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Published Version:
Baldi, E., Mazzon, M., Cavani, L., Quartieri, M., Toselli, M., Marzadori, C. (2023). Compost improves plant and soil macronutrient content in a 14-years orchard. NUTRIENT CYCLING IN AGROECOSYSTEMS, 125, 425-435 [10.1007/s10705-023-10258-0].

Availability:
This version is available at: https://hdl.handle.net/11585/923184 since: 2023-04-17

Published:

DOI: http://doi.org/10.1007/s10705-023-10258-0

~~The fate of generally unconsidered macronutrients in plant and soil: effect of different fertilization strategy on K, Ca, Mg and S~~

Compost improves plant and soil macronutrient content in a 14-years orchard

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Abstract

Adequate plant nutritional status and soil fertility preservation ~~should~~ can be achieved through ~~the employment of~~ sustainable agricultural management techniques. The challenge of intensive orchard cultivation, besides the risk of nutrient decline, is ~~the~~ to prevent~~ion of~~ the loss of soil fertility that could lead to soil degradation with a consequent negative impact on yield and fruit quality. The use of organic amendments could be a sustainable strategy to combine ~~elevated~~ high plant performance with soil fertility improvement.

This work aims at shedding light on the effects of compost addition with respect to an unfertilized control and a mineral fertilization treatment on macronutrient (K, Ca, Mg, and S) dynamics in plants and soil of a commercial nectarine orchard planted in 2001.~~Therefore, the manuscript aims at shading light on macronutrient (K, Ca, Mg and S) dynamics in plants and soil of a commercial nectarine orchard planted in 2001 and in which three fertilization treatments were compared: unfertilized control, mineral fertilization, and compost.~~

In the first 0.15 m of soil, compost addition resulted in higher values (26 - 42%) of all the parameters. Both fertilization treatments induced a 28% increase ~~of~~ in roots' S content compared to the control but did not induce macronutrient~~s~~ content variation in plant skeleton, pruned wood, and thinned fruits. In autumn leaves, all the macronutrients resulted in higher values (24 - 45%) with both mineral and compost fertilization, and the same was observed in fruit at harvest (increases of 15 - 31%). ~~Finally, in the first 0.15 m of soil, compost addition resulted with the higher values (+ 26 - 42%) of all the parameters.~~ In our study, the treatment with compost satisfied plants' nutrient demands as much as the mineral fertilizer. In addition, compost treatment also improved soil nutrient content while preserving yield. Our results show that it is possible to reconcile plant nutrient needs with the preservation of soil fertility with the aim of reaching agriculture sustainability. ~~Thus, the long-term use of mineral fertilizer, even if meeting plant's nutrient demand, could lead to soil macronutrient depletion. Whereas, organic amendments addition could not only satisfy plant's nutrient demand but also maintain soil quality and fertility through the higher macronutrients storage in the soil; this would lead to both higher plant performances and to economic and environmental benefits.~~

Keywords

Prunus persica, soil nutrient availability, compost, mineral fertilization, nutrient removal, soil macronutrient content.

1. Introduction

The ~~rising~~ increasing demand for high-quality nutritional food related to the ~~constant~~ steady increase ~~of~~ in population (El-Jendoubi et al., 2013) is leading to the necessity to ~~maximise~~ maximize yield ~~by~~ while minimizing ecosystem impacts deriving from agriculture. According to the report of the Food and Agriculture Organization of the United Nations (FAO, 2017), the requirements for adequate food supplies have to pass through sustainable agricultural management techniques. This issue also deals with adequate plant nutritional status and preservation/increase of soil fertility (Toselli et al., 2019a; Zhang et al., 2020). Plant nutrition depends on ~~is the result of~~ the nutrient cycle in and out of the orchard ecosystem. The inputs to the soil, for example, include mineral and/or organic fertilizers, atmospheric deposition, and biological nitrogen (N) fixation, while the outputs are represented by harvested fruits, nutrients lost by leaching, gaseous losses, and erosion (Toselli et al., 2019b). In case of a negative balance between inputs and outputs, the soil would come across a nutrient depletion that, in the long ~~-~~term, would lead to an unsustainable farming system (El-Jendoubi et al., 2013). The challenge of intensive orchard cultivation is, besides the risk of nutrient decline, the loss of soil fertility (both chemical and biological) that could lead to soil degradation (i.e. loss of soil organic matter, erosion, acidification, and pollution) with a consequent negative impact on plant performances (Zhang et al., 2020). Thus, the great challenge for modern farmers is to maintain and/or increase soil fertility in a sustainable way. This could be reached through the application of organic amendments (i.e. composts, biochar, and manures) that are widely ~~recognised~~ recognized to be ~~cheap~~inexpensive, to release ~~slowly release the~~ nutrients through mineralization slowly, and to enhance soil carbon (C) and organic matter increase (Mazzon et al., 2018; Sciubba et al., 2015) thus stimulating carbon dioxide sequestration. In addition, the application of organic matter ~~is able to~~can improve soil physical properties (Chatzistathis et al., 2020) as, for example, bulk density reduction and aggregate stability and water holding capacity increase (Adugna, 2016), positively affecting soil microbial community (Fawzi et al., 2010; Safaei Khorram et al., 2019) and increasing macro- and micro-nutrient availability (Baldi et al., 2021a; Fawzi et al., 2010). Organic amendments thus represent not only a source of N, phosphorus (P), and potassium (K) but also of calcium (Ca), magnesium (Mg), and sulphur (S) ~~that~~ which are equally considered ~~as~~ essential plant macronutrients (Barreto et al., 2021; Shiwakoti et al., 2020). In the study of Shiwakoti et al. (2020), the ~~farmyard manure~~ long-term (approximat~~iv~~ely 64 years) addition of farmyard manure (at the rate of 11.2 Mg ha^{-1} year^{-1}) evidenced higher macronutrient (K, S, and Mg) content in soil than the other treatments (pea vine and wheat residues, with and without N addition) mainly due to the high amounts of these nutrients that directly contribute to soil chemical fertility. Shiwakoti et al. (2020) also highlighted that manure could have activated soil cation exchange sites releasing organic colloids and consequently adsorbing K to the exchangeable sites and increasing its availability.

