opaque plastic mulch with localized irrigation equipment and fertilizing irrigation system. These beds are covered by macrotunnels with clear mulch, and fruit production is expected from December to end of May (López-Aranda, 2008).

Strawberry production has relied upon the use of methyl bromide in combination with chloropicrin as preplant soil fumigation treatments (Duniway 2002) to control soilborne pathogens, weeds, and nematodes. As a result of the Montreal Protocol and Regulation of the European Community no. 2037/2000 of 29 June on substances that deplete the ozone layer, the phaseout of methyl bromide for strawberry production was irreversible in the European Union countries since 2007 (Commission Decision (European Community), 2006). Since then, other chemical treatments, mainly the mixture of 1,3-dichloropropene plus chloropicrin, chloropicrin alone,

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dazomet plus 1,3-dichloropropene, and metam sodium, have been used successfully in Spain. Currently (2012/2013 crop season), the percentage of these chemicals that were employed for 8,200 ha for fruit production in Spain (7,000 ha of strawberry+1,200 ha of raspberry) were as follows: 1,3-dichloropropene plus chloropicrin (75 %), chloropicrin alone (10 %), dazomet (10 %), and metam sodium (2.5 %) (López-Aranda 2013). However, in Europe, the use of some of these molecules is being questioned and restricted (European Regulation 1107/2009 and European Economic Community Directive 91/414). For example, the use of dazomet, metam sodium, and metam potassium are authorized, but from May 2015 for dazomet and July 2016 for metam sodium or potassium, only one application in three seasons will be permitted, and the maximum rate is limited to 490 kg/ha for the case of dazomet and to 153 kg/ha for metam sodium or potassium. This rate would be appropriate for growers and nurserymen in the case of dazomet, but for metam sodium and metam potassium, this rate is significantly lower compared to 500 to 1,000 l/ha (600 to 1,200 kg/ha) range currently used in nurseries and production fields. The main chemical alternatives in the world, 1,3-dichloropropene and chloropicrin, have been banned (in the European Union) since 2010 and 2013, respectively, even though currently both remain the most important methyl bromide alternatives in the European Union (nearly 70 % of utilization on acreage). This fact is due to the legal possibility of the member states to allow temporary authorizations for particular agricultural industries (national emergency uses) of these fumigants. Currently, use of both 1,3-dichloropropene and chloropicrin is restricted to 120 days per year for strawberry, cut flowers, grapes, and some other horticultural crops (Ministry of Agriculture, Food and Environment of Spain; Resolution, 16th July 2013). However, the future of these limited authorizations for 1,3-dichloropropene and chloropicrin is very uncertain.

Several limitations on use of fumigants facilitated numerous efforts to identify new effective solutions for soil fumigation in the cultivation of strawberries in the Mediterranean area. Previous studies showed potential efficacy of several chemical control strategies for soil disinfestation in coastal Huelva and Mediterranean areas utilizing 1,3-dichloropropene plus chloropicrin, chloropicrin alone, dazomet, and metam sodium (López-Aranda 2013, Medina-Mínguez et al. 2012). However, due to the uncertain status of these materials, new chemical alternatives have been investigated (Ajwa and Othman 2013).

Nonchemical soil disinfestation for strawberry production, such as steam, soil solarization, soilless cultivation, biofumigation, and others methods, have also been studied as possible alternatives (Daugovish et al. 2013, Fennimore et al. 2013). However, these are still considered risky and/or not feasible as global alternatives to chemical fumigants (Fennimore et al. 2013). Therefore, they are not available for a generalized use in any significant strawberry-growing area.

