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Effects of Conservation Agriculture Practices on Tomato Yield and Economic Performance

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Abstract: Conservation agriculture practices, such as reduced tillage and the incorporation of cover crops, play a crucial role in improving the sustainability of organic farming systems. The aim of this two-year field trial was to evaluate five different organic technical itineraries (ST, IN1, IN2, M1, and M2) which differed on soil management practices adopted before processing tomato transplantation and regarding weed control strategies performed. Soil management practices in comparison consisted of conventional deep tillage (ST and M1) or reduced tillage together with the use of a cover crop mixture composed of common vetch and barley (IN1, IN2, and M2). Weed control strategies involved the use of biodegradable mulch together with mechanical weeding (ST and M2), or false seedbed technique and mechanical weeding (IN1, IN2, and M1). Weed biomass at harvest, tomato yield, and the operational and economic performance of each of the technical itineraries was evaluated. No significant differences emerged in terms of weed biomass at harvest between itineraries. Best yield results were obtained tendentially by ST and M2 when biodegradable mulch was used, with values equal to 42.14 and 41.47 Mg ha^{-1} in 2020 and 30.68 and 31.19 Mg ha^{-1} in 2021, respectively. Even though the itineraries where mulch film was used (ST and M2) resulted in significantly onerous processes, they also obtained the highest gross income compared to the other itineraries, with values of 30,998 and 29,900 € ha^{-1} in 2020, and of 16,060 and 15,186 € ha^{-1} in 2021, respectively. These results revealed the importance of using mulching to help cope with critical climatic conditions, such as drought seasons. Further studies are needed to evaluate the yield and economic advantages of both the effect of shallower soil tillage over a longer period in this specific context and the creation of ground cover with cover crops managed as dead mulch.

Keywords: conservation agriculture; reduced tillage; cover crop; false seedbed technique; mechanical weed control; thermal weed control; sustainable agriculture

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1. Introduction

Agricultural ecosystems account for 36% of land areas and provide food for over seven billion people. To satisfy the ever-growing demand for food, it is necessary to increase agricultural production [1,2]. Intensive agricultural practices, characterized by excessive fertilization, irrigation, and tillage, have been commonly adopted to achieve this goal, leading to progressive degradation of soil and water quality. These aspects, together with climate change issues, represent a threat to current and future agricultural production [3]. According to some studies, the intensive farming systems currently adopted could lead to a substantial reduction of agricultural production in future climatic conditions [4]. To counter the ongoing environmental decline, European governments have fostered agri-environmental policies, and the use of organic farming has increased, which is supporting the application of sustainable practices by farmers [5]. However, some aspects of organic agriculture are debated, such as the reliance on conventional intensive tillage to prepare soil before crop planting, to incorporate organic fertilizers, cover crops, crop residues, or to control weeds [6]. It is well known that inversion tillage practices, such as moldboard plowing, can have negative effects. These effects include causing the hardening of deeper soil layers, soil erosion, loss of water and organic matter, an increase of greenhouse gases (GHG) emissions, and biodiversity reduction [7]. In addition, these practices usually require high-powered tractors and high fuel consumption. Conventional tillage technologies usually also involve the performance of several operations in the field which, following the repeated machines soil trampling, contribute to soil compaction [8]. The introduction of conservation tillage practices that lead to environmental benefits by aiming to minimize the intensity and/or frequency of tillage operations would help to improve the sustainability of organic farming systems. Reduced tillage represents a common method of conservation tillage. It allows to limit the damage to soil structure decreasing the susceptibility to soil erosion, improves water infiltration, promotes biodiversity conservation and soil biological activity, thus favoring the maintenance of soil fertility [9,10]. Reduced tillage allows also limits the number of air-filled pores in the soil, keeping soil CO_2 emissions at a low level [11,12]. Hu et al. [12] observed that reduced tillage decreases CO_2 emission over conventional tillage by 5.9% for monoculture maize, 7.1% for monoculture wheat, and 6.7% for intercropping. However, there are discordant opinions on conservation tillage effect on N_2O emissions. Some authors argue that these can be increased compared to conventional tillage [13,14], while according to others these are not altered [15,16]. These practices also create economic benefits by allowing farmers to reduce costs for machinery, fuel, and labor, thereby enhancing economic returns in crop production [9]. Filipovic et al. [17] found that reduced tillage allows a decrease in fuel consumption of 1.5–2 times compared to conventional tillage. Nevertheless, some disadvantages are associated with the application of conservation tillage in organic farming in the long-term, such as increased weed pressure, especially from grasses and perennial weeds [6,18,19]. Cooper et al. [20] found an increase in weed incidence in organic systems with conservation tillage equal to 50% compared to systems in which plowing was performed.

Nowadays, there is a growing interest in the introduction of cover crops in crop rotation, particularly in organic farming systems, as they guarantee numerous agro-ecosystem services and are crucial for fertility management [21,22]. Indeed, cover crops can help to increase soil organic carbon, nutrient availability, soil aggregation, water conservation, microbial activity, weed and pest management, and can reduce the risk of soil compaction and erosion [23]. In organic farming systems, cover crops are often managed as green manure before the cash crop is planted; therefore, they are shredded and incorporated into the soil [21]. The choice of which cover crop species to use for green manure depends on the final objective to be achieved. Leguminous species are chosen for their ability to fix and supply large amounts of N, while non-legume species are mostly used to increase soil organic carbon stock, improve soil structure, reduce nutrient leaching, and prevent soil erosion. The adoption of a mixture of legumes and non-legumes can allow more agronomic and environmental benefits to be obtained [24]. Processing tomato is one of the most important vegetable crops in the Mediterranean area and in Italy, with a dedicated area of 65,180 ha and a national average yield of 84 Mg ha^{-1} in 2022 [25]. This crop is demanding in N, and green manuring is becoming increasingly widely accepted as a beneficial method for sustainable processing tomato production [26,27]. The adoption of a cover crop mixture composed of barley and vetch proved to be an effective and sustainable mixture for processing tomatoes production. This mixture provides a biomass with a good C/N ratio to be incorporated in the soil. It allows a stable N accumulation, guaranteeing a good availability of N for the crop while reducing N leaching compared to the use of only vetch as a cover crop [28,29].

