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Quality of Tomato (*Solanum lycopersicum* L.) Changes under Different Cover Crops, Soil Tillage and Nitrogen Fertilization Management

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Abstract: The purpose of this study was to evaluate the interaction effects of winter cover crops (hairy vetch, subclover and black oat) and a bare soil, cover crop biomass management (incorporated into the soil or left on the soil surface as death mulch), and nitrogen (N) fertilization level (0, 75 and 150 kg ha^{-1} of N) on fruit yield and fruit quality parameters of processing tomato. Hairy vetch residues increased the yield (+57%), color index (+8%) and sugar/acidity ratio (+7%) of marketable tomato fruits compared to bare soil regardless of cover crop biomass management. Black oat residues determined a poor marketable yield, especially in tilled soil (on average, −26%, compared to bare soil) and they had a tendentially negative effect on some parameters of tomato quality (high firmness and titratable acidity, low color index and pH). Subclover residues, when incorporated into the soil, determined similar marketable fruit yield to bare soil, although they had a more favorable effect on the color parameters of tomato fruits. The increasing of the N fertilization level from 0 kg ha^{-1} of N to 150 kg ha^{-1} of N always positively influenced the tomato yield and fruit characteristics. The results suggest that hairy vetch, compared to other cover crops, had a positive influence on tomatoes and it could be part of an environmentally friendly management package for sustainable tomato cultivation in Mediterranean conditions.

Keywords: sustainable agriculture; tomato fruit characteristics; tomato quality attributes; marketable tomato yield; cover crops

Citation: Massantini, R.; Radicetti, E.; Frangipane, M.T.; Campiglia, E. Quality of Tomato (*Solanum lycopersicum* L.) Changes under Different Cover Crops, Soil Tillage and Nitrogen Fertilization Management. *Agriculture* **2021**, *11*, 106. https://doi.org/10.3390/agriculture11020106

Academic Editor: Bettina Eichler-Löbermann
Received: 2 January 2021
Accepted: 25 January 2021
Published: 28 January 2021

1. Introduction

Tomato is a major component of the Mediterranean diet and it is recognized as one of the most important vegetables for human nutrition due to its content of bioactive compounds, in particular minerals, vitamins, organic acids, and antioxidants [1]. Italy is one of the major producers and suppliers of processing tomato (*Lycopersicon esculentum* Mill.), while it is the leading country in the European Union area [2]. In Italy, processing tomato production is conventionally based on deep tillage and the use of agrochemicals such as synthetic fertilizers, pesticides and herbicides. However, in the long term period, this kind of intensification management of agro-ecosystems has led to a series of environmental issues, such as the decrease in soil organic matter, an increase in the incidence of soil-borne diseases and nutrient run-off, which determine to the decline of crop yields and their sustainability [3]. As a consequence, there is a worldwide growing interest in alternative practices for achieving sustainable vegetable production systems, which emphasize the production of food crops and reduce of off-farm input, especially agrochemicals [4]. Nowadays, a sustainable approach to farming practices can refer to conservation of agriculture principles such as minimum soil disturbance and permanent soil cover with cover crops and mulches. The adoption of cover crops within the cropping systems can provide several benefits, i.e., reducing the need for fertilizers by recycling nutrients and fixing the atmospheric N in case of legume cover crops, reducing the incidence of soil-borne disease by providing habitat for beneficial insects, decreasing herbicide use by reducing weed pressure and increasing crop yield by improving soil health [5,6]. While it has been largely recognized that conservation tillage increases soil organic matter, soil structure and stability, which in turn reduce soil erosion, improve water holding capacity and microbial and earthworm activity [7–9]. In the Mediterranean environment, cover crops are usually sown in autumn after harvesting a main crop, to keep the soil covered with vegetation during the winter, and killed before sowing the following summer's vegetable crops [10]. Cover crop suppression can be realized by tilling the soil and incorporating their biomass into the soil as green manure, or alternatively by devitalizing the cover crops by herbicide or mechanical means and leaving their aboveground biomass on the soil surface as organic dead mulches [11,12]. It has been shown that different management practices of cover crop suppression have different effects on soil characteristics such as nitrogen (N) availability [13,14]; therefore, it is likely that they can also affect the quality parameters of the following main crop. Few researchers have focused on the effect of different management of cover crop residues on the quality of vegetable crops, with particular regard to the qualitative traits of tomato yield. Regarding the processing tomato quality in response to agronomical conventional management practices, there are many studies, but the effects of conservation practices, such as the use of cover crops in combination with reduced soil tillage, should be identified in order to establish a feasible management package for sustainable tomato cultivation. This study hypothesized that the adoption of different winter cover crop species, soil tillage management and N fertilization level could differently affect the tomato fruit characteristics under Mediterranean conditions. Therefore, the main objectives were (i) to evaluate the interaction effects of winter cover crops, soil tillage management and N fertilization level on fruit yield and fruit quality traits of processing tomatoes, (ii) to identify an environmentally friendly management practice to produce tomato under Mediterranean conditions.

2. Materials and Methods

2.1. Experimental Site and Design

Two cover crop-tomato sequences were carried out on the 2014 and 2015 growing seasons at the experimental farm "Nello Lupori" of the University of Tuscia (42°24′ Latitude, 12°03′ Longitude and 310 m a.s.l.), Viterbo, Italy. Field trials were performed in two adjacent fields, one for each year, previously cropped with durum wheat (*Triticum durum* Desf.). The experimental area is located in Central Italy and it has an attenuate thermo-Mediterranean climate (UNESCO-FAO classification) characterized by mean annual precipitation of 800 mm (average of the last 30-year period), mainly concentrated from September to May, and an average of 5 mm day^{-1} of potential evapotranspiration from July to August. Annual air mean temperature is 14.0 °C, the minimum temperature dropped few times below 0 °C, mainly in January and February, while the maximum air temperature above 35 °C, mainly in July and August. The soil type is classified as *Typic Xerofluvent* with the following characteristics in the 0–30 cm depth: 104 g kg^{-1} of dry soil clay, 133 g kg^{-1} of dry soil silt, 763 g kg^{-1} of dry soil sand; pH 6.9 (water, 1:2.5); organic matter 13.2 g kg^{-1} of dry soil (Lotti methods); and total N 0.98 g kg^{-1} of dry soil (Kjeldahl method).