Solarization is based on the utilization of solar radiation to raise the temperature of a soil at field capacity previously covered with a transparent polyethylene film. This method seeks to increase the maximum temperatures of the soil to a level lethal or sublethal to pathogens (Katan 1981). Previous studies have shown that when applied in combination with fumigants such as metam sodium at low dose, the results are comparable to those obtained with methyl bromide (López-Aranda 2013). Moreover, biofumigation relies on the use of gases resulting from the degradation of organic amendments and agroindustrial residues to control soil pathogens (Bello et al. 1999). Among these materials are livestock manure, paper industry, forestry, fisheries, shellfish, and agriculture residues, as well as plant residues with allelopathic compounds (Hoitink 1986). Decomposition of such materials releases nitrogenous compounds (ammonia, nitrate, nitrite), organic acids, hydrogen sulfide, and a large number of volatile compounds (aldehydes, ketones, etc.) which are responsible for the biocidal activity (Angus et al. 1994). In particular, biofumigation with the *Brassica* species biomass or seedmeal have resulted in some suppression of plant pathogens by biocidal compounds originating from the hydrolysis of glucosinolates in these materials (Kierkegaard and Sarwad 1998).

Information about the use of biofumigation in combination with solarization (biosolarization; Fig. 1) in the scientific literature is very recent and scarce. Most authors refer to the biosolarization as a remediation tool that accelerates degradation of pesticides in soil, likely as a result of the increase of the soil temperature (Fenoll et al. 2010), and for the control of soilborne fungi associated with yield decline, such as *Phytophthora capsici* or *Fusarium* spp., in temperate climate regions (Núñez-Zofio et al. 2011; Martínez et al. 2011). Anaerobic soil disinfestation that combined solarization and use of rice bran as carbon source was recently evaluated in California and provided 80–95 % control of *Verticillium dahliae* and strawberry yields 60–87 % greater than untreated



Fig. 1 Setting the plastic film for solarization after application of organic matter

control and comparable to 1,3-dichloropropene plus chloropicrin-fumigated soils (Shennan et al. 2013, Daugovish et al. 2011). Similar technology was used in Florida and provided significant reduction of *Macrophomina phaseolina* fungal pathogen (the causal agent of charcoal rot of strawberry) (Roskopf et al. 2011). However, the number of studies focusing on agronomic performance of strawberry in biosolarized soils is limited, and results have been inconsistent.

During the last years, a new strawberry plant collapse problems have been detected. Plant diagnostic analyses confirmed that these problems were associated with two soilborne fungi: *M. phaseolina* and *Fusarium oxysporum* (the causal agent of Fusarium wilt). Some authors have associated the changes in the fumigation products used and methods of application with the establishment of these two new soilborne pathogens on strawberry, especially with the use of preplant methyl bromide alternatives, applied to the beds, instead of the whole fields (Zveibil and Freeman 2005; Koike et al. 2012). The biosolarization appears promising for control of soilborne pathogens in temperate climate regions. Furthermore, Teruhiko et al. (2001) suggested that Fusarium wilt of strawberry could be controlled better by soil solarization than fumigation by either methyl bromide or chloropicrin.

However, biosolarization would be only considered as a viable alternative to fumigation if it can maintain fruit production at levels similar to fumigate soils. Currently, annual yields at Huelva are between 55,000 and 70,000 kg/ha (López-Aranda 2008). The strawberry is the basis for economical and social support of this region; thus achieving high levels of production is of great importance.

The objective of the present study was to evaluate the effect of different biosolarization techniques on yield parameters and on the incidence of soil fungal pathogens, in order to know the viability of these techniques for the production of strawberry in temperate climate regions.

2 Materials and methods

This work was performed during the crop seasons 2010/2011 and 2011/2012 in an experimental field located at Moguer (37° 17' N) in the coastal area of Huelva. Chemical fumigants have never been applied to soil in this experimental field. The soil was sandy (sand 86 %, clay 4 %, and loam 10 %) with a pH of 6.5, an organic matter content of 0.26 %, a total nitrogen content of 0.02 %, a phosphorus content of 68 mg kg⁻¹, and an electrical conductivity of 0.19 mmhos · cm⁻¹. The irrigation water had a pH of 5.6; an electrical conductivity of 0.32 mS cm⁻¹; a carbonate, bicarbonate, sulfate, chloride, nitrate, and nitrite content of 25, 29, 9.9, 96, 4.61, and <0.05 mg l⁻¹, respectively; and a sodium adsorption ratio of 3.38.