In vegetable cropping systems, mulching technique is frequently used. It brings various benefits, such as earlier crop production, higher yields and product quality, more efficient water use, soil erosion protection, pest control, and weeds suppression [30]. In organic farming systems, synthetic herbicides are not allowed, so mulching turns out to be crucial as means of weed control, along with mechanical means, such as weeders, or thermal methods, such as flaming. Films composed of biodegradable polymers currently represent an alternative to the traditionally used non-biodegradable materials. These films can be buried in the soil at the end of the cropping season and microbially degraded, thus reducing the amount of plastic waste left in the ground [31–33]. In the Mediterranean continental climate, Mater-Bi mulch proved to be a sustainable alternative to polyethylene in organic production [34]. Some authors [30,35] found no differences in terms of processing tomatoes yield when grown using Mater-bi or polyethylene film. Cirujeda et al. [36] observed similar results, both in terms of weed control and tomato yield, in farming systems where Mater-bi and polyethylene mulch were used. Comparing plastic mulch (PE mulch), mater-bi mulch, and brush hoe for their weed control effects, authors [37] observed a greater reduction of weed biomass with PE and Mater-bi mulch than with brush hoeing.

To the best of our knowledge, no studies have been conducted on the production of organic processing tomatoes in the Mediterranean area that compare soil management practices at different levels of intensity and different weed control strategies. The aim of this two-years field trial was to evaluate five different organic technical itineraries which differed regarding the soil management practices adopted before processing tomato transplantation and the weed control strategies performed. Soil management practices, in comparison, consisted of conventional deep tillage, or reduced tillage combined with the use of a cover crop mixture composed of common vetch and barley. Weed control strategies involved the use of biodegradable mulch together with mechanical weeding, or false seedbed technique and mechanical weeding. The itineraries were assessed for their impact on processing tomato yield, as well as the operational and economic performance.

2. Materials and Methods

2.1. Site Characteristics

A two-year field experiment (2020–2021) was performed at the Pasquini farm located at Suvereto, Livorno, Italy (43°02′59″ N 10°40′45″ E, 1 m.a.s.l.). The trial was performed on a field with loam soil (38.2% sand, 44.0% silt, and 17.8% clay). Soil organic matter content corresponded to 2.09%, total N was 1.12‰, available P was 4.6 ppm, and pH was 8.2. Electrical conductivity was 51.9 μS cm^{-1}, and cation exchange capacity was 10.7 meq 100 g^{-1}. The farm was managed in accordance with the criteria of organic farming (Reg. CE 834/2007). The area presented the typical Mediterranean climate with seasonal rainfall peaks in spring and fall. Figure 1 shows the monthly total rainfall (mm) and the mean minimum and maximum air temperatures at the experimental site for both years in which the trial was conducted along with the 10-year mean values.

2.2. Experimental Layout and Managament Systems

Two cycles of the same crop were carried out during the experiment involving processing tomato (*Solanum lycopersicum* L.). Processing tomato was planted in a double-row arrangement. The distances were 1.5 m between double-row centers, 0.4 m between rows, 1.0 m between double-rows, and about 0.4 m between tomato plants along the row. In 2020 and 2021, irrigation water was supplied during the vegetable growing season by means of dripline. Fertilization was executed in an identical manner during both years. Before tomato transplantation, 1.5 Mg ha^{-1} of dried manure pellets (NPK 6-15-0) were distributed. At the time of transplantation, 0.15 Mg ha^{-1} of microgranular organic fertilizer (NPK 13-0-0) and 0.1 Mg ha^{-1} of organic-mineral microgranular fertilizer (NPK 7-5-0) were applied through localized distribution. At each irrigation shift, 20 L ha^{-1} of liquid organic fertilizer (NPK 5-0-0) with fertigation were distributed. Pest control treatments were mainly aimed at containing *Tuta absoluta* (Meyrick), which is strongly present in the area where the trial was set up, and at preventing the onset of fungal diseases. Treatments took place mainly in the period between June and July in both 2020 and 2021. The treatments involved the use of copper oxychloride (2 kg ha^{-1}) for the control of fungal diseases and Bacillus thuringiensis (1 kg ha^{-1}) and Spinosad (1 kg ha^{-1}) for the control of *Tuta absoluta*. Five different technical itineraries, which differed mainly in the soil management practices that were adopted before tomato transplanting and the weed control strategies that were carried out, were evaluated. The itineraries were compared according to a randomized complete block design with three replications. Plot size was 75 m^2 (1 × 75 m).