Macronutrient soil availability throughout the growing season is fundamental for fruit trees. In a study on pomegranate nutrient dynamics, Maity et al. (2019) demonstrated that ~~most of~~ plant needs were mostly satisfied by uptake from the soil more than from the mobilization from plant reserves; as a consequence, if soil nutrients are not replenished through appropriate fertilization management, fruit yield and quality could be severely impaired. In a different study on various fruit trees (i.e. apple, peach, and mandarin), Cruz et al. (2019) showed that adequate K supply at fruit set is of fundamental importance for the final fruit quality. Maity et al. (2019) evidenced that a great amount of Mg was remobilized from leaves to fruit at the maturity stage, while S was mainly concentrated in shoots and Ca in the woody organs of pomegranate. El-Jendoubi et al. (2013) found that K, P, and N mainly accumulate in fruits, while Mg and Ca in abscised leaves. Moreover, it is estimated that peach trees in commercial orchards have a macronutrient requirement accounting for 74 - 425 g K tree^{-1}, 25 - 518 g Ca tree^{-1}, and 9 - 74 g Mg tree^{-1} (Baldi et al., 2021b) every year.

The key issue for fruit tree nutrition is the availability of nutrients in the soil during the entire vegetative season, consequently, the use of organic amendments, that gradually release nutrients through mineralization, could be a sustainable strategy able to combine elevated plant performance with the improvement of soil fertility (Baldi et al., 2021b).

This manuscript follows ~~3~~ three previous publications on C (Baldi et al., 2018), N (Toselli et al., 2019b), and micronutrients ~~on~~ in the same experiment (Baldi et al., 2021a), and aims at ~~shading~~ shedding light on ~~other nutrients such a~~the macronutrients K, Ca, Mg, and S. Indeed, the goal of the present study was to determine the effects of the long term mineral fertilization and compost addition in ~~the long term~~a nectarine orchard (14 years) on~~:~~ i) soil macronutrient content at the end of the 14-years life-time of the ~~nectarine~~ orchard, ii) macronutrient content in different plant organs, and iii) the relation between plant and soil macronutrient content.

2. Materials and methods

2.1 Orchard description and treatments

The experiment was carried out on a commercial nectarine orchard [*Prunus persica*, Batsch var. *nucipersica* (Bockh.) Schn.] planted in 2001 (Table 1). The orchard was located in the Po valley (Italy) near Ravenna (44°27′ N;12°13′ E), an area characterized by a temperate climate and a silt-loam soil (Calcaric Cambisol) with a total carbonate content (% $CaCO_3$) of 31 ± 1 and an active carbonate content (% $CaCO_3$) of 13 ± 1 (Baldi et al., 2021a, 2018). The p~~P~~lanting layout and main orchard management strategies are reported in Table 1. Since orchard plantation, three fertilization treatments were compared with four replicates (4 trees each) according to a complete randomized block design: unfertilized control (CK); mineral fertilization (MIN); and compost (COM). Specific information regarding the treatments ~~are~~ is reported in Table 1. Fertilizers were applied ~~on~~ to the tree row and tilled into the soil to a depth of 0.25 m, while pruned wood was left into the ground and chopped (Baldi et al., 2021a, 2018; Toselli et al., 2019b).

Table 1 – Nectarine orchard main characteristics and management strategies (Baldi et al., 2021a, 2018; Toselli et al., 2019b).

Management	**Description**
Variety and rootstock	Stark RedGold, grafted on hybrid GF677 (*P. persica* × *P. dulcis*)
Training system	Delayed vasette, distance of 5 m between the rows and 3.8 m between trees along the row
Irrigation	Drip irrigation system from June to September (vegetation season).
Phytosanitary treatments	~~Done a~~According to Crop Management Guideline of the region Emilia-Romagna (www.regione.emilia-romagna.it).
Soil management	Tree row was tilled superficially for weed control. Alleys were covered with spontaneous grass managed by mowing it 3 times a year.
Fertilization treatments	**Mineral fertilization (MIN)** Nitrogen (N) applied every year at the rate of 70 kg ha^{-1} yr^{-1} (60% in May and 40% in September); in 2004, N rate was increased to 120 kg ha^{-1} yr^{-1} and from 2006 to 130 kg ha^{-1} yr^{-1}. ~~Nitrogen was applied as ammonium nitrate (N = 35 %), while P and K were applied as a binary fertilizer (P = 10 %; K = 20 %); no micronutrients was provided in mineral fertilization.~~ Phosphorus (P) at 100 and potassium (K) at 200 kg ha^{-1} (applied only at planting). Rate established according to Integrated Crop Management Guideline of the region Emilia-Romagna (www.regione.emilia-romagna.it). Nitrogen was applied as ammonium nitrate (N = 35%), while P and K were applied as a binary fertilizer (P = 10%; K = 20%); no micronutrients was provided with mineral fertilization.

	Compost (COM) Applied at a rate of 10 t DW ha^{-1} yr^{-1}, equal to 240 kg N ha^{-1} yr^{-1}. Compost was obtained from domestic organic wastes (50%) mixed with pruning material (50%) after a 3-month stabilization. Average characteristics: DW of 73%, pH 9, EC 2.96 mS cm^{-1}, C/N ratio 10.2, and (in g kg_{DW}^{-1}) organic C 234, N 21.1, P 4.8, K 15.2.