The experiment was designed as a randomized complete block with four replications and seven treatments. The seven treatments studied each year were as follows: (a) non-treated control (25,000 kg/ha of fermented chicken manure, no solarization); (b) biosolarization with fresh chicken manure (25,000 kg/ha); (c) biosolarization with fresh chicken manure (12,500 kg/ha) plus *Trichoderma* (3.5 kg/ha TUSALTM, Certis, Spain; 1.10¹¹ ufc of T11 starin+1.10¹¹ ufc of T25 starin/ha); (d) biosolarization with fresh chicken manure (12,500 kg/ha); (e) biosolarization with *Brassica* pellets (*Brassica juncea*, BioFenceTM, Triumph, Italy) (2,000 kg/ha); (f) biosolarization with sugar beet vinasse (15,000 kg/ha); and (g) biosolarization with dried olive pomace (12,500 kg/ha). Every year, in mid-July, the organic amendments were incorporated into the soil to a depth of 20 cm using a rotovator. Plots were then sprinkler irrigated to field capacity and covered with a 0.05-mm thick transparent polyethylene plastic film for 4 weeks. In mid-September, after plastic removal, 50-cm wide beds were formed, one irrigation drip tape was installed in the middle, and beds were covered with black polyethylene mulch. Bare-root *Camarosa* plants from high-elevation nurseries (Castille-Leon, Spain, 41° 30' N, alt. 900–1,200 m a.s.l.) were planted in mid-October (López-Aranda 2008) at a rate of 72,000 plants/ha. Plants (140 plants per plot) were placed in double rows per mulched bed and spaced 25 × 25 cm. One month after planting, macrotunnels covered with 0.15-mm thick transparent plastic mulch were installed over the test areas. Crop management followed standard practices for macrotunnel strawberry production (López-Aranda 2008). The plants received 175 kg N/ha, 77 kg P/ha, 185 kg K/ha, 85 kg Ca/ha, and 14 kg Mg/ha, between mid-November and mid-May through the irrigation. *Camarosa* was used in the trials since it has been the most important cultivar in the area of Huelva from 1997 to 2010.

Plant mortality, early season yield (until end of March) and whole season yield (until end of May), plant vigor, and fruit weight were recorded throughout the production season.

2.1 Plant mortality

2.1.1 Percentage of plant survival

Total number of dead plants was recorded to obtain viable plant survival percentages five times during the crop season (14th January, 14th March, 29th March, 14th April, and 29th April). Plants were considered nonviable if wilted or dead from any cause, stunted, or showing viral symptoms.

2.1.2 Fungal pathogen incidence in dead plants

Dead plants from all plots were collected until mid-May for disease diagnostics. Plants were washed under running tap water, separated into roots and crowns parts, and surface

sterilized in 1 % aqueous solution of sodium hypochlorite for 2 min, rinsed twice in sterile distilled water, and dried in a laminar flow cabinet. Pieces of root and crown were then separately placed on nonselective potato dextrose agar medium (PDA). Cultures isolated were incubated in illumination conditions at 25 °C and inspected microscopically for identification. The incidence of mortality was expressed as percentage of dead plants.

2.2 Yield assessments

2.2.1 Plant vigor index

Ten randomly selected plants from each plot were observed throughout the growing season. Plant diameter of canopy was determined by taking two measurements (north–south and east–west) of the above ground foliage from each plant. This was done monthly from December to April. Vigor index was estimated as the area under the curve of the plant diameter progress.

2.2.2 Fruit yield and fruit weight

Fruit production data from the total number of plants per plot was obtained at least once each week throughout the production season (mid-January to mid-May). Fruit was graded into two commercial categories using the European regulations criteria for fresh fruit: first and second category. First plus second categories are named commercial or marketable category. First category is defined as a healthy fruit well shaped with a weight above 14–15 g per unit. The second category is defined as a healthy fruit that is shaped well and with a weight below 14–15 g per unit (and/or a healthy fruit lightly misshapen of size above 14–15 g). Nonmarketable fruits were rejected without recording (less than 2–3 % of harvested fruit). Yield data were recorded as kilograms per hectare. Fruit yield was evaluated for early season production (cumulative yield until end of March) and whole season production (cumulative yield until end of the growing season). Fruit size was estimated by weighting 40 randomly selected marketable fruits each from three harvests. Fruit weight was recorded as gram per unit.