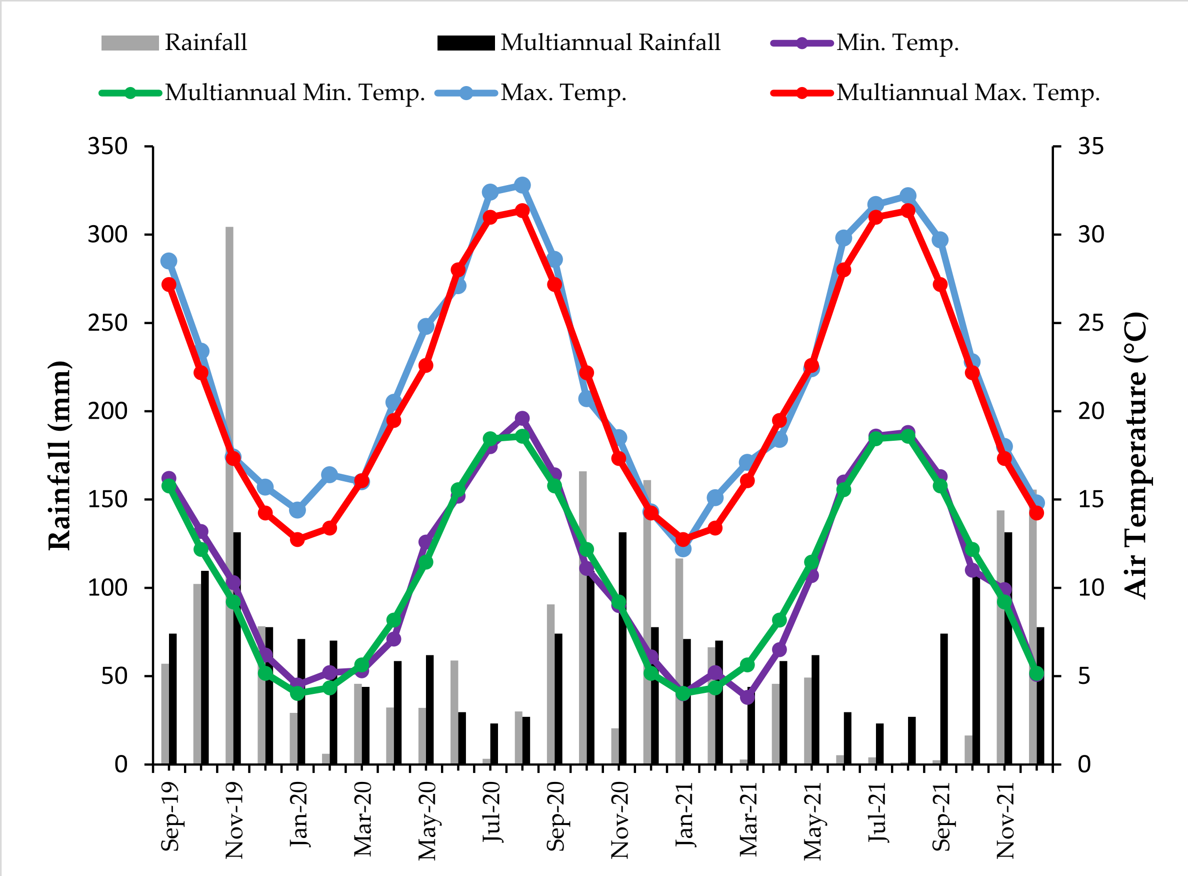

Figure 1. Monthly total rainfall (mm) and mean minimum and maximum air temperatures (°C) at the experimental site for both years in which the experimental trial was conducted along with the 10-year mean values.

Technical Itineraries

Several technical itineraries were tested. There was the standard itinerary adopted by the farmer based on conventional soil tillage before tomato transplanting, the application of biodegradable Mater-bi-based mulch film, and mechanical cultivation between double-rows after transplanting to control weeds (ST). There was an innovative itinerary where a cover crop mixture was sown on soil prepared with reduced tillage, then managed as green manure before transplanting; false seedbed technique was adopted, and mechanical cultivation was performed after transplanting to control weeds (IN1). A second version of the innovative itinerary was used, in which, in addition to the practices described for IN1, after tomato transplanting, weed control was also performed on the rows by means of side-flaming (IN2). For a more accurate evaluation of the strategies used in the standard and innovative itineraries, two "mixed" systems characterized by intermediate strategies between the itineraries ST and IN1 were tested. In the mixed itinerary M1, conventional tillage practices were carried out before transplanting, as in ST. False seedbed technique was adopted, mulch film was not applied, and mechanical cultivation was performed after transplanting to control weeds, as in IN1. This itinerary was tested to evaluate the mulch film effect on weeds and crop yield when conventional tillage is performed before transplanting. In the second mixed itinerary M2, a cover crop mixture managed as green manure was used before transplanting, as in IN1; mulch film was applied, and mechanical cultivation was carried out to control weeds, as in ST. This itinerary allowed for the evaluation of the mulch film effect on weeds and crop yield when reduced tillage practices and green manure cover crops were used. In all the technical itineraries, manual weeding was carried out just before harvesting to facilitate mechanical harvesting of tomatoes.

The conventional tillage carried out before transplanting in ST and M1 consisted of an intervention at a depth of 50 cm with a subsoiler (RTP/T, Nardi, Selci Lama, Italy) equipped with three straight tines that had a working width of 2.5 m. The intervention was performed on 14 February 2020 and 16 February 2021. This operation was followed by the use of a heavy cultivator (CASC7DP, Mipe Viviani, Monteriggioni, Italy) with seven rigid tines arranged in a "v" shape with a working width of 2.5 m at a depth of 30 cm on 21 February 2020 and 22 February 2021. Subsequently, two interventions with a rotary harrow (DRAGO DC., Maschio Gaspardo, Campodarsego, Italy) at a depth of 15 cm were carried out. One intervention was performed to refine the soil on 13 May 2020 and 4 May 2021, the other in proximity of tomato transplanting for surface crust breakage on 19 May 2020 and 14 May 2021. In IN1, IN2, and M2, before cover crop planting, the experimental area was tilled with a 3 m wide combined cultivator (MANDAM, Gliwice, Poland) at a depth of 20 cm. The machine was equipped with nine rigid tines, four couples of inclined discs and a roller for final soil leveling and compacting. This operation was carried out on 14 February 2020 and 16 February 2021. Subsequently, the rotary harrow working at a 15 cm depth was used to establish the seedbed and, at the same time, the sowing of the cover crop was performed with a seed drill (SC MARIA 300, Maschio Gaspardo, Campodarsego, Italy) on 14 February 2020 and 16 February 2021. Cover crop consisted of a mixture of barley (*Hordeum vulgare* L., with a seed rate of 120 kg ha^{-1}) and common vetch (*Vicia sativa* L., with a seed rate of 100 kg ha^{-1}). The high doses of the components of the mixture are motivated by the late sowing periods. Cover crops were then shredded with a flail mower (TORNADO, Maschio Gaspardo, Campodarsego, Italy) and incorporated in the soil using the above-mentioned combined cultivator working at a depth of about 20 cm on 18 May 2020 and 10 May 2021. In all the itineraries tested, the transplantation was carried out with a transplanter (F-MAX/2, Ferrari, Abbiategrasso, Italy) equipped with two transplanting elements, cup rotating distributor, dripline, and film mulch deposition systems on 3 June 2020 and 21 May 2021. In ST and M2, simultaneously with the tomato transplantation, mulch film was also applied. In these itineraries, weed control after transplantation was performed by two interventions with a cultivator developed by the farm owner and equipped with two couples of four spring tines. The operation was executed in the area not covered by the mulch film among double rows on 6 June and 8 July 2020 and 22 June and 8 July 2021. In IN1, IN2, and M1, before transplantation, the false seedbed technique was carried out by performing two interventions with a 2 m wide rolling harrow designed, fully realized, and patented at the University of Pisa [38]. The operation was carried out on 22 and 29 May 2020 and 14 and 18 May 2021. The machine is equipped with spike discs in the front that till the soil at 3–4 cm depth, and cage rolls at the rear of the unit that allow to separate weed seedling roots from the soil. To facilitate the passage of the rolling harrow, previously, an intervention with the rotary harrow was carried out on 19 May 2020 and 14 May 2021, which allows the soil crust to be broken. Subsequently, tomato was transplanted and weed control during the crop growing season was carried out with two interventions with a precision weeder designed and realized at the University of Pisa [38]. The precision weeder was used on 24 June and 8 July 2020 and 22 June and 8 July 2021. This machine was equipped with three weeding units, each of which was equipped with a central goose-foot sweep and two side 'L'-shaped sweeps along with a couple of flexible tines for intra-row selective weed control, with a working width of 3 m. Moreover, in IN2, immediately after the two interventions with the precision weeder, two weed control interventions were carried out on the rows with flaming. The flamer machine (PIRO-TRACK, Maito, Arezzo, Italy) was powered by LPG and consisted of four rod burners each 50 cm wide rotated at 90° with respect to driving direction to perform side-flaming. The operations performed in the five technical itineraries are shown in Table 1.