2.2 Plant sampling and analysis

In 2014, after 14 years of life, 4 trees per treatment were harvested and divided into organs ~~-~~as described by Baldi et al. (2021a, 2018) and Toselli et al. (2019b). Briefly, thinned fruits were collected in spring and weigh~~t~~ed, and a representative sample was~~ then~~ oven-dried and milled (2 mm). In July, a sample of 40 young fully expanded leaves was collected from the apical part of shoots, and the leaf area was measured by a portable area meter (Li-3000, LiCor inc., Lincoln, Nebraska). Leaves were then washed, oven-dried, and milled at 2 mm. At harvest, in August, plant yield was recorded; afterward~~s~~, ~~on a representative sample of fruits, ~~fresh weight (FW) and dry weight (DW) of flesh and kernel were measured on a representative sample of fruits; dried flesh and kernel were weighted and milled. In September, one tree per plot was enclosed into a plastic net to collect autumn leaves that were weigh~~t~~ed, leaf area measured, dried, and milled. In December 2014, at the end of the commercial life of the orchard, the same trees were harvested, divided into roots, trunks, branches (age > 2 years), and current year shoots (twigs), and weigh~~t~~ed. A subsample of each organ was oven-dried, weigh~~t~~ed, and milled. ~~The sample of r~~Roots ~~was ~~were washed with deionized water to remove soil residues.

A sample (0.3 g) of each plant organ was mineralized according to the US EPA Method 3052 (Kingston and Jassie, 1988) in an Ethos TC microwave (Milestone, Bergamo, Italy), filtered (Whatman 42®), and analyz~~s~~ed for Ca, K, Mg, and S by ~~Inductively ~~inductively ~~Coupled ~~coupled

~~Plasma~~ plasma ~~Optical~~ optical ~~Emission~~ emission ~~Spectrometer~~ spectrometer (ICP-OES; Ametek Spectro, Arcos, Kleve, Germany). Blank and certified reference materials (NIST standard reference material SRM 1573a tomato leaves and SRM 1570a spinach leaves) analyses were performed. Relative uncertainty, calculated as the relative deviation of the measured element concentration to its certified value, was typically better than ± 5%.

~~Mineral~~ The mineral content in different parts of the plant (leaves, fruits, branches, trunk, and roots) was calculated by multiplying each mineral concentration by the DW of the specific organ.

The biomass of the skeleton was calculated as the sum (without pruning wood) of trunk, branch, and twigs > 2 years (identified according to their insertion into branches) measured at the end of the experiment. Skeleton and root nutrient content were divided by the age of the orchard (13) assuming a constant annual increase of weight and nutrient accumulation, and considering the increase of the first year (2001) was negligible since orchard ~~plantation~~ was ~~done~~ planted at the end of the year.

2.3 Soil sampling and analysis

In December 2014, an 80 cm deep soil core (70 mm diameter) was collected in the row of each plot with a soil column cylinder auger that was inserted into the soil using a tractor. The core was carefully removed from the auger and divided into four parts according to depth: 0 - 0.15 m, 0.16 - 0.25 m, 0.26 - 0.45 m and 0.46 - 0.65 m. Soil from each depth was separately weighted and oven dried at 105°C for 24 hours to evaluate soil bulk density (BD) ~~that~~ which was calculated as the ratio between DW and the volume of each core. In addition, soil samples were collected, always in the row, with an auger at 0-0.15 m, 0.16-0.25 m, 0.26-0.45 m, and 0.46-0.65 m ~~of~~ depth. Each sample (made of 4 sub-samples) was sieved (2 mm), cleaned from roots and visible plant residues, and air-dried or stored at 4°C. A ~~sub~~ sub-sample was then used to evaluate soil total concentration of Ca, K, Mg, and S. Briefly, samples were subjected to wet mineralization by treating 0.5 g of dry sample with 6 mL of hydrochloric acid (37%), 2 mL of nitric acid (65%) and 2 mL of hydrogen peroxide (30%) in an Ethos TC microwave lab station (Milestone, Bergamo, Italy) according to the methods ISO 12914:2012 and 22036:2008. Solutions were filtered (Whatman 42®) and the element concentration was determined by plasma spectrometer (ICP-OES; Ametek Spectro, Arcos, Kleve, Germany). Blank and certified reference material (BCR reference material No 141R calcareous loam soil) analyses were performed; relative uncertainty, calculated as the relative deviation of the measured element concentration to its certified value, was typically better than ± 5%. Soil pseudo-total mineral element content at the end of the orchard life-time was calculated by multiplying the nutrient concentration by the soil bulk density at the respective depth intervals. Electrical conductivity (EC) was measured on a suspension of 10 g of fresh sample and 20 mL of deionised water that was stirred for 120 min at 25°C and filtered before measurement. Soil potential cation exchange capacity (CEC) was estimated using the ammonium acetate method (Sumner and Miller, 1996).

2.4 Statistical analysis

After assumption verification (Shapiro-Wilk for normality and Bartlett for homogeneity of variance), p~~P~~lant organ data were ~~analysed~~ analyzed with a one-way ANOVA with treatment as a factor (three levels: unfertilized control, mineral fertilization, and compost)~~ after assumption verification (Shapiro-Wilk for normality and Bartlett for homogeneity of variance)~~. Whether necessary, data were transformed using the Box-Cox procedure to fit the ANOVA assumption. Similarly, data on macronutrient content for~~of~~ autumn and summer leaves ~~macronutrient content~~ were analysed with a ~~two~~one-way ANOVA with ~~treatment and~~ season as a factor~~s~~. When significant differences occur (P ~~≤~~ < 0.05), an HSD post-hoc test (Tukey's test) was applied to separate the means. A Principal Component Analysis (PCA) was carried out using plant organ data ~~that~~ show~~ed~~ing significant differences ~~for~~ in the treatment~~s~~s. Soil data were ~~analysed~~ analyzed using a split-plot design, with treatments (three levels: unfertilized control, mineral fertilization, and compost) as the main factor and sampling depths (four levels: 0 - 0.15, 0.16 - 0.25, 0.26 - 0.45, 0.46 - 0.65 m) as the sub-factor. ANOVA assumption verification and means separation were ~~done as~~performed as described -for plant organs (R Core Team, 2021).

3. Results

Fertilization treatments, no matter which one, induced on average a 28% increase ~~of~~ in roots' S content compared to the control (Table 2). The fertilization treatments did not induce a variation of Ca, K, Mg, and S content in the plant skeleton, pruned wood, and thinned fruits (Table 2). On the contrary, all the considered macronutrients ~~considered~~ (Ca, K, Mg, and S) ~~were~~ increased in autumn leaves (in a range from 24 to 45%) by both mineral and compost fertilizations. Similar results in ~~correspondence of~~ the two fertilization treatments (with increases between 15 and 31%) ~~was~~ were observed in fruit at harvest with the exception of Ca content that did not show any differences among treatments (Table 2).