Each year, a split-split-plot experimental design with four replications in randomized blocks was used, the experimental factors were: (a) three cover crop species [hairy vetch (*Vicia villosa* Roth., var. Capello), subclover (*Trifolium subterraneum* L., var. Campeda) and black oat (*Avena strigosa* L., var. Donata)] and a no covered soil (hereafter called bare soil); (b) two different soil tillage adopted for managing cover crop residues [green manure where cover crop residues were chopped and incorporated into the soil in a layer 0–30 cm deep to simulate conventional tillage (hereafter called T) and no-tilled soil where cover crop residues were mowed and left in strips on the soil surface as organic dead mulch in order to simulate no-tillage (hereafter called NT)]; (c) three levels of N fertilization applied on tomato crop [0, 75 and 150 kg of N ha^{-1} (hereafter called N_0, N_{75} and N_{150}, respectively)]. The experimental main plot size was 132 m^2 (12 × 11 m), the sub-plot size 66 m^2 (12 × 5.5 m) and the sub-sub-plot size was 22 m^2 (4 × 5.5 m).

2.2. Field Experiment Description

In September of each year (2013 and 2014), the soil was plowed to a depth of 30 cm and fertilized with 100 kg of P_2O_5 ha^{-1} as triple superphosphate, then the soil was disked twice (about 15 cm depth) for the seedbed preparation. The seeds of all cover crop species were broadcasted manually and superficially buried by harrowing on 18 September 2013 and 16 September 2014. In both years, the same seeding rate was adopted for cover crop species (60, 35 and 100 kg ha^{-1} for hairy vetch, subclover, and oat, respectively). Bare soil plots were managed similarly to the cover crop plots and were kept free throughout the growing season of cover crops by chemical means (glyphosate) applied twice during the winter season when weed species started to emerge. In May, all cover crops were mechanically killed at the same time on 7 May 2014 and 4 May 2015 and their aboveground biomass was managed in order to prepare tomato transplanting bed as follows: (a) finely chopped by straw chopper and incorporated into the soil using mold-board plough to at depth of 30 cm and disk harrowed twice (T); (b) mowed at 5 cm to soil surface and placed in strips as organic mulch by means of hay-conditioner farm machine (NT). The mulch strips were approximately 80 cm wide and 180 cm center mulch strip to center mulch strip [11]. In the bare soil plots, the tomato transplanting bed were prepared as follows: (a) the soil was ploughed and disk harrowed twice (T); (b) the soil was left no-tilled (NT). About one week after cover crop killing on 15 May 2014 and 12 May 2015, respectively, one-month old tomato seedlings (*Solanum lycopersicum* L., var. San Marzano Kero) of 15 cm height were transplanted manually in paired rows at a distance of 40 cm from one another and a distance of 140 cm between the paired rows at the density of 3 plants m^{-2}. In NT, the tomato seedlings were transplanted into the mulch strips with the minimal disturbance, and the cover crop residues surrounded each tomato plant. Drip irrigation tape was applied over the mulch layer and the soil surface on each tomato row. The amount of irrigation water was estimated by class A pan evaporimeter and converted by crop coefficient to determine the water input [15]. The N fertilizer (0, 75, and 150 kg N ha^{-1}) was administered through ferti-irrigation as urea twice, half the amount 30 days and half 60 days after tomato transplanting. In all plots, weed management was carried out according to the practices adopted in the study area by twice application of herbicide (active principle Metribuzin). Tomato fruits were collected manually for processing in the same state of ripeness (80% of ripened fruit) [16,17]. The tomato harvest was made at one time separately for each treatment as follows: on 23 August 2014 and 10 August 2015 in hairy vetch, on 25 August 2014 and 11 August 2015 in subclover, on 28 August 214 and 14 August 2015 in bare soil, on 30 August 214 and 15 August 2015 in black oat."

2.3. Field Measurements

The air temperature and rainfall of the study period were collected from an automated meteorological station located 200 m from the experimental site. In Table 1 are reported the weather data over the 2-year study period (2014 and 2015). In both years, 10 tomato plants, from the middle paired rows of each plot, were destructively harvested by removing the tomato fruits and cutting the tomato plant at the soil level. Tomato fruits were collected based on: marketable tomato yield (number and weight) considering red and disease free fruits, and un-marketable tomato fruits divided into green fruits (number) and rotten fruits (number).

Table 1. Weather data (monthly average of the daily minimum and maximum temperatures, and monthly total amount of rainfall) over the 2-year study period (2014 and 2015).

Months	Air Temperatures				Rainfall (mm)	
	Minimum (°C)		Maximum (°C)			
	2014	2015	2014	2015	2014	2015
March	4.5	4.9	15.7	14.6	77	71
April	7.1	6.1	19.2	19.0	85	19
May	9.2	10.5	21.8	24.5	14	1
June	14.3	15.0	27.7	28.9	140	22
July	15.7	18.9	27.8	32.8	77	23
August	16.0	18.5	29.0	32.0	51	14
September	14.6	14.8	25.6	26.2	59	52

2.4. Physical and Chemical Analyses of Marketable Tomato Fruits

After field harvesting, a total of 30 marketable tomato fruit samples (3 fruits per tomato plants) per experimental treatment were taken to the laboratory of Food Science and Technology of the University of Tuscia for analytical measurements. The remaining part of the tomato fruits were oven dried at 70 °C until constant weight in order to determine dry matter (total solid). The 30 tomato fruit samples were carefully washed in order to remove dirt and dried with adsorbent paper then they were used for measuring the diameters, both longitudinal and equatorial adopted as fruit size indicators [18], by means of caliber.