Table 1. List of operations performed in the five technical itineraries tested during the two-year field experiment.

		ST	IN1	IN2	M1	M2
Soil Tillage	Conventional tillage (subsoiler, heavy cultivator, and rotary harrow).	✓	-	-	✓	-
	Reduced tillage (combined cultivator).	-	✓	✓	-	✓
Cover Crop	Combined harrowing and sowing, shredding and burial with combined cultivator.	-	✓	✓	-	✓
Weed Control	Mulch film application and mechanical weeding.	✓	-	-	-	✓
	False seedbed technique and mechanical weeding after transplanting.	-	✓	✓	✓	-
	Side-flaming.	-	-	✓	-	-

✓ indicates the management strategy implemented in each itinerary regarding Soil Tillage, Cover Crop and Weed Control; ST—standard itinerary; IN1—innovative itinerary 1; IN2—innovative itinerary 2; M1—mixed itinerary 1; M2—mixed itinerary 2.

A 4WD tractor (Case IH, Racine, USA) powered by a 155-kW diesel engine was used for the interventions with subsoiler, heavy cultivator, combined cultivator, rotary harrow, and for the combined intervention of harrowing and cover crop sowing. For cover crop shredding and false seedbed technique, a 4WD tractor (Kubota, Osaka, Japan) powered with a 40.44 kW diesel engine was used. A 2WD FIAT 70/90 tractor (FiatAgri, Torino, Italy) with a 51.47 kW diesel engine was used for mechanical weeding, flame weeding, fertilizing operations, and phytosanitary treatments.

2.3. Data Collection

2.3.1. Agronomic Parameters

Concerning the agronomic aspects considered, cover crops biomass, weed biomass at harvest, and fresh tomato berries weight were surveyed. Sampling of the aboveground biomass of cover crops was carried out in mid-May in both 2020 and 2021 on sample areas of 0.5 m^2 each. Measurements of weed biomass at harvest and tomato berries weight were carried out on a square frame of 0.25 m^2, positioned to contain a tomato plant in the center. In both years, weeds and berries surveys were carried out in the first and second week of September. Only berries that reached commercial maturity were collected. Two measurements for each replicate were carried out for the above-mentioned parameters during both years of the trial. The collected samples of cover crops, weeds, and tomato berries were processed and examined at the laboratory of the Agri-environmental Research "Enrico Avanzi" Centre, San Piero a Grado (Pisa), Italy. Both weeds and cover crops biomass were oven-dried at 60 °C until constant weight was reached, and dry biomass was determined. The collected berry samples were examined, processed, weighed, and classified by degree of ripeness at the above-mentioned laboratory.

2.3.2. Operational Performance

Operational parameters, such as working width, working depth, working speed, theoretical field times, turning times, supply times, and idle times were considered. Theoretical field times correspond to the time the machines effectively operate at an optimum working speed and work over their full width of action. Supply times refer to the time required for fuel and technical means refueling. Idle times represent the time necessary for operators to improve the correct positioning of plants during transplantation. For the calculation of the machines forward speeds during the various operations, the travel times for a straight section of 30 m located inside the experimental area were timed. These parameters were used to evaluate, the field time and fuel consumption per unit area of each operation carried out in each of the five itineraries.

2.3.3. Economic Performance

For the evaluation of the technical itineraries economic performance, gross salable production (GSP), average variable costs over the two years (VC), and gross income (GI) were considered. GSP was obtained by multiplying the yield achieved by each technical itinerary by the market price of organic processing tomatoes, which was considered equal to 1170 EUR Mg^{-1} and 1120 EUR Mg^{-1} in 2020 and 2021, respectively [39]. Concerning the average variable costs (VC), costs of labor, fuel, agricultural operations, and technical means were considered. An hourly rate of 20 EUR h^{-1} was used for labor. For each agricultural operation, the cost of labor was calculated knowing the time required and the number of operators employed. For the fuel costs estimation, an average market price of agricultural diesel equal to 0.88 EUR kg^{-1} was considered. The agricultural operations unit costs were estimated as the sum of the variable costs due to the use of tractors and operating machines coupled to tractors for each operation. Fixed costs (depreciation, interest, and miscellaneous expenses related to the useful life of the machines expressed in hours), variable maintenance and repair costs were taken into consideration. Concerning the technical means, costs relating to mulch film, LPG for flame weeding, cover crop seeds, irrigation, fertilization, and phytosanitary treatments were considered. Gross income was obtained from the difference between GSP and total VC.

2.4. Statistical Analysis

Two-way ANOVA test was performed to evaluate the effect of cover crop species, year and interaction among factors on cover crop dry biomass. Two-way ANOVA test was performed also to assess the effect of the technical itinerary, year, and interactions among factors on weed biomass at harvest, and fresh tomato berries weight. ANOVA was performed using SPSS software (IBM SPSS Statistics for Mac, Version 25.0. Armonk, NY, USA: IBM Corp.). Normality distribution was evaluated using the Kolmogorov–Smirnov test, while the Breusch–Pagan test was employed for homoskedasticity. After the ANOVA test, the Bonferroni post hoc test at the 0.05 probability level was performed when necessary.

3. Results

3.1. Dry Biomass of Cover Crops and Weeds

ANOVA revealed that cover crops biomass was affected by species ($p < 0.05$), year ($p < 0.05$), and interaction between these factors ($p < 0.01$). Overall, barley produced more biomass than vetch (4.34 vs. 2.61 Mg ha^{-1}), and, in terms of average biomass produced by the two species per year, better results were obtained in 2021 rather than in 2020 (4.08 vs. 2.87 Mg ha^{-1}). In 2020, vetch produced less biomass than in 2021 and also less than barley in both 2020 and 2021 (0.83 vs. 4.39, 4.92, and 3.76, respectively), while no significant differences emerged between the biomass produced by vetch in 2021 and that of barley in 2020 and 2021 (Figure 2).