Table 2 – Macronutrient content (g pt^{-1}) in plant organs ± standard error (based on field replicates). Different lowercase letters indicate significant ($P < 0.05$) differences between treatments (CK = unfertilized control, MIN = mineral fertilization, COM = compost).

Plant organs	Treatments	Ca	K	Mg	S
Pruned wood	CK	26 ± 1	9.9 ± 0.7	2.2 ± 0.2	1.4 ± 0.1
	MIN	43 ± 1	17 ± 1	3.5 ± 0.3	2.5 ± 0.1
	COM	30 ± 7	13 ± 3	2.6 ± 0.6	1.9 ± 0.4
	p.value	*0.150*	*0.098*	*0.178*	*0.097*
Thinned fruits	CK	0.62 ± 0.14	2.6 ± 0.6	0.29 ± 0.07	0.27 ± 0.06
	MIN	0.44 ± 0.12	2.0 ± 0.6	0.22 ± 0.06	0.21 ± 0.06
	COM	0.87 ± 0.17	3.5 ± 0.7	0.38 ± 0.07	0.36 ± 0.07

	p.value	*0.168*	*0.257*	*0.259*	*0.251*
Fruit at harvest	CK	2.3 ± 0.2	43 ± 1 ^{b}	3.6 ± 0.1 ^{b}	2.0 ± 0.1 ^{b}
	MIN	2.4 ± 0.1	51 ± 2 ^{ab}	4.8 ± 0.3 ^{a}	2.8 ± 0.1 ^{a}
	COM	2.4 ± 0.2	57 ± 1 ^{a}	4.8 ± 0.2 ^{a}	2.8 ± 0.1 ^{a}
	p.value	*0.867*	***0.010***	***0.012***	***0.006***
Autumn leaves	CK	118 ± 3 ^{b}	43 ± 2 ^{b}	14 ± 0.3 ^{b}	2.6 ± 0.2 ^{b}
	MIN	181 ± 23 ^{a}	70 ± 7 ^{a}	21 ± 2 ^{a}	4.7 ± 0.5 ^{a}
	COM	156 ± 9 ^{a}	66 ± 4 ^{ab}	19 ± 2 ^{a}	4.5 ± 0.4 ^{a}
	p.value	***0.010***	***0.026***	***0.012***	***0.013***
Roots	CK	21 ± 3	5.6 ± 0.2	3.0 ± 0.5	0.32 ± 0.02 ^{b}
	MIN	21 ± 4	5.2 ± 0.5	3.0 ± 0.5	0.43 ± 0.03 ^{a}
	COM	24 ± 0.3	6.1 ± 0.7	3.6 ± 0.2	0.45 ± 0.03 ^{a}
	p.value	*0.771*	*0.313*	*0.659*	***0.001***
Skeleton	CK	45 ± 2	12 ± 1	3.8 ± 0.3	1.8 ± 0.1
	MIN	60 ± 7	16 ± 2	5.2 ± 0.7	2.4 ± 0.2
	COM	56 ± 7	17 ± 1	5.0 ± 0.6	2.5 ± 0.2
	p.value	*0.328*	*0.220*	*0.329*	*0.126*

No significant differences between fertilization treatments were observed in the concentration of nutrients in summer leaves (Table 3); the only exception was Mg which resulted in a 13% higher concentration in the control compared to the two fertilization strategies (Table 3).

Table 3 – Macronutrient concentration (g 100 g^{-1} DW) ± standard error (based on field replicates) in leaves sample in summer. Different lowercase letters indicate significant ($P < 0.05$) differences between treatments (CK = unfertilized control, MIN = mineral fertilization, COM = compost).

Treatments	**Ca**	**K**	**Mg**	**S**
CK	2.2 ± 0.1	1.2 ± 0.04	0.44 ± 0.01 ^{a}	0.16 ± 0.03
MIN	1.9 ± 0.1	1.1 ± 0.01	0.39 ± 0.01 ^{b}	0.15 ± 0.01
COM	1.9 ± 0.1	1.2 ± 0.04	0.39 ± 0.01 ^{b}	0.15 ± 0.01
p.value	*0.088*	*0.088*	***0.013***	*0.947*

The comparison of macronutrient~~s~~ content in autumn and summer leaves highlighted the significant impact of the ~~season~~ phenological state for all ~~the~~ four macronutrients considered in this study (Figure 1). Specifically, higher concentrations of Ca and K were observed in autumn than in summer leaves; the opposite was observed for Mg and S.