Flesh color measurements were carried out with a colorimeter mod. CM-2600d (Konica Minolta Sensing Inc., Osaka, Japan) on three randomly selected areas of each selected tomato fruit (D65 illuminant). The surface color quality of the tomato fruits was described on the basis of L*, a* and b* parameters (CIELAB color space system). L* represents the lightness ranging from 0 (black) to 100 (white), while a* and b* parameters represent X-Y coordinates indicating color direction [a* ranges from −100 (green) to +100 (red), and b* ranges from −100 (blue) and +100 (yellow)]. From the color parameters, the results were also expressed by mean of color indexes calculated as follows (Camelo and Gómez, 2004): a*/b*; and Color Index (CI = 2000 (a*)/(L* × C)).

For all chemical parameters analyzed, three measurements were taken per each replication and then the averages of the readings were considered. The pH was measured following the official method "pH Measurement of Water" (AOAC 973.41) with a pH-meter mod. FE20 (Mettler Toledo, Milan, Italy). The soluble solids content (SSC), expressed in °Brix, was measured in the fruit juice using a digital refractometer mod. WM-7 (Atago Co. Ltd., Tokyo, Japan). The tritable acidity (TA) was determined by titrating against standard NaOH solution 0.1 mol L^{-1} until pH 8.1, using phenolphthalein as an indicator and expressed as percentages of malic acid (AOAC 942.15). Sugar/Acid ratio (SAR) of the tomato fruits was calculated as the ratio of SSC to TA. Firmness was measured with a digital penetrometer mod. 53,205 (TR Turoni & Co., Forlì, Italy) equipped with an 8-mm-diameter tip and the results were expressed as the maximum force (N) required to penetrate the probe into the tomato pulp.

2.5. Data Handling and Statistical Analysis

For all measured data and parameters, the analysis of variance (ANOVA) was performed using JMP statistical software package, version 4 (JMP ®, Cary, NC, USA). A split-split-plot experimental design was adopted for tomato agronomical characteristics and all the physical and chemical quality measurements, where the cover crop was treated as the main factor, the soil tillage as the split factor, and the N fertilization level as the split-split-factor. The analysis of variance was carried out for the 2 years considering the year as a repeated measure across time. The mean values of the treatments were compared using Fisher's protected Least Significant Difference (LSD) test at the 0.05 probability level. To test the statistical differences in the composition of the tomato fruit characteristics among cover crop, soil tillage, and N fertilization level groups, a multi-response permutation procedure (MRPP) was performed using Blossom software (USGS, Reston, Virginia, USA). MRPP calculates the mean within group distance of the observed pattern and then uses permutation procedures to determine whether this distance is greater than expected by chance. The results of the MRPP analysis provides a T-statistic that describes the separation among groups (the more negative T is, the stronger the separation is) and its associated significance. Canonical discriminant analysis (CDA) was carried out to evaluate the association between experimental treatments (soil tillage and N fertilization under cover crop, cover crop and N fertilization under soil tillage, and cover crop and soil tillage under N fertilization) on the occurrence of marketable tomato fruit characteristics. A vector diagram based on the total canonical coefficient of each marketable tomato fruit characteristic from the canonical function was combined into the same plot [19]. Pearson's linear correlation test was computed to detect significant correlations between marketable tomato fruit characteristics.

3. Results

3.1. Tomato Fruits at Harvesting

The numbers of marketable, rotten and green tomato fruits were generally affected by all main effects ($p \leq 0.05$) and by the interaction between cover crop and soil tillage ($p \leq 0.01$). The marketable fruit was higher in 2015 compared to the 2014 tomato growing season (25.2 vs. 20.2 n. plant^{-1}, respectively) and in hairy vetch compared to the other cover crop treatments (on average, 34.0 vs. 18.9 plant^{-1}, respectively, Table 2). Although soil tillage, as the main effect, was not significant ($p > 0.05$), there was an interaction between cover crop and soil tillage (Figure 1). Marketable tomato fruit amounts were similar in hairy vetch and bare soil regardless of soil tillage, while in subclover it was higher in tilled soil than no tilled soil; conversely, in black oat it was higher in NT compared to T treatments (Figure 1). As expected, the number of marketable tomato fruit was higher in N_{150}, intermediate in N_{75} and lower in N_0 (Table 2). The weight of marketable fruit per plant followed a similar trend, except for cover crop treatments, where it was the highest in hairy vetch followed by bare soil, while it was the lowest in subclover and black oat (on average, 257.7, 178.3, and 130.9 g of DM plant^{-1}, respectively).

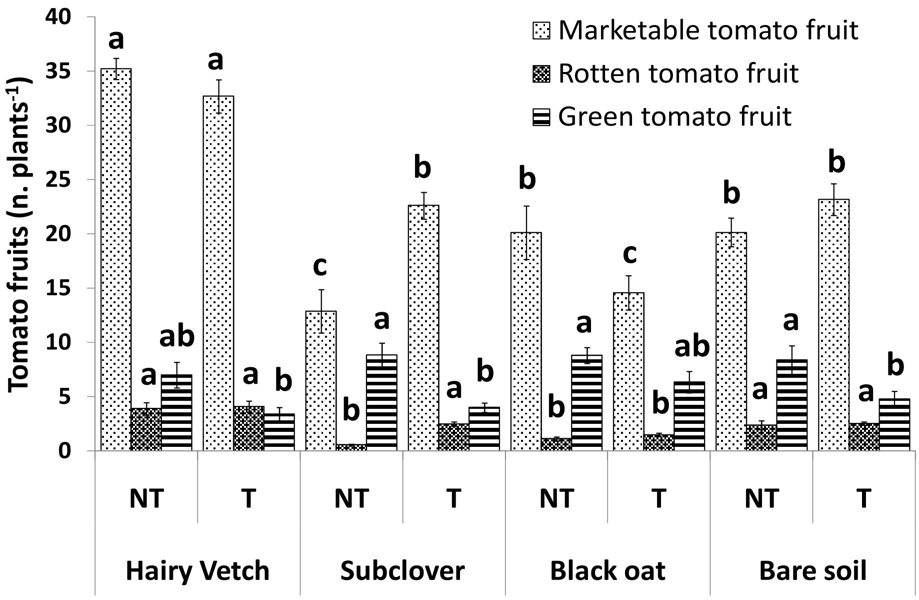

Figure 1. The interaction effect of cover crop and soil tillage on marketable, green and rotten tomato fruits. Values belonging to the same characteristic followed by the same letter are not significantly different according to LSD (0.05). NT = no-tillage; T = conventional tillage.