Regarding weed dry biomass at harvest, ANOVA revealed that neither the management strategies, nor the year, nor the interaction among factors affected the parameter ($p = 0.665$, $p = 0.453$, $p = 0.277$, respectively).

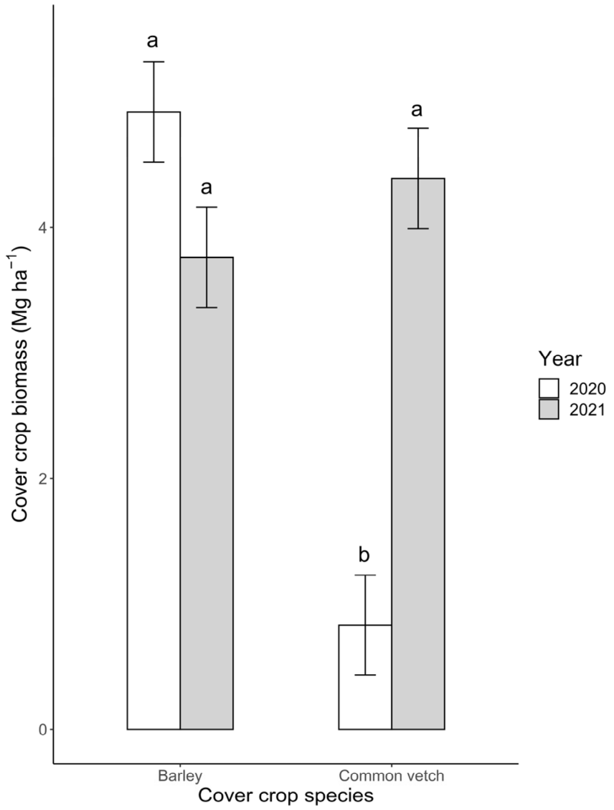

Figure 2. Effect of the interaction among cover crop species and year on cover crop biomass produced. Mean denoted by different letters are significantly different at $p < 0.05$ (Bonferroni test). Error bars indicates upper and lower 95% confidence intervals.

3.2. Fresh Tomato Berries Weight

ANOVA showed that both the technical itinerary ($p < 0.001$) and the interaction among factors ($p < 0.01$) affected the biomass of fresh tomato berries, while the year ($p = 0.470$) did not affect the parameter. In 2020, technical itineraries that produced the highest harvest results were ST and M2, with values equal to 42.14 and 41.47 Mg ha^{-1}, respectively, without showing differences between them. The itineraries in which mulch film was not applied achieved lower results compared to ST and M2, and they were similar to each other. Among these itineraries, the one that obtained the lowest yield in absolute value was IN2, where flame weeding was carried out (13.81 Mg ha^{-1}), followed by IN1 (15.25 Mg ha^{-1}) and M1 (25.12 Mg ha^{-1}). In 2021, the itineraries that produced the highest harvest result in absolute value were still ST and M2 with values slightly above 30 Mg ha^{-1}. However, results obtained with these itineraries were not statistically different from those obtained with IN2, M1, and IN1, which were equal to 24.82, 26.14, and 15.89 Mg ha^{-1}, respectively. It is possible to observe that the IN1 result in absolute values is relevantly lower than those achieved with the other four itineraries (Figure 3).

In 2021, fresh berries weight achieved by ST on average were lower than in 2020. On the other hand, the itineraries in which Mater-bi film was not used (IN1, IN2, and M1) achieved higher results in absolute value compared to 2020. Overall, ST recorded a higher fresh berry weight compared to M1, IN2, and IN1 (36.41 Mg ha^{-1} vs. 25.63, 19.31, and 15.57 Mg ha^{-1}, respectively) and similar to M2. M2 obtained a greater fresh berry weight (35.83 Mg ha^{-1}) than IN1 and a similar weight to IN2 and M1. No differences emerged between M1 and IN2 for this parameter, while IN1 obtained a lower fresh berry weight compared to ST, M1, and M2 (Figure 4).

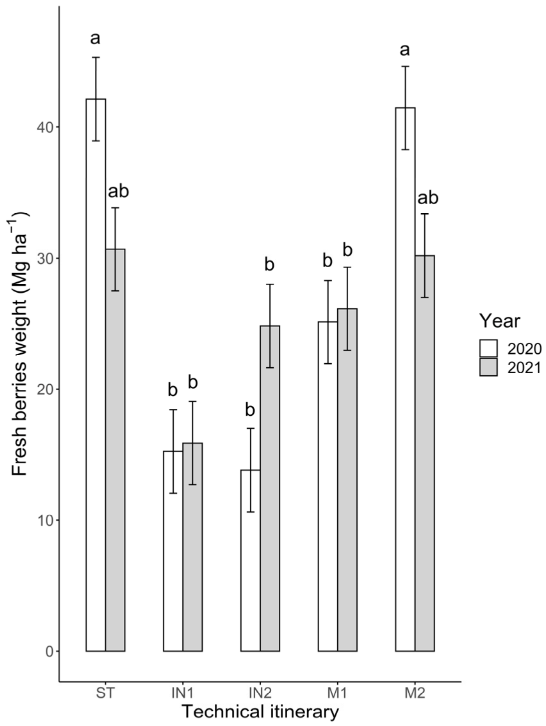

Figure 3. Effect of the interaction among technical itinerary and year on fresh berries weight. Mean denoted by different letters are significantly different at $p < 0.05$ (Bonferroni test). Error bars indicates upper and lower 95% confidence intervals. ST—standard itinerary; IN1—innovative itinerary 1; IN2—innovative itinerary 2; M1—mixed itinerary 1; M2—mixed itinerary 2.

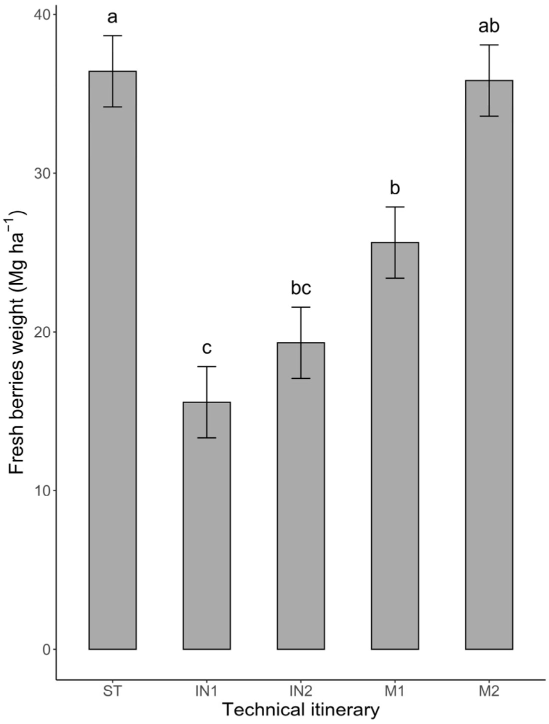

Figure 4. Effect of technical itinerary on fresh berry weight. Mean denoted by different letters are significantly different at $p < 0.05$ (Bonferroni test). Error bars indicates upper and lower 95% confidence intervals. ST—standard itinerary; IN1—innovative itinerary 1; IN2—innovative itinerary 2; M1—mixed itinerary 1; M2—mixed itinerary 2.