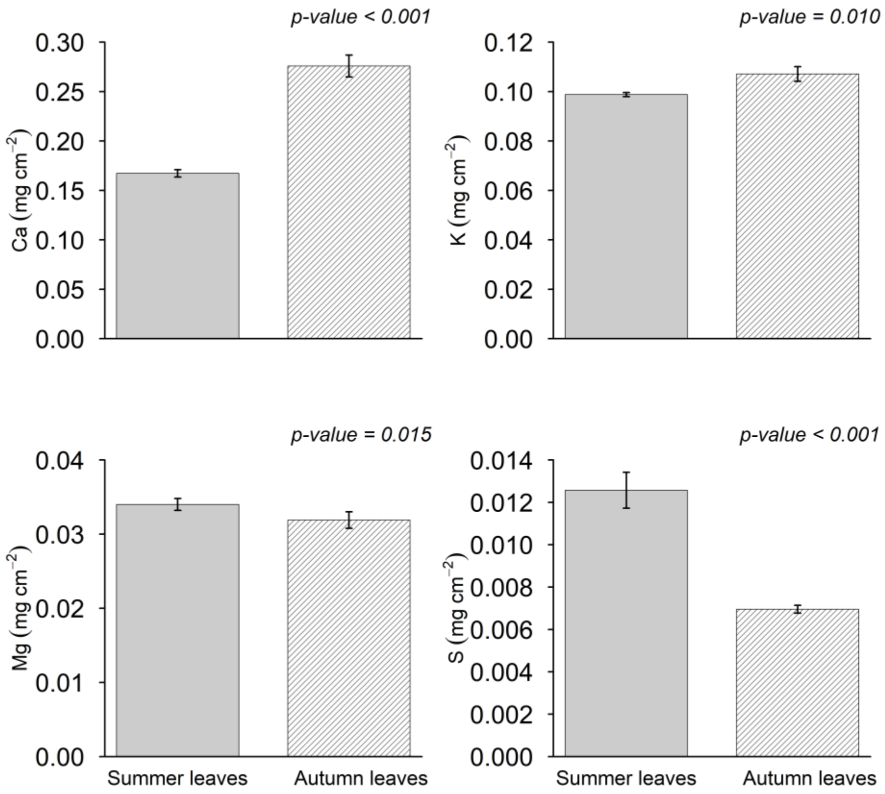
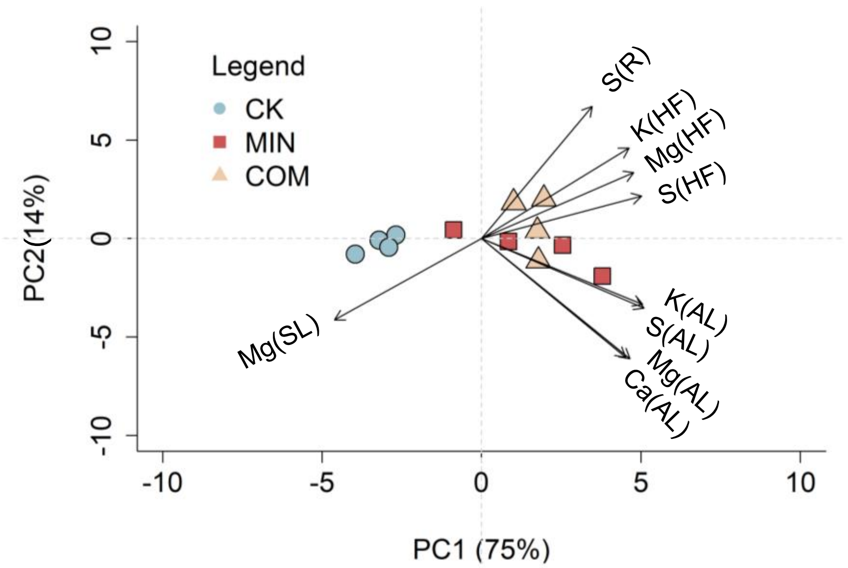


Figure 1– Means of summer and autumn leaves content of calcium (Ca), potassium (K), magnesium (Mg) and sulphur (S). Error bar represent the standard error (based on four leaf samples collected in field replicates) and the significant differences (P ~~≤~~ < 0.05) are reported.

A PCA (Figure 2) was ~~done~~ performed using ~~with macronutrients content in~~data from those organs whose macronutrient content was ~~that were~~ significantly affected by the fertilization treatments (Table 2). The treatments clusterized were split ~~resulted~~ in~~to~~ two main ~~cluster~~ groups (according to PC1 ANOVA results): the unfertilized control ~~in~~ on the left side of the plot, and the two fertilization strategies (mineral and compost) ~~in~~ on the right side of the plot. These two groups showed to be clearly defined ~~with~~ by the Mg content in summer leaves that characterized the unfertilized control group (Figure 2). A clear separation in plot space was also evident between macronutrient~~s~~ content in the autumn leaves (bottom-right side of the plot) and in the fruit at harvest and roots (upper-right side of the plot).



	ANOVA factor Fertilization treatment	
PC1 (75%)	F	20.97
	p-value	**< 0.001**
	COM = MIN > CK	
PC2 (14%)	F	1.92
	p-value	0.209
	COM = MIN = CK	

Figure 2– Principal component (PC) analysis with macronutrient~~s~~ content (calcium (Ca), potassium (K), magnesium (Mg) and ~~sulfur~~sulphur (S)) in the most relevant plant organs: harvested fruits (HF), roots (R), autumn leaves (AL), and summer leaves (SL). T~~In t~~he table ~~are reported~~ reports the statistical output of the ANOVA done on the PC (Treatments: CK = unfertilized control, MIN = mineral fertilization, COM = compost) with t~~.~~he significant differences ($P < 0.05$).

In the first 0.15 m of soil, the addition of compost increased CEC, EC, Ca, K, Mg, and S compared with control and mineral fertilization (Fig. 3). With the exception of CEC and Ca, the positive effect of compost was observed also in other soil layers (Fig. 3) and in particular EC was higher in all soil profiles, while the concentration of K, Mg and S were higher than in the control and mineral fertilization between 0 and 45 cm of depth. The effect of compost decreased with depth for all the investigated parameters ~~investigated~~; however, while the concentration of K and Mg decreased constantly with depths, the EC decreased until 25 cm and then ~~was~~ remained steady from 26 to 65 cm, and the concentration of Ca, S and CEC decreased until 15 cm and then ~~was~~ remained steady from 16 to 65 cm (Fig. 3). Unfertilized control and mineral fertilization did not show significant differences in nutrient concentrations and in both treatments only a slightly decreasing trend with depth was observed for K and Mg concentration. In control and mineral fertilization, S concentration was higher in the deepest layer than in the ~~superficial~~ shallowest one (Fig. 3).