Table 2. The main effects of growing season, cover crop, soil tillage, and N fertilization on tomato straw, marketable, rotten and green tomato fruits at tomato harvesting. Mean values belonging to the same factor without common letters are statistically different to LSD ($p \leq 0.05$). NT = no-tillage; T = conventional tillage; N_0, N_{75} and N_{150} = 0, 75 and 150 kg of N ha^{-1}.

	Tomato Fruit			
	Marketable		**Rotten**	**Green**
	(Number Plant^{-1})	**(g of Dry Matter Plant^{-1})**	**(Number Plant^{-1})**	
Growing season				
2014	20.2 b	148.0 b	2.8 a	6.6 a
2015	25.2 a	201.0 a	1.8 b	6.2 a
Cover crop				
Hairy vetch	34.0 a	257.7 a	4.0 a	5.2 b
Subclover	17.7 b	130.7 c	1.5 b	6.4 ab
Black Oat	17.3 b	131.0 c	1.3 b	7.6 a
Bare soil	21.7 b	178.3 b	2.5 ab	6.6 ab
Soil Tillage				
NT	22.1 a	166.7 a	2.0 b	8.3 a
T	23.3 a	182.0 a	2.6 a	4.6 b
N fertilization				
N_0	18.2 c	135.7 c	2.1 b	5.6 b
N_{75}	23.0 b	176.3 b	2.4 ab	6.9 a
N_{150}	26.8 a	211.0 a	2.5 a	6.8 a

The number of rotten fruits was higher in 2014 compared to 2015 and tilled soil compared to no tilled soil (2.8 vs. 1.8 and 2.6 vs. 2.0 n. plant^{-1}, respectively). In general, hairy vetch showed a high number of rotten fruits followed by bare soil, subclover and black oat (on average, 4.0, 2.5, 1.5 and 1.3 n. plant^{-1}, respectively, Table 2). The number of rotten fruits tended to increase as the N fertilization level increased (2.5, 2.4, and 2.1 n. plant^{-1} at N_{150}, N_{75}, and N_0 fertilization level, respectively, Table 2). Regarding the green fruits, their number per plant was similar in both growing seasons, while it was high in black oat, intermediate in subclover and bare soil, and low in hairy vetch (on average, 7.6, 6.5, and 5.2 n. plant^{-1}, respectively). Generally, the administration of N fertilization tended to increase the number of green fruits (6.9 vs. 5.6 n. plant^{-1} with and without N, respectively), as well as the NT treatment (8.3 vs. 4.6 n. plant^{-1} in NT and T, respectively), even if this effect was significant only in subclover and bare soil (Figure 1).

3.2. Marketable Fruit Physical Characteristics

The equatorial and longitudinal diameters were adopted as metrics for evaluating the marketable tomato fruit size. Both diameters were higher in 2015 than in the 2014 tomato growing season (5.28 and 6.63 vs. 4.94 and 6.32 cm, respectively, Table 3), while no differences were observed regarding the soil tillage treatments.

The equatorial diameter was higher in hairy vetch, black oat and bare soil, compared to subclover (on average, 5.15 vs. 5.00 cm, respectively), which also showed a low longitudinal diameter (Table 3). The firmness of the marketable tomato fruits was affected by all treatments. It was higher in 2015 compared to 2014 and in NT compared to T. Regarding cover crop and N treatments, the tomato fruits showed the highest value of firmness after black oat (8.14 N) and where the N was not administered to the tomato crop (8.13 N in N_0, Table 3).

Even the color parameters and indexes of ripeness of marketable tomato fruits were affected by the treatments as main effects (Table 4).

Table 3. The main effects of growing season, cover crop, soil tillage, and N fertilization on equatorial diameter, longitudinal diameter and firmness of marketable tomato fruits at tomato harvesting. Mean values belonging to the same factor without common letters are statistically different to LSD ($p \leq 0.05$). NT = no-tillage; T = conventional tillage; N_0, N_{75} and N_{150} = 0, 75 and 150 kg of N ha^{-1}.

	Equatorial Diameter (cm)	**Longitudinal Diameter (cm)**	**Firmness (N)**
Growing season			
2014	4.94 b	6.32 b	6.68 b
2015	5.28 a	6.63 a	7.82 a
Cover crop			
Hairy vetch	5.14 a	6.43 ab	6.63 b
Subclover	5.00 b	6.28 b	7.07 b
Black Oat	5.18 a	6.67 a	8.14 a
Bare soil	5.14 a	6.53 ab	7.18 b
Soil Tillage			
NT	5.12 a	6.49 a	7.34 a
T	5.09 a	6.47 a	7.17 b
N fertilization			
N_0	5.01 b	6.41 b	8.13 a
N_{75}	5.13 ab	6.55 a	7.19 b
N_{150}	5.18 a	6.48 ab	6.44 c

Table 4. The main effects of growing season, cover crop, soil tillage, and N fertilization on color parameters and indexes of ripeness of marketable tomato fruits at tomato harvesting (L* = lightness, a* = color direction from green to red, b* = color direction from blue to yellow, CI = color index). Mean values belonging to the same factor without common letters are statistically different to LSD ($p \leq 0.05$). NT = no-tillage; T = conventional tillage; N_0, N_{75} and N_{150} = 0, 75 and 150 kg of N ha^{-1}.