3.3. Operative Performances of the Technical Itineraries

ST and M2 resulted in the most onerous technical itineraries in terms of average field time with values of 318.7 and 319.3 h ha^{-1}, respective, which is approximately 65% higher compared to IN1, IN2, and M1. Average field times of IN1, IN2, and M1 were similar in both years, with values of 190, 197.5, and 191.9 h ha^{-1}, respectively (Figure 5).

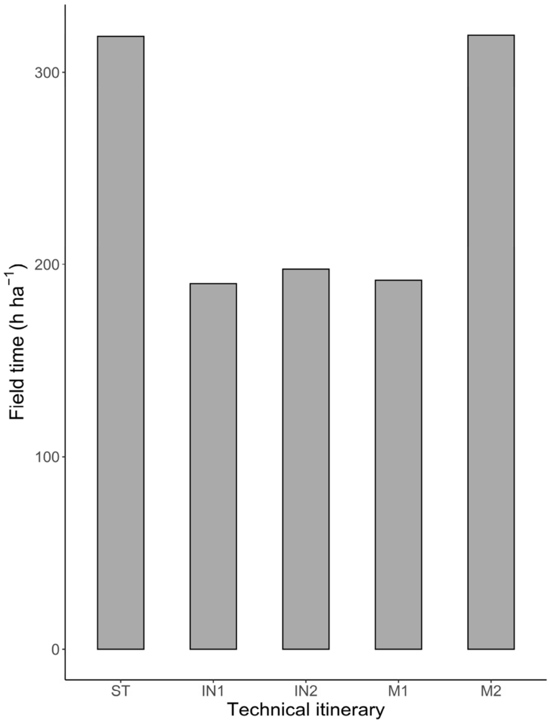

Figure 5. Average total field time of each technical itinerary in 2020 and 2021. ST—standard itinerary; IN1—innovative itinerary 1; IN2—innovative itinerary 2; M1—mixed itinerary 1; M2—mixed itinerary 2.

When mulch film was applied, eight operators were needed for transplanting, five of which took steps to remedy the non-optimal placement of the seedlings and to check adequate film spreading. When transplanting was performed on bare soil, instead, four operators were sufficient and the time to check and optimize seedlings placement were also reduced. Field time required to perform transplanting when mulch film was applied was equal to 200 h ha^{-1}, while on bare soil it was equal to 40 h ha^{-1}, and was therefore five times lower. Thus, transplanting on bare soil leads to a manpower management efficiency that is 2.5 times greater than transplanting on mulch film.

ST and M2 presented also the highest average fuel consumption, with values equal to 323.1 and 300.4 kg ha^{-1}, respectively, with no relevant differences among them. IN1, IN2, and M1 showed similar results that ranged from 225.0 to 258.6 kg ha^{-1} (Figure 6).

Transplanting on film mulch also involved a higher fuel consumption compared to transplanting on bare soil (136.5 vs. 54.6 Kg ha^{-1}) with an increase of 150%. The soil management strategies adopted before transplanting relevantly influenced the technical itineraries fuel consumption. This is evident from the differences in consumption in the comparison of ST and M2, and between IN1 and M1, whose itineraries varies only in terms of soil management practices applied before transplanting. Reducing the depth of tillage offers the advantage of decreasing fuel consumption by approximately 10%. The use of flame weeding led to a slightly higher fuel consumption rather than that of field times compared to IN1 in which weed control was carried out only with mechanical weeding.

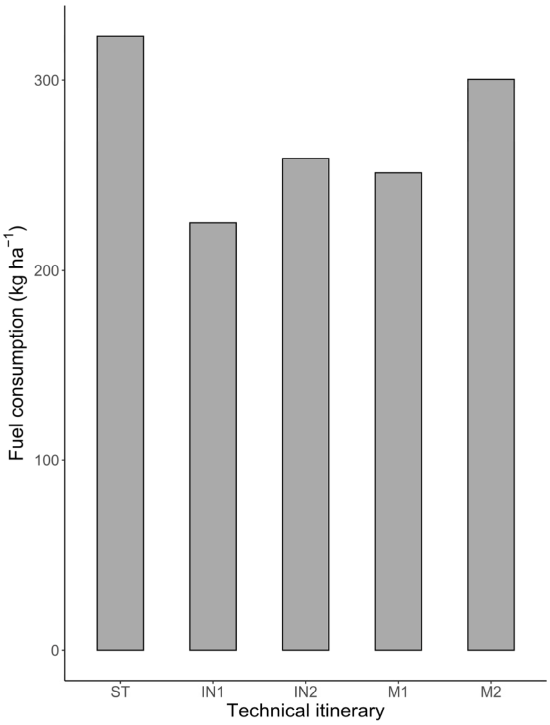

Figure 6. Average total fuel consumption of each technical itinerary in 2020 and 2021. ST—standard itinerary; IN1—innovative itinerary 1; IN2—innovative itinerary 2; M1—mixed itinerary 1; M2—mixed itinerary 2.

3.4. Economic Performances of the Technical Itineraries

The economic performance values of each technical itinerary in terms of gross salable production (GSP), average variable costs (VC), and gross income (GI), are shown in Table 2.

Table 2. Economic performances of the technical itineraries in comparison expressed as gross salable production (GSP), average variable costs (VC), and gross income (IG).