Data were submitted to analysis of variance, and treatment means were compared with Fischer's protected least significant difference test at the 5 % significance level (Statistix 8.0; Analytical Software, Ltd., La Jolla, CA, USA). Prior to analysis, percentages were transformed to improve homogeneity of variances as arcsine square root. The incidence of mortality was expressed as percentage of dead plants.

3 Results and discussion

The analysis of variance indicated that the yield, percentage of second class, and fruit weight showed significant differences among treatments in both early and total yield for the two sources of variation considered (season and treatment). Similarly, there were also significant differences among treatments in plant vigor along the crop season, and in the percentage of plant mortality at the end of the experiment.

Results of analysis of variance of plant mortality, early, and whole season yield, plant vigor, and fruit weight showed that the effect of [season × treatment] was not significant ($p > 0.05$). Therefore, the means were calculated for the two seasons combined. Results of ANOVA on percentage of second-class fruit in early yield showed that the effect of [season × treatment] was significant ($p < 0.05$), thus data for this variable were analyzed by each season.

3.1 Plant mortality and fungal disease assessments

High plant survival percentages were recorded (above 90 %) throughout the crop season in all treatments except the non-treated control that showed a significantly lower plant survival since mid-March (below 90 %; $p < 0.001$) until the end of the season (below 66 %; $p < 0.001$). All the biosolarization treatments tested maintained a high percentage of plant survival at the end of the growing season, and no differences were detected among them (Fig. 2).

In this study, *M. phaseolina* was consistently isolated from crowns and roots of the samples tested (Fig. 3). *M. phaseolina* was often isolated independently or in combination with *Pythium* spp., *Rhizoctonia* spp., *Cylindrocarpon* spp. (the casual agents of black root rot, BRR, in strawberries), and *Fusarium* spp. *Colletotrichum acutatum* and *Phytophthora cactorum* were isolated at the lowest frequencies from crowns and roots of symptomatic plants of all treatments and control (Fig. 4).

Reduction in disease incidence due to the application of organic amendments with solarization has been previously described in pepper (Martínez et al. 2011; Núñez-Zofio et al. 2011) and was at least partially attributed to the production of NH_3 and an increase in soil microbial activity, which can help control soilborne pathogens through competition, antibiosis, parasitism/predation, etc. (Núñez-Zofio et al. 2011). Daugovish et al. (2011) reported up to 94 % reduction in *Verticillium dahliae* in soils heavily infested with the pathogen (20–30 microsclerotia per gram of soil) after anaerobic disinfection with rice bran under clear mulch. Microbiological changes in soil environment have also been documented as a mechanism of pathogen suppression and resulting improved crop productivity (Mazzola 2011).

The control of soilborne pathogens by biocidal products released during the decomposition of brassicaceous manure has been reported as an effective control method (Kierkegaard