	L*	**a***	**b***	**a*/b***	**CI**
Growing season					
2014	36.0 a	34.4 a	31.0 b	1.11 a	41.3 a
2015	34.8 b	34.0 a	33.4 a	1.02 b	41.0 a
Cover crop					
Hairy vetch	34.6 c	35.7 a	32.0 a	1.12 a	43.0 a
Subclover	35.2 b	35.3 a	32.6 a	1.09 a	41.8 b
Black Oat	35.8 ab	32.8 b	32.1 a	1.02 b	40.0 c
Bare soil	36.0 a	33.1 b	32.1 a	1.04 b	40.0 c
Soil Tillage					
NT	35.7 a	34.0 b	32.4 a	1.05 b	40.6 b
T	35.1 b	34.5 a	32.0 b	1.08 a	41.7 a
N fertilization					
N_0	36.1 a	33.6 b	33.1 a	1.02 c	39.5 c
N_{75}	35.6 b	34.4 a	32.3 b	1.07 b	41.0 b
N_{150}	34.6 c	34.7 a	31.2 c	1.11 a	43.0 a

In the 2014 growing season, only the L* and the a*/b* ratio increased, while the b* decreased compared to 2015. Hairy vetch and subclover showed the highest values of a* and a*/b* ratio, while bare soil and black oat had the highest values of L*. The color index (CI) was high in hairy vetch (43.0), intermediate in subclover (41.8) and low in black oat and bare soil (on average, 40.0). The soil tillage (T) increased the a*, a*/b* ratio and CI compared to NT. Regarding the N fertilization level, there was an increase in L*, b* and a decrease in CI and a*/b* ratio with increasing N dose (Table 4).

3.3. Marketable Fruit Chemical Characteristics

The marketable fruit chemical characteristics were affected by the growing season, cover crop and N fertilization, while the soil tillage had no significant effects (Table 5).

Table 5. The main effects of growing season, cover crop, soil tillage, and N fertilization on chemical quality parameters of the marketable tomato fruits at tomato harvesting. Mean values belonging to the same factor without common letters are statistically different to LSD ($p \leq 0.05$). SSC = Soluble Solid Content; TA = Titratable Acidity; SAR = Sugar/Acidity Ratio. NT = no-tillage; T = conventional tillage; N_0, N_{75} and N_{150} = 0, 75 and 150 kg of N ha^{-1}.

	SSC (°Brix)	**pH**	**TA (%)**	**SAR**
Growing season				
2014	5.66 a	4.28 b	0.42 a	13.16 a
2015	5.32 b	4.46 a	0.40 a	12.26 b
Cover crop				
Hairy vetch	5.23 c	4.42 a	0.37 b	13.21 a
Subclover	5.44 b	4.38 ab	0.40 ab	12.97 a
Black Oat	5.76 a	4.30 b	0.44 a	12.30 b
Bare soil	5.53 b	4.35 ab	0.43 a	12.36 b
Soil Tillage				
NT	5.44 a	4.37 a	0.39 a	12.52 a
T	5.54 a	4.35 a	0.43 a	12.90 a
N fertilization				
N_0	5.68 a	4.31 b	0.43 a	12.62 b
N_{75}	5.48 ab	4.38 a	0.41 ab	12.74 a
N_{150}	5.31 b	4.40 a	0.39 b	12.77 a

The SSC was higher in 2014 than in 2015 growing seasons (5.66 vs. 5.32 °Brix, respectively); moreover, it was the highest in black oat, intermediate in subclover and bare soil and low in hairy vetch (on average, 5.76, 5.53, 5.44 and 5.23 °Brix, respectively). Regarding the N fertilization, SSC decreased as N fertilization increased (5.68, 5.48, and 5.31 in N_0, N_{75}, and N_{150}, respectively) (Table 5). The titratable acidity (TA) was high in black oat and bare soil (0.44 and 0.43%, respectively), as well as at the N_0 fertilization level (0.43%), while no differences were observed between the growing seasons. The SAR values were higher in hairy vetch and subclover compared to black oat and bare soil (on average, 13.1 vs. 12.3, respectively), while they increased as the N fertilization level rose (12.62, 12.74, and 12.77 in N_0, N_{75}, and N_{150}, respectively, Table 5).

3.4. Overview of the Marketable Tomato Fruit Quality

The differences in the quality of marketable tomato fruits, within the cover crop, soil tillage and N fertilization treatments at tomato harvesting, were evaluated utilizing the multi-response permutation procedure (MRPP, Table 6).

The results of the MRPP analysis confirmed that the differences for distinct previously defined groups were generally highly negative and significant, except for bare soil vs. black oat and hairy vetch vs. subclover (Table 6). The maximum distance within cover crop groups was observed in hairy vetch vs. black oat (on average, −16.1 T between years), followed by subclover vs. black oat and bare soil vs. hairy vetch (on average, between years −10.1 and −9.5 T, respectively). Regarding the N fertilization, although the differences for distinct previously defined groups were all significant, as expected, the distance within different levels was higher in N_O vs. N_{150} compared to N_0 vs. N_{75} and N_{75} vs. N_{150}. The CDA analysis showed a tendency towards differentiation among tomato fruit characteristics under different cover crops, particularly according to N fertilization level (Figure 2).

Table 6. Test statistics from the multi-response permutation procedure (MRPP) for multiple paired comparisons to evaluate the main effects of cover crops, soil tillage and N fertilization on tomato fruit quality at tomato harvesting in 2014 and 2015. *p* is the probability of significant differences among cover crop and soil management groups. The T statistic is the weighted mean within group distance. NT = no-tillage; T = conventional tillage; N_0, N_{75} and N_{150} = 0, 75 and 150 kg of N ha^{-1}.