			ST		IN1		IN2		M1		M2	
		Unit	**2020**	**2021**	**2020**	**2021**	**2020**	**2021**	**2020**	**2021**	**2020**	**2021**
GSP		€ ha^{-1}	49,301	34,364	17,837	17,798	16,153	27,801	29,386	29,276	48,522	33,808
VC	Labor	€ ha^{-1}	6373		3838		3961		3837		6396	
	Fuel	€ ha^{-1}	284		198		227		221		264	
	Machinery	€ ha^{-1}	4585		4639		4905		4710		4580	
	Technical means	€ ha^{-1}	7060		6780		6804		6460		7380	
	Total VC	€ ha^{-1}	18,303		15,456		15,898		15,230		18,622	
GI		€ ha^{-1}	30,998	16,060	2381	2342	254	11,903	14,156	14,046	29,900	15,186

GSP—gross salable production; VC—average variable costs; GI—gross income; ST—standard itinerary; IN1—innovative itinerary 1; IN2—innovative itinerary 2; M1—mixed itinerary 1; M2—mixed itinerary 2.

In 2020, the itineraries that achieved the highest GSP were ST and M2. The itineraries where mulch film was not employed recorded a lower GSP compared to ST and M2, with a reduction of approximately 57%. In 2021, ST and M2 are still the technical itineraries that obtained the highest GSP results. However, in 2021, IN2 and M1 results were not consistently lower than those obtained by ST and M2, with a reduction of approximately 16% on average. GSP achieved by IN1 in 2021 was relevantly lower compared to the other itineraries, as was observed tendentially in 2020.

In terms of total average VC, the most expensive systems were ST and M2 with values of 18,303 and 18,622 EUR ha^{-1} total. Instead, the other systems were similar to each other. Fuel cost was higher in ST in both years. The machinery costs resulted in a slightly higher overall value for IN2 compared to the other itineraries. Soil management technique did not affect machinery costs. Concerning the technical means costs, M2 reported a higher costs compared to the other itineraries, followed by ST, while M1 recorded the lowest costs. The purchase of technical means had the most relevant impact on the total variable cost of itineraries. In contrast, fuel costs had a lower influence on the total variable costs when compared to labor, technical means, and machinery costs. The itineraries connected with higher GI values appeared to be ST and M2 in both years, without showing relevant differences. Finally, it is possible to observe that, compared to the first year of the trial, a reduction in GI of around 50% on average was recorded in the second year for both ST and M2. Instead, values of IN1 and M1 were similar, and that of IN2 resulted in relevantly higher values, with an increase of 45.8%.

4. Discussion

4.1. Cover Crops Biomass Production and Weed Control

The biomass produced by common vetch in 2020 was lower than in 2021 (0.83 vs. 4.39 Mg ha^{-1}) and, compared to barley, lower in both 2020 and 2021 (4.92 and 3.76 Mg ha^{-1}, respectively). Therefore, in 2020, the mixture was mostly composed of barley, and this could be explained by reduced rainfall registered in January and February 2020 compared to 2021, and the resulting lower water availability at that time.

The different weed control strategies tested appeared to have similar effects on spontaneous flora. Considering that weed biomass at harvest was just over 0.4 Mg ha^{-1} on average in both experimental years, it is possible to affirm the high efficiency of all weed control strategies adopted. Results achieved are consistent with those obtained by Raffaelli et al. [38]. Authors compared a conventional weed control system which relied on the use of chemical and mechanical methods with an alternative system based on the use of false seedbed technique and precision weeder. Both management approaches were considered effective, resulting in an average weed biomass at tomato harvest of 0.68 and 0.36 Mg ha^{-1}, respectively. Therefore, mechanical weed control strategies provided good results despite the challenging conditions during weeding. For example, the presence of surface crust, which mainly concerned the first tomato growing season, prevented the weeder's flexible tines from properly controlling weeds in the intra-row space. This was observed also by Cirujeda et al. [37], which stated that the presence of heavy soil or soil crust does not allow for the optimal functioning of tools such as torsion weeders. Overall, the results obtained can also be considered positive in consideration of the limited effectiveness of the false seedbed technique due to surface crust. In the itineraries with film mulch (ST and M2), weeds presence at harvest was attributable to the ability of some plants to pierce the film. Additionally, weeds took advantage of the ecological niches left free by the hole made in the film during transplanting. This has also been observed by other authors [30,40] according to whom biodegradable films can be perforated by some weed species, probably due to their degradation and gradual loss of mechanical consistency over time.

4.2. Processing Tomato Yield

In 2020, ST and M2 obtained the highest fresh berries weight results (42.14 and 41.47 Mg ha^{-1}, respectively), without showing differences between them. Such results are of the same order of magnitude as those obtained by Ronga et al. [41] for processing tomato in an organic farming system. The itineraries without mulch film (IN1, IN2, and M1) achieved lower yields compared to ST and M2. The IN2 itinerary, where flame weeding was implemented, recorded the lowest yield in absolute value (13.81 Mg ha^{-1}). This demonstrates that, in 2020, mechanical weeding was probably more decisive than the intervention of flame weeding. In 2021, ST and M2 were still the itineraries that obtained the highest yield in absolute value, with values slightly above 30 Mg ha^{-1}, partially confirming results obtained in the first year of the trial. However, in this case, yields obtained by IN2, M1, and IN1 (with values of 24.82, 26.14, and 15.89 Mg ha^{-1}, respectively) were not statistically different compared to ST and M2. The higher result obtained by IN2 in absolute value in 2021 compared to IN1 was probably due to the timelier weeding interventions on the row with flaming, although the weed biomass at harvest was not statistically different. On average, in 2021, yield obtained by ST were lower than in 2020 due to the adverse climatic conditions characterized by drought and high temperatures in July and August. Instead, in the itineraries where the Mater-bi film was not employed (IN1, IN2, and M1) the climatic conditions in 2021 probably had fewer adverse impacts. This is evident from the higher results in absolute value obtained compared to 2020. This yield increase is probably due to the lack of surface crust formation and the higher N input available for the crop associated to the higher biomass production by common vetch in 2021. The absence of soil crust could have allowed a higher efficiency of mechanical weeding interventions in 2021, contributing to obtain better yield performances on bare soil (IN1, IN2, and M1). Indeed, mechanical weeding, in addition to controlling weeds and aerating the soil, favors the breaking of soil capillaries, thus preventing water evaporation from the soil [42]. It must also be considered that the adoption of conservative management practices, such as reduced tillage and cover crops, does not always lead to obtaining appreciable benefits in the short term [43]. Several authors observed that the conversion from conventional to conservation tillage practices can lead in the first 4–5 years to some disadvantages in terms of soil properties. These disadvantages include an increase in bulk density and a decrease in soil porosity. However, these can be followed by progressive improvements in terms of soil structure, organic carbon stabilization, availability of nutrients, and, therefore, crop yield [44–46]. In general, ST achieved a higher yield (36.41 Mg ha^{-1}) compared to M1, IN2, and IN1 (25.63, 19.31, and 15.57 Mg ha^{-1}, respectively) and similar to M2 (35.83 Mg ha^{-1}). Therefore, the use of mulch film appeared to be crucial in terms of tomato yield. This is in agreement with Testani et al. [47]. Authors observed a higher tomato yield for the system where Mater-bi film was used than in the system where a cover crop mixture of barley and vetch were managed as green manure. Moreover, it is possible to observe the absence of relevant differences between itineraries based on conservation agriculture practices such as reduced tillage and those with conventional deep tillage. This is especially evident when mulch film was present (ST and M2). This trend showed the importance of ground cover on tomato yield. Ground cover also performed various useful functions, such as the promotion of soil moisture conservation, making it possible to cope with critical climatic conditions, such as drought seasons [30]. This is an important result in favor of adopting conservation agriculture practices. It also supports the progressive abandonment of deep tillage practices which are costly, boost organic matter mineralization, and are related to high GHG emission compared to reduced tillage [7,8].

