

**Effect of selenium enrichment on metabolism of tomato
(*Solanum lycopersicum*) fruit during post-harvest ripening**

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4 **post-harvest ripening.**
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7 *Running title:* Ripening and post-harvest shelf-life of Se-enriched tomato fruit
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25 **Abstract**
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29 BACKGROUND: Selenium (Se) enrichment of plants seems effective in enhancing the health-
30 related properties of produce, and in delaying plant senescence and fruit ripening. The current study
31 investigated the effects of Se on tomato fruit ripening. Tomato (*Solanum lycopersicum* L.) plants
32 were grown in hydroponics with different Se-enriched nutrient solutions. Se, as sodium selenate,
33 was added at rate of 0 mg L⁻¹ (control), 1 mg L⁻¹, and 1.5 mg L⁻¹.
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37 RESULTS: Selenium was absorbed by roots and translocated to leaves and fruit. Se enrichment did
38 not significantly affect the qualitative parameters of fruit at commercial harvest, instead it delayed
39 ripening by affecting specific ripening-related processes (respiration, ethylene production, color
40 evolution) during postharvest. In the current experiment 100 g of tomato hydroponically grown with
41 a 1.5 mg Se L⁻¹ enriched solution provided a total of 23.7 µg Se. Selenium recommended daily
42 intake is 60 µg for women and 70 µg for men, thus the daily consumption of 100 g of enriched
43 tomato would not lead to Se toxicity, but would provide a good Se diet supplementation.
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47 CONCLUSIONS: The cultivation of tomato plants in a Se-enriched solution appeared effective in
48 producing tomato fruit with improved performances during storage and postharvest shelf life, and
49 also with greater potential health-promoting properties.
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54 **Keywords:** hydroponics; Se-enriched fruit; storage; shelf-life
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INTRODUCTION

Mineral nutrition is one of the main factors affecting several aspects of fruit and vegetable production: phytochemical content [1], growth and development, susceptibility to biotic and abiotic stresses, pre- and postharvest performances [2]. The effects of essential micronutrients on fruit quality have been widely described [3, 4], whereas only few studies have reported the effects of non-essential micronutrients on the qualitative characteristics of fruit [5].

Selenium (Se) is classified as a non-essential micronutrient for plants, but despite this, Se seems to delay plant senescence and fruit ripening, and therefore to decrease postharvest losses. These benefits are likely due to its ability in increasing antioxidant defenses as previously described [6–8]. In particular, Xue and colleagues (2001) [9] reported that selenium supplementation resulted in improved glutathione peroxidase (GSH-Px; EC 1.11.1.9) and superoxide dismutase (SOD; EC 1.15.1.1) activities, together with a reduced decline in tocopherol content. In tomato fruit, Se concentration negatively correlated with the content of some reactive oxygen species (ROS), such as hydrogen peroxide and superoxide, and positively correlated with glutathione peroxidase and glutathione reductase activity [8, 10]. In tomato plants, treatments with Se induced positive effects on the oxidative status of fruit and delayed fruit ripening [11–13].

Se has been proved to delay postharvest losses also affecting ethylene production in different produce, such as broccoli [14], tomato [8, 12] and in some leafy vegetables [7]. In peach and pear, foliar and fruit selenium spraying delayed the reduction of flesh firmness and the onset of fruit ripening, thus improving the fruit shelf-life [15]. Se plays a crucial role in human diet and animal feed. As a component of selenoaminoacids and selenoproteins, Se has been previously considered an essential trace element, a natural antioxidant, and an effective anticarcinogenic agent [16, 17]. Thus, improving the dietary Se intake, without exceeding the toxic threshold, i.e. 400 μg of Se per day [18], may have long-term health benefits [19]. The Se-enrichment of vegetables represents a safe way to increase its intake, since the organic compounds of Se contained in plants are more bioavailable than inorganic forms [20]. Vegetables grown in hydroponics can be fortified by adding Se to the nutrient solution, which allows the control of Se available for plants, avoiding hyperaccumulation [7, 12, 21].

The present study aimed to better evaluate the efficacy of Se in delaying postharvest ripening and increasing fruit quality. The effects of different Se treatments (i.e. 0, 1 and 1.5 mg Se L⁻¹, added to the nutrient solution as sodium selenate) on fruit quality and postharvest ripening were investigated by measuring physiological (ethylene production, respiration rate, softening, color changes), and biochemical (non-structural carbohydrates and carotenes biosynthesis, chlorophylls degradation) parameters in fruit of Se-enriched tomato plants after harvest.