	2014		2015	
Cover Crop	**T**	***p***	**T**	***p***
Bare soil vs. Hairy vetch	−8.0674	<0.0001	−10.8343	<0.0001
Bare soil vs. Subclover	−3.9767	0.0061	−7.9005	0.0002
Bare soil vs. Black Oat	−1.5314	0.0797	−0.3263	0.2699
Hairy vetch vs. Subclover	−1.5790	0.0760	−3.2065	0.1060
Hairy vetch vs. Black Oat	−13.6474	<0.0001	−18.5215	<0.0001
Subclover vs. Black Oat	−8.7869	<0.0001	−11.3442	<0.0001
Soil Tillage				
T vs. NT	−2.8026	0.0224	−3.0354	0.0184
N fertilization				
N_0 vs. N_{75}	−8.1257	<0.0001	−9.5142	<0.0001
N_0 vs. N_{150}	−21.5300	<0.0001	−23.6248	<0.0001
N_{75} vs. N_{150}	−7.5466	0.0002	−12.1054	<0.0001

In hairy vetch, the first two canonical variables generally accounted for approximately 76% and 61% of the total variance in the 2014 and 2015 tomato growing seasons, respectively. In both years, firmness and L* seemed to be associated with N_0 regardless of soil tillage, while TA in 2014 was associated with N_{75} and in 2015 with N_{150}. a*, a*/b* and CI vectors were in the same orientation space as the N_{75} and N_{150} fertilization level, while SAR and SSC seemed to be associated with N_{150}, especially in the 2015 growing season (Figure 2). In subclover, the first two canonical variables explained 69% and 55% of the total variance in the 2014 and 2015 tomato growing seasons, respectively. Generally, Firmness and TA were associated with N_0, especially in NT soil management, while pH, CI, a*/b*, a*, SAR were in the same orientation space of N_{150} regardless of soil tillage (Figure 2). In black oat, the total variance explained by the first two canonical variables was 67% and 62% in 2014 and 2015 tomato growing seasons, respectively. Generally, pH, a*, a*/b*, and CI vectors were in the same orientation of N_{150} fertilization level regardless of soil tillage; this trend was particularly evident in the 2014 growing season, while SAR seemed to be associated with N_{75} fertilization, especially in bare soil and black oat (Figure 2). Conversely, b* seemed to be associated with no-tillage N_0, while firmness was in the same orientation space as tillage N_0. In bare soil, the first two canonical variables explained 76 and 68% of the total variance in the 2014 and 2015 tomato growing seasons, respectively. In both years, CI, a*/b*, SAR and a* vectors were generally associated with tillage N_{150}, while pH was associated with no-tillage N_{150}, especially in 2014. The other vectors seemed to be associated with N_0, with a certain level of differentiation between soil tillage, especially in the 2015 tomato growing season (Figure 2). In both years, there was a strong correlation among the different quality parameters measured for marketable tomato fruits (Table 7).

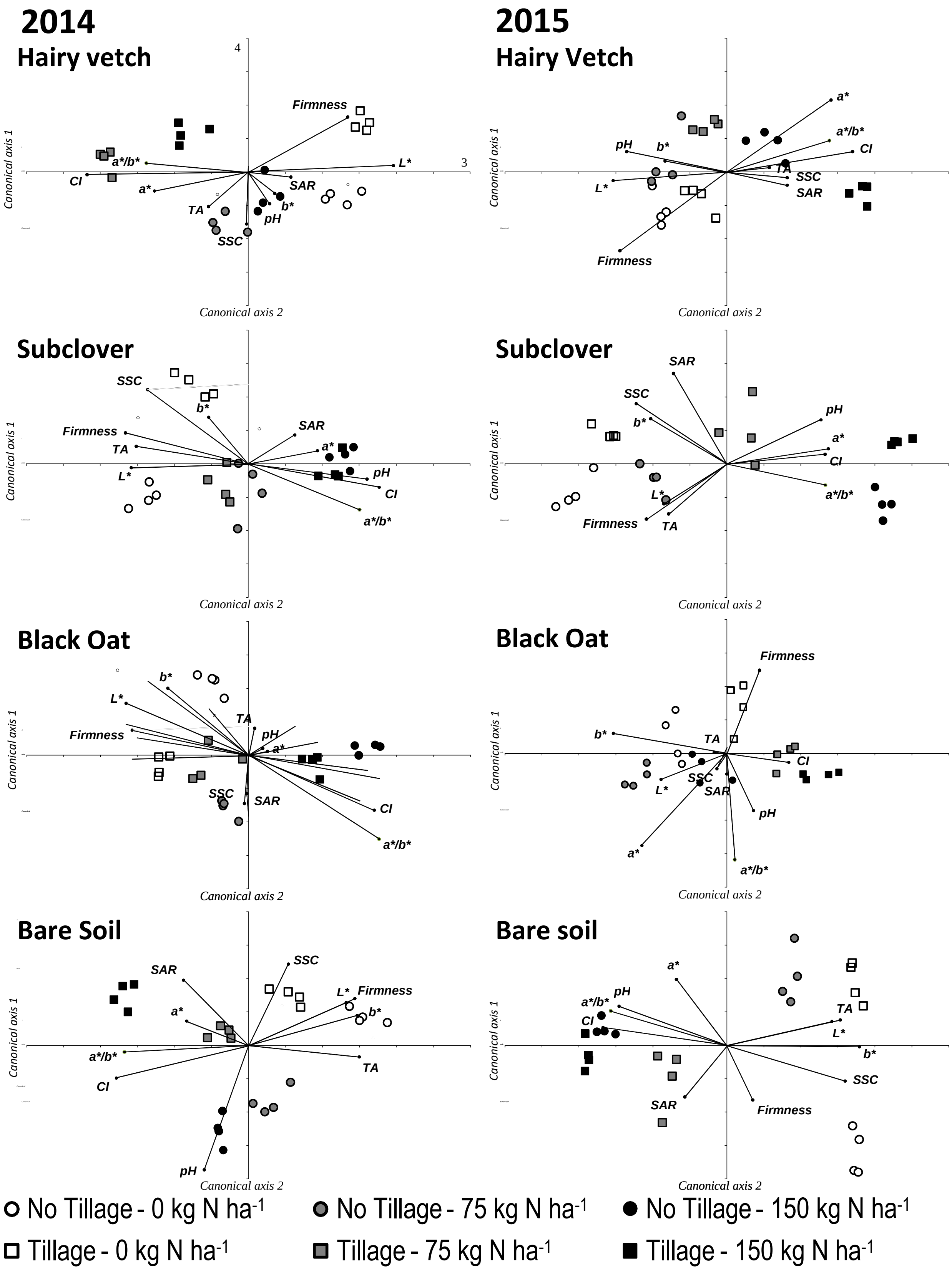

Figure 2. Biplot from a canonical discriminant analysis (CDA) of tomato fruit characteristics under different cover crops in 2014 and 2015 growing seasons. SSC = Soluble Solids Content; TA = Tritable Acidity; SAR = Sugar/Acid Ratio; L* = lightness; a* and b* = color parameters; CI = Color Index.