4.3. Total Field Time and Fuel Consumption of the Technical Itineraries

The higher values recorded by ST and M2 in terms of average total field time (318.7 and 319.3 h ha^{-1}, respectively) and fuel consumption (323.1 and 300.4 kg ha^{-1}, respectively) are mainly related to transplanting operations on mulch film. Transplanting on mulch film requires a longer field time than transplanting on bare soil (200 h ha^{-1} vs. 40 h ha^{-1}). In the first case, eight operators are needed, while in the case of transplanting on bare soil, four operators are sufficient. This results in a manpower management efficiency when transplantation was carried out on bare soil 2.5 times higher compared to the transplantation on mulch film. This is in line with Feldman et al. [48], according to which the use of film mulch can lead to a higher labor requirement for both mulch spreading and planting. Transplanting on film mulch also required a higher fuel consumption compared to transplanting on bare soil, with an increase of 150%. Therefore, these differences in transplantation technique had relevant consequences on these operational parameters. Soil management strategies adopted before transplanting relevantly impacted the technical itineraries' fuel consumption. This is also confirmed by Moitzi et al. [49]. These authors, testing a moldboard plough, a short disc harrow, a universal cultivator, and a subsoiler at different working depths, noticed a rise in fuel consumption as the working depth increased. Authors stated that, as the working depth increased, both drawbar pull and slip increased, and, therefore, fuel consumption rate also increased. This is also in agreement with Pratibha et al. [50], who observed a higher energy input for conventional tillage compared to conservative practices, such as reduced or zero tillage. This result was attributed to a greater depth and number of tillage operations, which resulted in higher machine usage and higher fuel consumption. Thus, a reduction in tillage depth, in addition to the advantages described above, also creates benefits by allowing a reduction in fuel consumption, albeit limited and corresponding to about 10% in the present study.

4.4. Gross Salable Production, Average Variable Costs, and Gross Income

In both 2020 and 2021, ST and M2 were the itineraries that produced the highest results in terms of GSP. This result is in line with the yield trend. Other systems characterized by the lack of mulch film achieved lower GSP compared to ST and M2. The lower GSP of IN1 in 2020 and 2021 and of IN2 in 2020 compared to the other itineraries is mainly related to a lower yield achieved.

The total average VC resulted higher in ST and M2, with values of 18,303 and 18,622 EUR ha^{-1}, while the other itineraries achieved similar results. This is mainly due to the use of mulch film, which was remarkably expensive. Indeed, although Mater-bi film is a more environmentally friendly alternative to polyethylene mulch and allows disposal cost savings through soil incorporation with tillage, its main constrain is its higher cost [51]. Moreover, transplanting on film mulch not only incurred significant expenses in terms of technical means, but also had an impact on fuel consumption and labor costs. In both years, fuel costs were higher in the ST itinerary, highlighting how conventional deep tillage had a greater impact on fuel consumption compared to conservation agriculture practices, such as reduced tillage. In terms of technical means costs, M2 recorded a higher cost compared to the other itineraries due to the use of both cover crops and mulch film. M1 achieved the lowest costs, as in this case, no technical means were used beyond those used in all the other systems. Technical means purchase represented the cost item with the greatest impact on the total variable cost of itineraries. Instead, fuel cost showed a lower incidence to the total variable costs compared to labor, technical means, and machinery costs.

By comparing GI values referring to the results obtained in the first and second year of the trial with those of the GSP and tomato yields, respectively, it is possible to observe a similar trend. This underlines that GI was mainly influenced by yield and GSP, and not by the costs incurred. ST and M2 achieved a higher GI value during both years, without showing relevant differences. This highlights how crucial it is in critical pedo-climatic conditions, such as those in the trial, to maintain soil cover with mulch and thereby positively affect plant microclimate, favor adequate weed control, and conserve soil moisture [30].

5. Conclusions

The present study highlights that, in the particular pedo-climatic conditions in which the study was conducted, there were several limitations in achieving optimal yield performance for organic processing tomato. The best yield results were obtained tendentially by the technical itineraries where permanent coverage with Mater-bi film was used (ST and M2). Therefore, even though this technique resulted in significantly onerous processes in terms of labor, fuel consumption and technical means, it can lead to productive and economic benefits, especially in such critical environmental conditions. Concerning soil management, working depth did not significantly affect tomato performance, either in terms of yield or gross income. Indeed, with the same weed management system, no differences emerged tendentially in tomato performance among itineraries where conventional deep tillage and conservative shallower tillage practices were carried out. This is a significant outcome for the gradual abandonment of deep tillage techniques in favor of conservative agriculture practices, such as reduced tillage. The use of the cover crop mixture composed of barley and common vetch managed as a green manure seemed to be a beneficial method for processing tomato production, as the crop is N demanding. These effects emerged particularly in the second year of the test, in which the higher biomass production by vetch compared to the previous year positively influenced the tomato yield performance in the organic farming systems. By applying conservation agriculture practices, such as reduced tillage and the use of cover crops, improvement of organic farming systems sustainability could be favored. Indeed, these practices can lead to several environmental benefits, such as CO_2 emissions reduction and increase in soil fertility. Further studies are needed to evaluate the effect of shallower soil tillage practices over a longer period in these specific pedo-climatic conditions. Moreover, in this context, it would be useful to evaluate the creation of soil cover with cover crops managed as dead mulch, both in terms of yield and economic advantages.

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