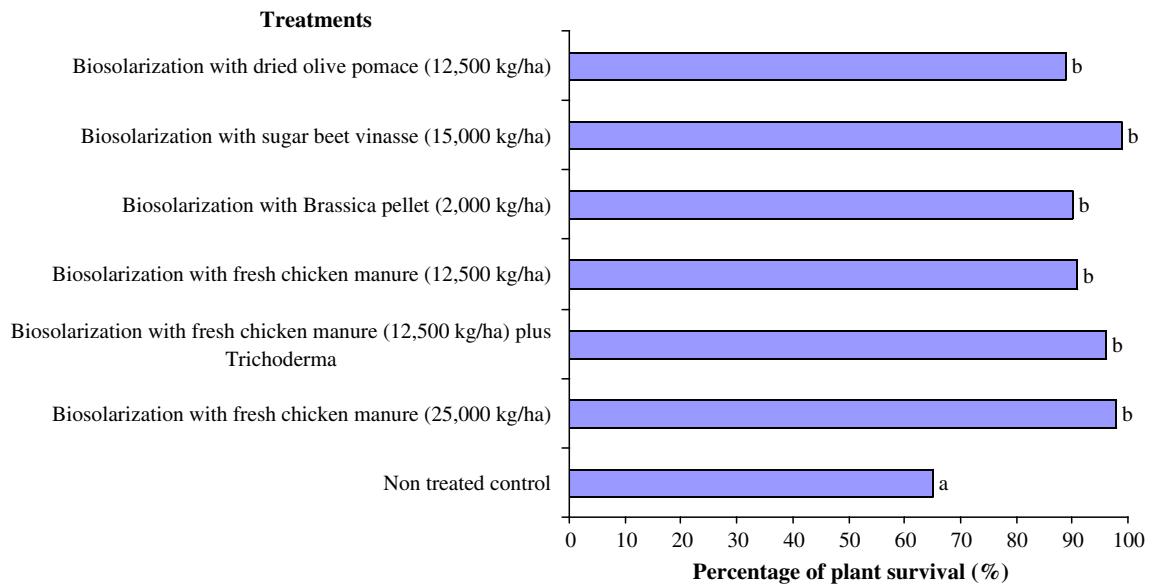


Fig. 2 Percentage of plant survival from different biosolarization treatments. Values are means of four replicates. Means followed by the same letter in each column were not significantly different ($p < 0.05$) by the LSD test

and Sarwad 1998). *Brassicaceae* species contain high levels of glucosinolates which produce biocidal compounds such as isothiocyanates. Of these, *B. juncea*, *Brassica carinata*, and *Brassica nigra* are among the most effective in suppressing *Phytophthora* spp. isolates from strawberry plants (Zurera et al. 2007). In our case, the biocidal effect of the *Brassica* on the soilborne pathogen led to a yield improvement compared to the untreated control, but not as pronounced as with treatments that included biofumigation with fresh chicken manure (Table 1). These data indicated that biosolarization protected strawberry plants from the charcoal rot disease

infection through most of the production season. Complete eradication of *M. phaseolina* from soil remains a non-attainable target, since even soil fumigation with methyl bromide, 1,3-dichloropropene plus chloropicrin, or chloropicrin alone did not provide complete crop protection in fields infected with this pathogen (Daugovish et al. 2009).

3.2 Yield assessments

Plants from non-treated plots were significantly smaller ($p < 0.05$) (area under the curve of 45.1 cm²) than those from