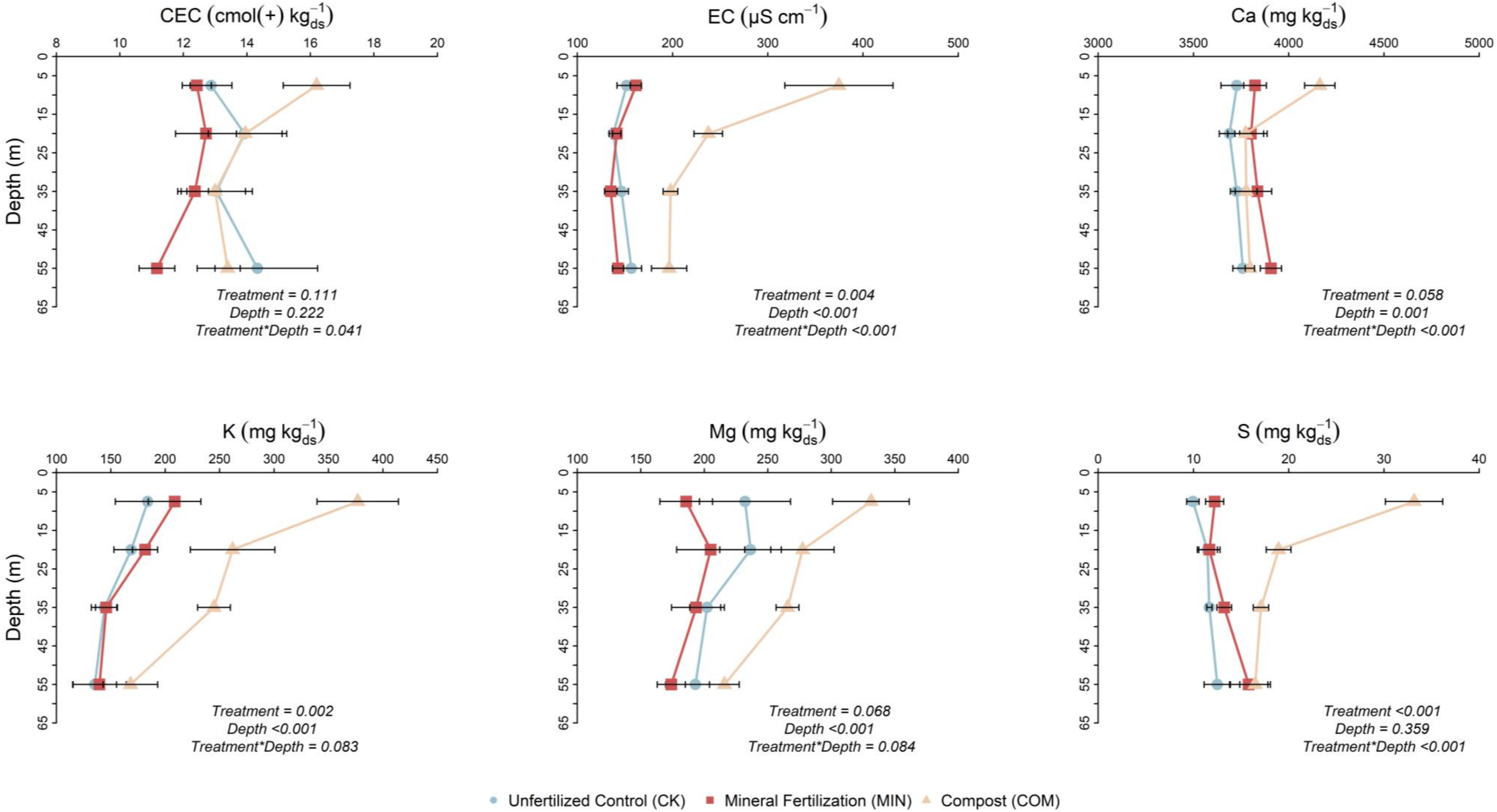


Figure 3 – Means of soil cation exchange capacity (CEC), electrical conductivity (EC), and soil calcium (Ca), potassium (K), magnesium (Mg) and sulphur (S) content at four sampling depth (0 - 0.15, 0.16 - 0.25, 0.26 - 0.45, 0.46 - 0.65 m) for the three fertilization treatments (CK = unfertilized control, MIN = mineral fertilization, COM = compost). Error bars represent the standard error (based on data on field replicates) and the significant differences (P ~~≤~~ < 0.05) between "Treatment", "Depth", and "Treatment*Depth" interaction are reported.

4. Discussion

~~In this study and as already observed previously (El-Jendoubi et al., 2013) plants macronutrients were mainly allocated in autumn leaves and in fruits at harvest. However, while in roots, skeleton, pruned wood, autumn leaves, and summer leaves Ca contents were highest among all the other macronutrients, K was the most important macronutrient in thinned fruit and fruit at harvest. Similarly, El-Jendoubi et al. (2013) showed that each nutrient was characterized by a precise allocation pattern: fruits were the largest sink for K, while Mg and Ca were mainly accumulated in abscised leaves.~~

4.1 Calcium and potassium returned to soil with leaf abscission ~~abundance and allocation~~

In this study and as already observed previously (El-Jendoubi et al., 2013) plants macronutrients were mainly allocated in autumn leaves and in fruits at harvest. However, while in roots, skeleton, pruned wood, autumn leaves, and summer leaves Ca contents were highest among all the other macronutrients, K was the most important macronutrient in thinned fruit and fruit at harvest. Similarly, El-Jendoubi et al. (2013) showed that each nutrient was characterized by a precise allocation pattern: fruits were the largest sink for K, while Mg and Ca were mainly accumulated in abscised leaves.

The difference between the amount of nutrients in summer leaves (sampled in ~~summer~~ July) and at natural abscission gives an estimation of the fraction of nutrients remobilized at the end of the vegetative season and stored inside the woody part of the plant. In the present experiment, Ca and K showed higher concentrations in autumn leaves than in those sampled in summer indicating no net remobilization through the season. ~~A s~~Similar behavior was reported in almond trees (Muhammad et al., 2015). As a consequence, Ca and K allocated ~~in autumn~~to leaves returned ~~into~~ to the soil after abscission and ~~degradation~~decomposition, thus ~~becoming again~~returning partially available for root uptake (Baldi et al., 2021b) after mineralization~~.~~. ~~On the other hand, little quantities~~

~~of Ca and K reservation are available for spring new growth.~~ However, despite what was expected and what was observed in other ~~study~~ studies (Dang et al., 2022; do Carmo et al., 2016), in ~~this~~ our case, soil Ca and K concentration increased in the surface horizon and in the whole soil profile respectively, only when compost was applied (Ca~~O~~ and K mean content of compost ~~was~~ were of ~~8.2~~5.8 ± 1.0 % and 1.5 ± 0.2 %, respectively), and not in control and mineral fertilized plots, meaning that the source of additional Ca was the organic fertilizer rather than the litter ~~made of~~formed by abscised leaves. ~~This~~ The ~~lack of effect~~fact that abscised leaves and/or mineral fertilizer have no such effect on soil Ca content was probably in relation to the natural soil's high abundance in total and active carbonate content ($CaCO_3$) (Baldi et al., 2018), indicating a large soil endowment in carbonates thus making it impossible to observe variation in soil Ca content even in the long term.