MATERIALS AND METHODS

Plant material and experimental design

Tomato plants (*Solanum lycopersicum* L. cv. Red Bunch) were grown from February to June 2016, at the Department of Agriculture, Food and Environment of the University of Pisa, Italy (lat. 43° 40' N). Tomato seeds were sown, on 12th February, in 254-cell plug-trays filled with rock wool and vermiculite, and germinated in a growth chamber at 25°C. 14 days after sowing, seedlings were placed into rock wool blocks (75x75x65 mm) and transferred to a heated greenhouse. After 22 days, three rock wool blocks were placed on each rock wool slabs (1.000x150x75 mm) distributed on six benches. Thirty plants were placed on each bench. A complete randomised block experimental design was adopted with three replicates for each treatments. Each replicate consisted of 30 plants grown in six gullies (5-m long and 0.80-m wide) connected to an individual collecting tank (300 L). Each replicate consisted of 30 plants grown in the six rock wool slabs. The plants were grown vertically with a single stem at a density of three plants m⁻², and pollination was done by mechanical vibration of the flower clusters. Drip irrigation was performed two times per day for the first two weeks, then four times per day till the end of the experiment, according to the growth stage of tomato plant.

Sodium selenate was added once to the nutrient solution at a rate of 0 (control), 1, and 1.5 mg Se L⁻¹ two weeks after transplanting (April 1). Two benches, for a total of 60 plants, were allocated to each treatment.

The nutrient solution contained 14 mM N-NO₃, 1 mM P-H₂PO₄, 2.77 mM S-SO₄, 4 mM Ca, 8 mM K, 1.5 mM Mg, 1 µM Cu, 15 µM Fe, 10 µM Mn, 1 µM Mo, 5 µM Zn. The pH and electrical conductivity (EC) values were 5.6 and 2.29 dS m⁻¹ respectively, and were checked every 2 days. The nutrient solution was renewed every three weeks or whenever the EC was higher than 6 dS m⁻¹. Climatic parameters were continuously monitored by a weather station located inside the glasshouse. The minimum, maximum and mean air temperatures were 11.2, 39.4 and 22.6 °C, respectively. The relative humidity was 58.7 %. The daily mean and the cumulative solar radiation were 8.7 and 743 MJ m⁻² respectively.

Two different fruit collections were performed in order to evaluate the effects of Se enrichment on tomato fruit quality (first collection) and on postharvest ripening (second collection). Ten plants per treatment were randomly selected for each harvest.

Lateral shoots and the leaves below the bottom of most-truss with ripening fruit were regularly removed.

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3 Tomatoes were collected at commercial maturity when 50 % of fruit was at the red ripe stage (i.e.
4 71, 82 and 85 days after transplanting for the first, second and third truss, respectively) to evaluate
5 the effects of Se treatments on tomato quality. The red fruit were analyzed for Se content.
6 Qualitative analyses, oxidative stress markers analyses and antioxidant enzyme activity were carried
7 out on fruit of the first truss of 6 plants for each treatment.
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10 16 fruit from each of the first three trusses were harvested at colour break stage (i.e. 63, 74 and 85
11 days after transplanting for the first, second and third truss, respectively) to evaluate the effects of
12 Se on post-harvest ripening. Fruit of each truss from each treatment were kept separately and stored
13 at 21°C. The following parameters were periodically measured during storage: visual evaluation of
14 ripening, weight loss, fruit elasticity, ethylene production, respiration rate. In addition, non-
15 structural carbohydrates and pigments contents were measured only in fruit of the first truss. Fresh
16 (FW) and dry (DW) weights of red fruit were recorded at each harvest.
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24 **Fruit analyses**

25 *Se concentration*

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27 Total selenium concentration was determined in fruit samples oven-dried at 50 °C for 1 week and
28 then ground in a mortar. After digestion with nitric and perchloric acids and reduction by
29 hydrochloric acid, following Zasoski and Burau [22], the digests were analyzed by hydride
30 generation atomic absorption spectrophotometry (Varian VGA 77) [23].
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35 *Qualitative analysis*

36 Soluble solid content (SSC) was directly determined in the fruit juice using a digital refractometer
37 (model 53011, Turoni, Italy). Titratable acidity was determined using NaOH 0.1 N to the end point
38 of pH 8.2 and expressed as citric acidity percentage. The taste index and maturity were calculated
39 using the equation proposed by Navez et al. [24] starting from the Brix and the titratable acidity
40 values as indicated in Hernández Suárez et al. [25]: maturity = °Brix/acidity; taste index = (°Brix/20
41 × acidity) + acidity.
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48 *Malondialdehyde (MDA) assay*

49 For the measurement of malondialdehyde (MDA) content, fresh fruit material was extracted with
50 ethanol. The absorbance of reaction mixture was measured at 600, 532 and 440 nm, and the results
51 expressed as mmol of MDA equivalents g⁻¹ FW [26].
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56 *Antioxidant Enzymes activity*

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3 For the measurement of Ascorbate Peroxidase (APX; EC 1.11.1.11), catalase (CAT; EC 1.11.1.7)
4 and superoxide dismutase (SOD; EC 1.15.1.1) activity, 0.5 g of fresh material were extracted with
5 Na-P buffer 66 mM pH 7 + EDTA 1 mM. APX, CAT and SOD activities were evaluated as
6 described by Lyons et al (1999) [27] measuring the extract absorbance at 290, 240 and 560 nm,
7 respectively. Results were corrected for the relative extinction coefficient for APX and CAT, and
8 expressed as $\mu\text{mol ASA g}^{-1} \text{FW min}^{-1}$ and as $\mu\text{mol H}_2\text{O}_2 \text{g}^{-1} \text{FW min}^{-1}$, respectively. SOD activity
9 was expressed in unit (U).