Table 7. Correlation coefficients ® table between features measured for the marketable tomato fruits. Pearson's r-value are calculated in each year (2014—data in the grey cells and 2015—data in the white cells, respectively), n = 96. TS = Total Solid; SSC = Soluble Solids Content; TA = Tritable Acidity; SAR = Sugar/Acid Ratio; a*/b* = color parameter ratio; CI = Color Index. The significance level is *, **, ***, or ns, significant at $p < 0.05$, $p < 0.01$, $p < 0.001$, or $p > 0.05$, respectively.

Pearsons' r	TS	SSC	pH	TA	SAR	a*/b*	CI	Firmness
TS	—	0.570 ***	−0.587 ***	0.214 *	0.182 ns	0.557 ***	0.620 ***	−0.497 ***
SSC	0.256 *	—	−0.595 ***	0.243 *	0.475 ***	0.621 ***	0.626 ***	−0.472 ***
pH	−0435 ***	−0.610 ***	—	−0.425 ***	−0.026 ns	−0.714 ***	−0.742 ***	0.638 ***
TA	0.316 **	0.557 ***	−0.470 ***	—	−0.725 ***	0.265 **	0.475 ***	−0.388 ***
SAR	−0.094 ns	0.435 ***	−0.123 ns	−0.498 ***	—	0.148 ns	−0.029 ns	0.038 ns
a*/b*	0.375 ***	0.621 ***	−0.504 ***	0.639 ***	−0.051 ns	—	0.831 ***	−0.638 ***
CI	0.438 ***	0.412 ***	−0.413 ***	0.525 ***	−0.118 ns	0.783 ***	—	−0.669 ***
Firmness	−0.296 **	−0.562 ***	0.350 ***	−0.400 ***	−0.159 ns	−0.508 ***	−0.241 *	—

Generally, TS, SSC, TA, a*/b*, and CI were positively correlated with each other, while they were negatively correlated with pH and firmness. SAR index was positively correlated with SSC and negatively correlated with TA, while there was a positive correlation between pH and firmness.