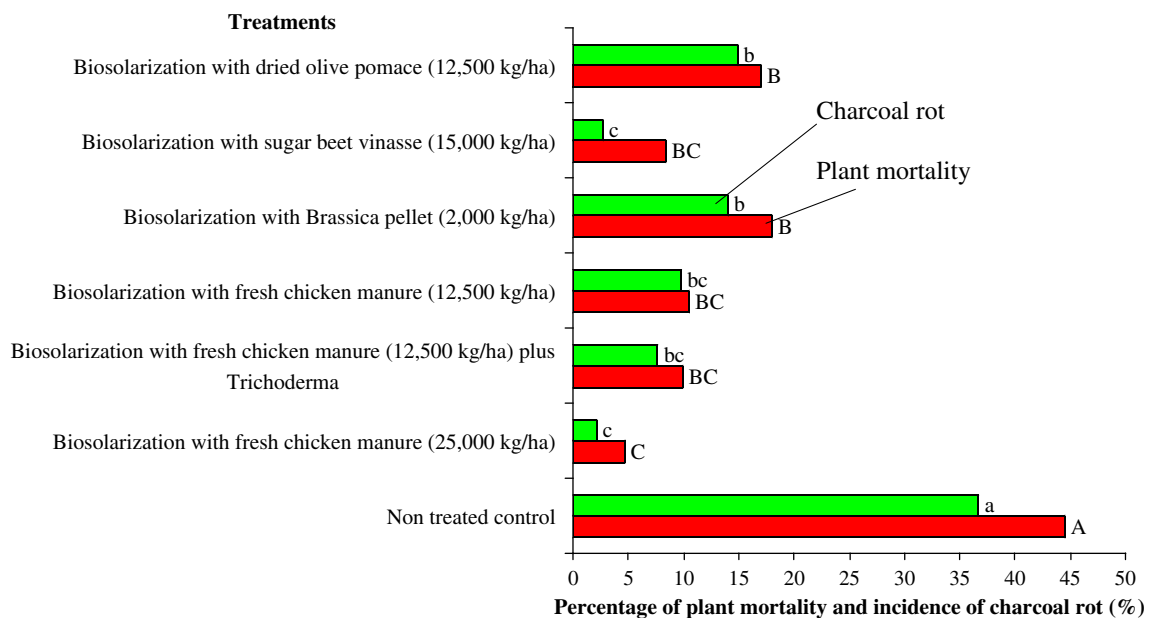


Fig. 3 Effect of soil disinfection treatments on percentage of mortality and incidence of charcoal rot caused by *Macrophomina phaseolina* (means 2010/2011 and 2011/2012 seasons). Means within a column followed by the same letter are not significantly different ($p < 0.05$) by the LSD test

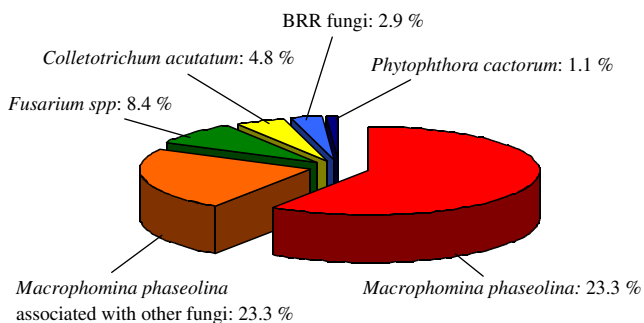


Fig. 4 Incidence of fungal plant pathogens (in percent) isolated from crowns and roots of symptomatic strawberry plants (means 2010/2011 and 2011/2012 seasons)

biofumigation treatments with fresh chicken manure (mean area under the curve of 55.2 cm²). Although the non-treated control plots received fermented manure in the same dose as the B treatment (biosolarization with fresh chicken manure, 25,000 kg/ha) to equalize the input of organic matter and nitrogen among treatments, when combined with solarization, the effect on the plant development was clearly evident.

Strawberry early and total marketable yields were influenced by the treatments. The lowest early yield was observed in the non-treated control. The higher values were observed in treatments which included biofumigation with fresh chicken manure, and in the treatment of biosolarization with dried olive pomace (12,500 kg/ha). Total yield was also higher in treatments biosolarized with fresh chicken manure and with dried olive pomace.

The season by treatment interaction was significant for the percentage of second-class fruit in early yield; therefore, this variable was separately analyzed for each growing season (2010/11 and 2011/12; Fig. 5). In 2010/11, the lowest percentage of second-class fruit during early production occurred in all treatments including biosolarization with fresh chicken manure, while biosolarization with sugar beet vinasse

compost (15,000 kg/ha) failed to improve the percentage of second-class fruit in comparison with the non-treated control. In 2011/12, all the treatments tested showed significantly lower percentage of second-class fruit in early production than the non-treated control. No significant differences for this variable were observed among the three treatments with fresh chicken manure and those including biosolarization with *Brassica* pellets and with dried olive pomace. Treatment with sugar beet vinasse compost showed the highest percentage of second-class fruit.

The season by treatment interaction was not significant for the percentage of second-class fruit in total yield. Similarly to what was observed in early production, the lowest percentages were in biofumigation treatments with fresh chicken manure and with dried olive pomace (Table 1). Treatment with sugar beet vinasse compost resulted in lower amount of second-class fruit than in the non-treated control, but was the highest among all other treatments.