4.2 ~~K and Mg in plant and soil~~Compost contributed to soil and plants K and Mg content

Differently from Ca, ~~the fertilization treatments (~~both mineral fertilizer and compost~~) induced an~~ increased ~~of~~ K and Mg content ~~also~~ in fruits at harvest (Table 2). This effect was also observed by ~~Increase of K content in fruits was observed also in another study on nectarine (~~Delian et al.~~,~~ (2012), who reported a higher concentration of potassium than magnesium in nectarine fruits at harvest~~where at harvest macronutrients concentration in fruits followed the order K > Ca > Mg~~. Potassium ~~is not an essential element for organic molecules and it is not considered a structural element (Delian et al., 2012); however, it~~ is involved in many physiological and biochemical processes related to plant growth, crop quality, and plant response to stress factors (Delian et al., 2012; Wang et al., 2018). An excess in available ~~P~~potassium is ~~also~~ known to induce a Mg~~-~~ deficiency in the plant due to the unidirectional competition for uptake ~~between K and Mg for which an increase in K concentration reduces Mg uptake~~ (Xie et al., 2021). In ~~this~~ our study, independently from the fertilization treatment (mineral or organic), the ~~lower~~ lowest K/Mg ratio (approx. 1.8) was

~~determined~~ measured in plant roots with respect to the other plant organs, ~~(approx. 1.8) thus~~ indicating that the increase in K concentration in plant organs did not inhibit plants' efficiency to uptake Mg (Xie et al., 2021)~~ was not limited by the high plant K concentrations~~. The apparently similar plant uptake of K and Mg is confirmed also by the content of these elements in soil samples at the end of the commercial orchard life-time. Indeed, soil samples were not depleted in K nor Mg with values that ranged between 150 – 400 mg kg dw^{-1}, considering that optimum soil concentrations lie between 240 and 300 mg kg dw^{-1} for K (Xie et al., 2021) and between 25 and 180 mg kg dw^{-1} for Mg (Fox and Piekielek, 1984). Moreover, at the end of the experiment, significantly higher values of both K and Mg content were measured with compost fertilization treatment (compost ~~K_2O and~~ Mg~~O~~ mean concentration was ~~of 1.4 ± 0.2 % and~~ 0.~~72~~ 43 ± 0.07 %~~ respectively~~); this may ~~indicating~~ indicate a ~~its~~ greater contribution of compost to soil nutrient content with respect to the ~~other~~ mineral fertilization treatments. Similar results ~~for these macronutrients~~ were also observed in previous studies (Acharya et al., 2019; do Carmo et al., 2016)~~ and could be also related to compost chemical characteristics~~.

4.3 ~~Sulfur~~Sulphur content had a different trend with compost and mineral fertilization~~ destiny in plant roots and soil: fertilization treatment effects~~

Mineral and compost fertilization enhanced S content in fruits at harvest and in summer leaves more than in autumn leaves. At the end of the nectarine orchard commercial life-time, S content in roots was still high with ~~the two~~both treatments indicating a potential availability for bud ~~sprout~~ break in the next ~~vegetation~~ vegetative season. ~~Indeed, S is a component of some secondary metabolites used for plant's physiological functions and development (Narayan et al., 2022). This p~~Plant ~~activity~~ production of secondary metabolites is ~~supposed to be~~ supported by soil S content which ~~indeed~~ resulted particularly high in correspondence of compost ~~addition~~treatment. Compost ~~as an organic~~

~~matter supply increased~~ increases soil organic matter, the largest reservoir of S (in organic form) in~~to~~ soil~~.~~, and~~Thus~~ compost (in our study characterized by a 0.~~44~~ 18 ± 0.04 % of S~~O3~~ mean content) or soil organic matter decomposition could result in organic sulfur mineralization into the SO_4^{2-}, which is available to plants (do Carmo et al., 2016; Narayan et al., 2022). ~~However, while s~~Soil ~~S~~ sulfur content decrease~~d~~d with depth in ~~correspondence of~~ the plots treated with compost ~~addition~~, while it slightly increased or did not change with depth in the control and mineral fertilized plots. This different trend could be ascribed to the different S forms present in the soil: the organic one related to compost, and thus mainly present in the upper soil layers~~,~~; and the inorganic one, which ~~accumulate~~ moves deeper in the soil profile, and is probably less available to plants and more subjected to leaching and/or co-precipitation as calcium, magnesium or sodium ~~sulphate~~ sulfate (Scherer, 2001).

4.4 Compost ~~effects on soil chemistry~~increased soil CEC and EC

Compost contributes to the increase of exchangeable cations (i.e. Ca^{2+}, K^{+}, and Mg^{2+}) creating favorable conditions for cation exchange (Acharya et al., 2019; Dang et al., 2022). Fourteen years of compost addition significantly increased soil CEC and EC not only in the first (0 - 0.15 m) but also in the deeper soil layers. Changes in the CEC of soils are directly linked to the negative charges in the SOM and in the humified compounds (do Carmo et al., 2016) and to the colloidal nature of organic matter (Kumar Bhatt et al., 2019). Similarly, soil EC increase can be explained by the inputs of nutrients and salts contained in the compost and by the soil organic matter mineralization rate. Notwithstanding, the increase ~~of~~ in soil EC values needs to be considered carefully, since above a critical range of 750 - 3490 μS cm^{-1} plant growth could be damaged (do Carmo et al., 2016).