4. Discussion

Our results showed that the marketable fruits were higher in 2015 compared to 2014 probably due to the more suitable air temperatures during the tomato growing season. In fact, in 2015 the average air temperatures were close to those recommended by Shamshiri et al. [20] as optimal air temperatures for tomato leaf development, fruit growth and fruit set (Table 1). Regarding soil tillage, the number of marketable tomato fruits in hairy vetch and bare soil was independent of soil tillage, while in black oats it was higher when cover crop residues were mown and left in strips on the surface of the soil (NT), compared to when cover crop residues were chopped and incorporated into the soil (T). We also observed that, in the subclover cover crop, the number of plants of marketable tomato fruits was higher in T than in NT. Thus, our results suggested that the incorporation of cover crop residues into the soil was effective in increasing marketable tomato fruit numbers, mostly in hairy vetch cover crop. Overall, from our work, the existence of an interaction between the chosen cover crop and soil tillage emerged. These results are in agreement with those reported by Chahal and Van Eerd [21], which highlighted the positive and synergistic influences of cover crops and the maintenance of crop residues in improving the quality of the soil. The mechanism for explaining cover crop-derived increases in tomato yield is not yet clear; however, it appears to be soil mediated. For some authors [22], the effect of cover crops on tomato yield would be due to the increase in microbial N in the soil associated with mulching or the incorporation of residues of cover crops. On the other hand, winter grass cover crop species are known to have great potential to capture residual N, while winter legume cover crops are able to fix a large amount of atmospheric N, so they can provide enough N to achieve a high yield of a subsequent crop. The higher marketable tomatoes observed in hairy vetch, compared to other cover crops, could indicate a high release of N into the soil by this winter cover crop species. Some researchers [23] have shown that hairy vetch accumulated the greatest N content, probably due to its greater N-fixing ability than other cover crops. A similar effect of the cover crop on tomato yield was reported by Muchanga et al. [24], who observed that tomato's total yield was significantly greater in hairy vetch incorporation than in hairy vetch mulch. In our study, the presence of the hairy vetch cover crop increased the number of marketable tomatoes both when it was incorporated into the soil (T), and when it remained as a surface mulch (NT). This fact might be ascribed to inherently rich and fertile soil at our experimental farm. Among the non-marketable tomato fruits, we counted the rotten ones, and we noticed that, in general, the number of rotten fruits was less in NT compared to T. Furthermore, we observed that, as expected, the number of marketable tomatoes was highest in N_{150}, intermediate in N_{75}, and lower in N_0. At the same time, however, rotten fruit also increased with the level of fertilization. Our result is in agreement with the observations of other authors [25] who showed that N fertilization caused a significant increase in the total and marketable yield, but also in the rotten and unmarketable yield. Ronga et al. [26] suggested that an overdose of N supplies negatively impacted fruit yield as higher values of rotten fruit (+37%, compared to other means of treatment) were noted when tomato was fertilized with 350 kg ha^{-1} of N. Equatorial and longitudinal diameters were used to assess the size of marketable tomato fruits. Both diameters were higher in 2015 than in the 2014 tomato growing season. According to Jędrszczyk et al. [27] field-grown tomatoes are particularly sensitive to low temperatures, and air temperature can affect the size of marketable tomato fruits. In our study, air temperatures were consistently higher in 2015 than in 2014 (Table 1), this could have had a beneficial effect on fruit length and width. The equatorial diameter was larger in hairy vetch, black oat, and bare soil than in subclover. No differences were observed regarding soil tillage treatments. Moreover, we noted that the firmness of the marketable tomato fruits was affected by all treatments. It was higher in 2015 compared to 2014 and in NT compared to T. Firmness measurement is a prime indicator of fruit quality, and is very important for establishing fruit shelf life. The lack of rainfall during the tomato harvesting period, observed in 2015 compared to 2014 (Table 1), might have caused higher firmness of tomatoes and fewer rotten fruits (Table 2), while the higher firmness in NT is difficult to explain considering that the mechanisms involved in the development of fruit firmness have yet to be clarified [28]. Concerning the crossing effects of cover crops and N treatments, the tomato fruits showed the highest value of firmness after black oat, and in no N (N_0). Although, in some studies, the highest values of fruit firmness were noticed at the rates of 100 and 150 kg N ha^{-1} [25], our trials showed the highest value of firmness where the N was not administered to the tomato crop. In agreement with our results, Knee [29] reported that fruit firmness decreases with increasing N supply and content in fruits since firmness is bonded to cell turgor and wall characteristics, while the main effect of N is on the growth rate of the fruit with consequences on the consistency properties of the cells. Regarding the color parameters of marketable tomato fruits, they were affected by the treatments as main effects. Color in tomato is a very important external characteristic and is a major factor in the consumer's purchase decision. On the other hand, color parameters express colors in numerical terms along the L*, a*, and b* axes (from white to black, green to red, and blue to yellow, respectively) within the CIELAB color sphere, which are mathematically combined to calculate the color indexes. Our data indicated that hairy vetch and subclover showed the highest values of a*/b* ratio, while bare soil and black oat had the highest values of L*. The color index (CI) was high in hairy vetch, intermediate in subclover, and low in black oat and bare soil. Color index and a*/b* increased with a higher percentage of red color. L* values indicated that there was a change in lightness, particularly an increasing L* value indicated the brightening of the red color. The soil tillage (T) increased the a* and a*/b* ratio, and decreased L*, compared to NT. In addition, regarding the N fertilization level, with increasing N dose there was an increase in the a*, a*/b* ratio, and CI, while L* decreased. The upward trend of the a*/b* ratio was in disagreement with the results of some authors who signaled no effect of N fertilization on this parameter [25], and with other researchers [26] who found that the value of the a*/b* ratio decreased with the N supply. Arias et al. [30] reported that the L* and lycopene content produced a very good correlation coefficient, and, while the lycopene concentration had increased, L* decreased, and the tomatoes changed from a light to a dark color. They also reported that the increase in the a* and a*/b* ratio is directly associated with lycopene synthesis. Likewise, our results denoted changes in the values of L*, a*, and a*/b* that could be associated with lycopene synthesis. Therefore, in our research, the increase in N fertilization and the soil tillage (T) could improve the tomato quality, thanks to the greater synthesis of lycopene, which is the most important carotenoid of the tomato for its antioxidant activity and therefore represents a primary factor of quality. Additionally, it has been observed that the CDA analysis showed a tendency towards differentiation among tomato fruit characteristics, particularly according to the N fertilization level. Generally, in both years, firmness and L* seemed to be associated with N_0 regardless of soil tillage and cover crops, while a*, a*/b* and CI vectors were in the same orientation space as the N_{75} and N_{150} fertilization level. It is important to note that, in our experimental conditions, we observed that the chemical characteristics of the marketable fruits were influenced by the growing season, cover crops, and N fertilization, while soil tillage had no significant effects. Overall, in both years, the different levels of N fertilization and the different cover crop species significantly influenced the tomato's qualitative characteristics, while the management of cover crop biomass had a minor impact on fruit quality. Due to the differences observed in our study, it is possible to identify environmentally friendly management practices to produce tomatoes sustainably under Mediterranean conditions.

5. Conclusions

This study improved our understanding of the adoption of different winter cover crop species, soil tillage management strategies and N fertilization levels, and their effect on the tomato fruit yield and quality characteristics. Overall, compared with the bare soil, cover crops influenced the tomato productivity and quality depending on different species used. The results suggested that hairy vetch residues, compared to other cover crops tested in this research, had a positive influence on tomatoes. In fact, they increased the yield, and the physical and chemical characteristics, of marketable tomato fruits. Conversely, black oat residues decreased yield and had a tendentially negative effect on many characteristics of tomato quality. Generally, the management of cover crops residues had a major impact on marketable tomato yield compared to fruit quality. The incorporation of cover crop residues increased tomato yield after subclover, but it had a negative effect after black oat, while no differences were found after hairy vetch compared when the residues were left on the soil surface in no-tilled soil. As expected, the N fertilization level positively influenced the tomato yield and fruit characteristics. However, considering the short period of this study, further research is required to clearly understand the benefits of various cover crop species, combined with different soil tillage and N fertilization management strategies, on the quality of tomato fruits, in order to identify environmentally friendly management practices under Mediterranean conditions.

Author Contributions: All authors contributed to manuscript writing. Conceptualization, E.R. and E.C.; investigation, E.R. and E.C.; data curation, E.R.; formal analysis, E.R.; review and editing, E.C., R.M. and M.T.F.; supervision, R.M. and M.T.F.; funding acquisition, E.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financed by the European Union FP7 Project n.289277: OSCAR (Optimizing Subsidiary Crop Applications in Rotations).

Institutional Review Board Statement: Not applicable for studies not involving humans or animals.

Informed Consent Statement: Not applicable for studies not involving humans.

Data Availability Statement: The data presented in this study are available on request from the co-author Emanuele Radicetti who performed data curation and formal analysis.

Acknowledgments: The authors acknowledge Claudio Stefanoni and Fulvia Gatti for their valuable technical help in the field and laboratory activities.

Conflicts of Interest: The authors declare no conflict of interest.

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