Average data of fruit weight in early and total yield are presented in Table 1. In all cases, in early and total yield, the non-treated control had smaller fruits than in other treatments (Table 1). Among treatments, those including biofumigation with fresh chicken manure and the one with dried olive pomace had the heaviest fruit.

The incorporation of organic matter, mainly non-composted amendments, carries a risk of soil salinization that should be taken into account (Núñez-Zofio et al. 2011). Several authors, such as Litterick et al. (2004), support the application of composted organic amendments instead of fresh manures, since composting provides a stabilized product and reduces the amount of organic compounds with potential phytotoxic effects (Gliotti et al. 1997). However, composting has some disadvantages such as N loss due to NH₃ volatilization and to a lesser extent, leaching and denitrification (Eghball et al. 1997). Our research also aimed to understand

Table 1 Yield parameters of strawberry as influenced by the fumigation treatments (means 2010/2011 and 2011/2012 seasons)

Early period			Whole season		
Treatments	Yield (kg/ha)	Mean fruit weight (g)	Yield (kg/ha)	Second-class fruits (%)	Mean fruit weight (g)
A	22,153 d	24.58 d	44,784 d	17.83 a	23.45 c
B	30,991 ab	27.84 a	71,476 ab	12.71 c	26.13 a
C	32,593 a	27.34 ab	73,754 a	12.59 c	25.76 ab
D	29,162 bc	27.63 a	66,399 bc	12.58 c	25.67 ab
E	28,144 c	25.98 c	63,946 c	13.73 bc	24.85 b
F	27,542 c	26.34 bc	64,617 c	14.79 b	24.93 b
G	29,788 bc	27.50 ab	66,799 bc	12.93 c	25.74 ab

A non-treated control, B biosolarization with fresh chicken manure (25,000 kg/ha), C biosolarization with fresh chicken manure (12,500 kg/ha) plus *Trichoderma*, D biosolarization with fresh chicken manure (12,500 kg/ha), E biosolarization with *Brassica* pellets (2,000 kg/ha), F biosolarization with sugar beet vinasse (15,000 kg/ha), G biosolarization with dried olive pomace (12,500 kg/ha)

Values are means of four replicates. Means followed by the same letter in each column were not significantly different ($p < 0.05$) by the LSD test

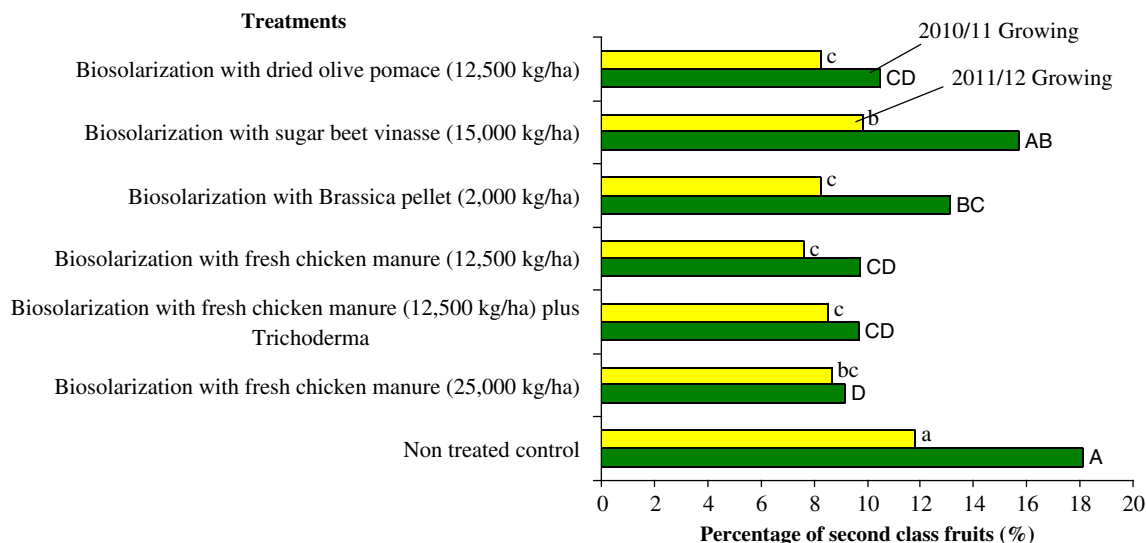


Fig. 5 Influence of the fumigation treatments on the percentage of second-class fruits in early yield in two growing seasons (2010/11 and 2011/12). Values are means of four replicates. Means followed by the same letter in each column were not significantly different ($p < 0.05$) by the LSD test