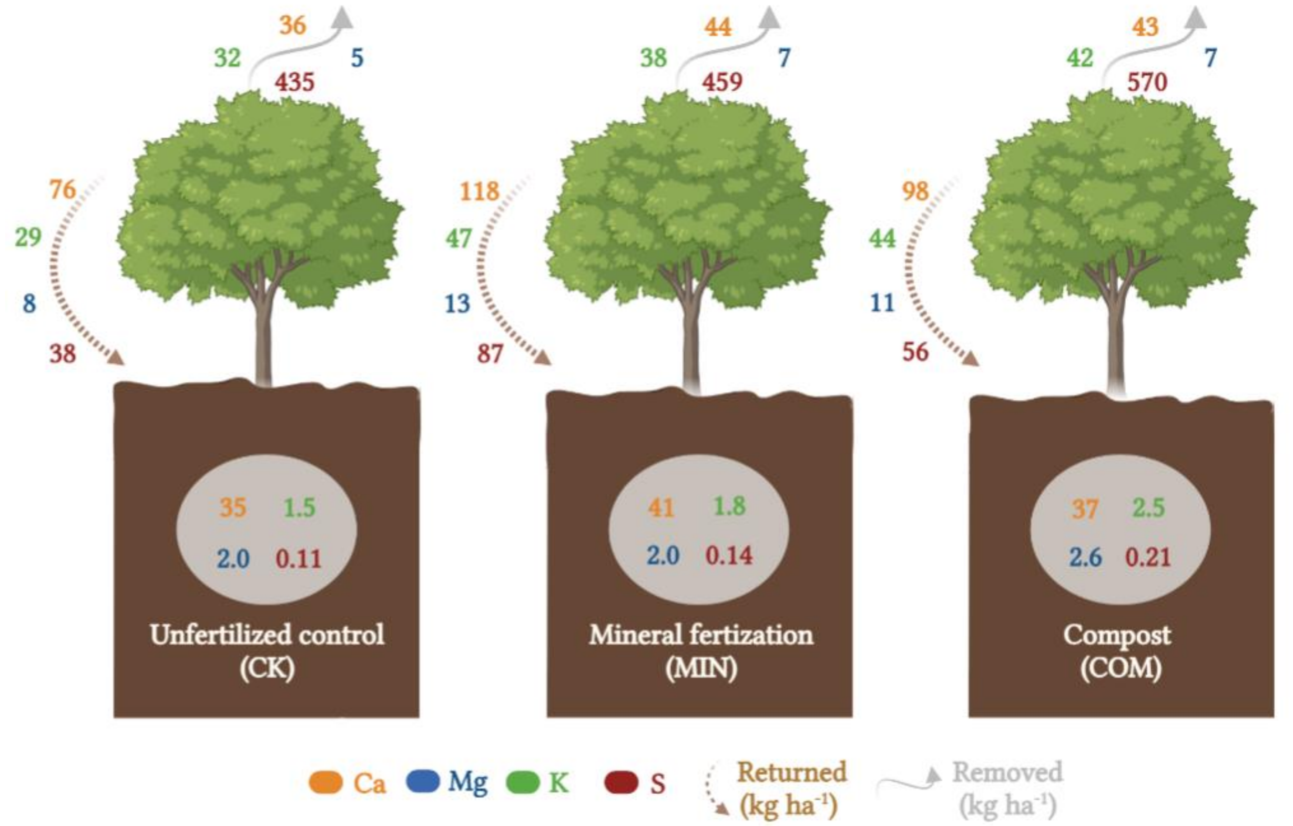


Figure 4 - Macronutrient dynamics in the soil-plant system. Ca, K, Mg and S content removed from the plant (solid grey arrow) and recycled from plant to soil (dashed brown arrow) are expressed in kg ha^{-1}, while Ca, ~~content in soil is expressed in g over kg dry weight and~~ K, Mg, and S ~~soil~~ content in soil ~~are~~ is expressed in ~~mg over kg dry weight~~Mg ha^{-1}.

5. Conclusion

Considering the goals of this study we ~~have~~ found that: (i) ~~Long~~long-term compost addition facilitates macronutrients storage in the soil and ~~thus indicating that it would favour soil macronutrients availability for the next crops (Figure 4). Moreover, organic amendment addition, not only maintains~~this is functional both for the current crops and for future ones (Fig. 4); (ii) ~~T~~the supply of compost ~~addition~~, besides maintaining soil quality and fertility, ~~but~~ also meets plant~~'s~~ nutrient demand thus leading to higher plant performances and to economic and environmental benefits~~.~~; (iii) ~~T~~the synchronization between plant needs and nutrient soil availability is fundamental for a correct fertilization management since it avoid plants' nutritional imbalance and, at the same time, reduce the risk of nutrient leaching. The use of compost makes it difficult to guarantee the mentioned synchronization, but significantly contributes to soil nutrient content and soil quality increase. ~~On the other hand, t~~The exclusive use of mineral fertilizer, if not carefully managed, even if meeting the plant's nutrient demand, could lead to macronutrient depletion due to scarce reserve creation in the soil; on the other hand, mineral fertilizer represents a source of nutrients readily available to plant uptake. Therefore, the choice of the fertilizer to be used needs to be calibrated on soil and plant requirements taking into account their potential effects (either positive or negative, i.e. the increase of soil organic matter content or the increase of nutrient leaching) on the environment.~~.~~

Future studies should take into consideration the effects of other organic amendments not only in relation to soil and plant nutrient availability, but also on the effects that compost decomposition could have on the amount of CO_2 emitted or sequestered by the orchard, and the impact of macronutrient dynamics on soil microbial communities structure and activity.

Acknowledgments

We would like to thank Dr. Andrea Simoni and Dr. Giampaolo Di Biase for performing the ICP-AES measurements.

Authors Contribution

Conceptualization: Elena Baldi, Moreno Toselli; **Methodology:** Elena Baldi; **Formal analysis and investigation:** Elena Baldi, Martina Mazzon, Maurizio Quartieri, Luciano Cavani; **Writing – original draft preparation:** Martina Mazzon; **Writing – review and editing:** Martina Mazzon, Elena Baldi, Luciano Cavani; **Resources:** Moreno Toselli, Claudio Marzadori; **Supervision:** Moreno Toselli, Claudio Marzadori.

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