the effects of lower doses of amendment (fresh chicken manure). The nitrogen content of the fresh chicken manure used in this experiment ranged between 2 and 3 % of its fresh weight, and the water content was around 20 %.

Summer temperatures recorded during the treatments application (32.8 and 20.2 °C; means maximum and minimum, respectively, of both seasons) and soil texture (described above) have contributed to rapid decomposition of organic matter. However, application of organic amendments to soil over several years may lead to slight increases in soil organic matter and, therefore, the cation exchange capacity of the soils, especially for those with low cation exchange capacity. Thus, nutrient retention in these soils and long-term plant nutrient availability are likely to increase as well.

Although addition of *Trichoderma* in the treatment with fresh chicken manure did not improve fruit production in the season of application, the increase in *Trichoderma* species could be interesting to take into account due to their activity as biocontrol agents increasing natural suppression of pathogens in soil over time (Tran 1998).

According to our experience (over 10 years applying biosolarization with fresh chicken manure continuously in the same strawberry experimental farm), in contrast with the use of standard chemical disinfectants, nonchemical methods, such as the biosolarization, displayed an additive effect year after year, progressively improving productivity of the site (Medina-Mínguez et al. 2012). Improvements observed over the years can be summarized as follows: (1) slight increase in the organic matter content of the soil (0.4 to 0.9 %, from 2000 to 2010); (2) better weed control, especially of *Portulaca oleracea*, *Poa annua*, and *Lolium rigidum* in agreement with those described by López-Martínez et al. (2006); and (3) increase of the vegetative growth and yield of strawberry

cultivars. In the case of Camarosa, there was an increase in production from 600 to 700 g/plant to more than 1,100 g/plant over 10 years (Medina-Mínguez et al. 2012).

Treatments A and B have been applied to the same plot over 14 years while the rest of treatments during the past 3 to 5 years. From one year to the next, residual deposits of manure that remained in the soil in the form of humus is minimal since manure degradation is almost complete in a single season. However, application of manure year after year will likely lead to incremental increases in organic matter content of the soil.

The study results show that it may be possible to grow strawberries in temperate areas without chemical soil disinfection. Yields obtained with some of the alternatives tested (i.e., alternatives that include fresh chicken manure) are similar or even higher than those reported in conventionally fumigated crop systems (around 54,000–60,000 kg/ha; López-Aranda 2008). Also, biosolarization with dried olive pomace has shown promising results. Biosolarization does not significantly increase the current costs of strawberry production since it requires only the polyethylene film and the cost of installing and removing it (Medina-Mínguez et al. 2012). The cost of biosolarization is around 850 euros/ha which is about 20 % less than the treatment with 1,3-dichloropropene plus chloropicrin that is around 1,100 euros/ha. To assure that application of these amendments is feasible, it is necessary to have them available in close proximity to areas of application. Additionally, effective biosolarization is mostly restricted to warm, sunny areas as it is dependent upon high solar radiation. Solarization is typically recommended for 30–45 days during the months when the soil maximum temperatures are between 45 and 50 °C at 10-cm depth; however, when combined with biofumigation, the soil temperature could be as low as 40 °C (Medina-Mínguez et al. 2012).

Therefore, other strategies must be developed for regions with colder climate such as northern Europe.

4 Conclusion

According to the results, biofumigation plus solarization techniques could be considered as a sustainable alternative to the use of chemicals for soil disinfection of strawberry in temperate areas that may ensure long-term productivity of strawberry cultivation. Among the evaluated organic amendments, fresh chicken manure, so far, provided the best results. This technique is expected to have a cumulative medium to a long-term effect on soil productivity.

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