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11 For the analysis of glutathione peroxidase (GSH-Px; EC 1.11.1.9) activity, fresh fruit samples were
12 extracted with Na-P buffer 66 mM pH 7. The absorbance of the assay mixture was measured at 412
13 nm and the results expressed as $\mu\text{moli GSH g}^{-1} \text{FW min}^{-1}$. For the calibration curve growing
14 concentrations of glutathione (GSH) were used [28].

21 22 *Visual evaluation*

23 The visual evaluation of fruit post-harvest ripening was performed 1, 4, 6, 8 and 10 days after
24 harvest for the first truss, 1, 3, 8, 10, 12 and 15 days after harvest for the second truss, and 3, 6, 10
25 and 12 days after harvest for the third truss. Fruit were classified by comparing the individual color
26 to the ripening stages reported in the “United States standards for grades of fresh tomatoes” [29].
27 The number of fruit at each ripening stage was recorded and a ranking was used to evaluate the
28 development of fruit colour.

29 At each ripening stage was assigned a growing score from breakers to red fruit [29]. The average
30 ripening stage of each set of fruit was calculated according to the formula:

$$31 \text{ ripening stage} = \frac{32 \text{ n.f. breakers} \times 2 + \text{ n.f. turning} \times 3 + \text{ n.f. pink} \times 4 + \text{ n.f. light red} \times 5 + \text{ n.f. red} \times 6}{33 \text{ n.f. total}}$$

34 35 *Weight loss*

36 6 fruit for each truss of each treatment were weighted at harvest, and then every 3 days during
37 storage at 21°C and 70-75% RH for 15 days.

38 39 *Fruit elasticity*

40 A durometer was used to measure fruit elasticity (Non-Destructive Penetrometer, Model 53210, TR
41 Turoni srl, Italy) 0, 4, 6, 8, 11 and 13 days after harvest for the first truss, 0, 2, 7, 9, 11 and 14 days
42 after harvest for the second truss, and 0, 3, 6, 10 and 12 days after harvest for the third truss. Six
43 fruit for each truss of all treatments were pressed at the opposite sides of their exponential axes, and
44 results were expressed as shore.

Ethylene production and respiration rate

Ethylene production and respiration rate were measured 0, 3, 5, 7 and 9 days after harvest in fruit of the first truss, 0, 3, 5, 7, 9 and 11 days after harvest in the fruit of the second and third truss. During this period fruit were stored at 21°C. Four fruit for each truss of each treatment were placed in four 85 mL glass tubes (Pyrex, France) and closed with holed plastic screw caps supplied with caoutchouc rubber septa. Analysis was performed according to Malorgio et al. [7].

Non-structural carbohydrate content

Carbohydrates were extracted from ground samples as previously reported [30] and quantified using a Agilent 1200 series HPLC binary pump system (Agilent, Berks., UK) coupled with either an Agilent refractive index detector (RID) G1312A. Chromatography was carried out with a Phenomenex Rezex RCM monosaccharide Ca²⁺ (8%) 300x7.8 mm column fitted with a Phenomenex Carbo Ca²⁺ 4x3 mm guard column. The concentrations of glucose, fructose and sucrose were calculated against a calibration curve prepared with authentic standards (Sigma-Aldrich, Dorset, UK) and the results were expressed on a fresh weight basis.

Pigments content

Pigments were extracted from 100 mg ground freeze-dried tomato fruit samples as previously reported [31] and quantified using an Agilent 1200 series HPLC binary pump system (Agilent, Berks., UK) coupled with either an Diode-Array Detection (DAD). Chromatography was carried out with a reverse phase column 250x4 mm i.d., 5 µm particle size. The concentrations of lycopene, β-carotene and chlorophylls were calculated by comparison against an external calibration curve prepared with authentic standards (Sigma-Aldrich, Dorset, UK) and the results expressed on a fresh weight basis.

Statistical analysis

Data were subjected to one-way analysis of variance (ANOVA) with Se treatments as variables. The means were separated using the least significance difference (LSD) (P<0.05). Statistical analysis was performed using Statgraphics Plus 5.1.

RESULTS AND DISCUSSION

Effects of selenium on tomato fruit quality at harvest

The addition of Se to the nutrient solution determined a significantly dose-dependent increase of Se concentration in tomato fruit of all trusses, and the average Se concentration decreased from the

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3 first to the second and third trusses (Table 1). The fruit Se content was in the range of 0.94-2.76 mg
4 kg^{-1} DW when plants were treated with 1 mg Se L^{-1} , and 2.08-3.54 mg kg^{-1} DW when plants were
5 added with 1.5 mg Se L^{-1} . These values are approximately three times lower than those reported by
6 Pezzarossa et al. [12] which found a fruit Se concentration of 10.33 mg kg^{-1} DW in plants added
7 with 1 mg Se L^{-1} as sodium selenate. These differences could be ascribed to the different growing
8 period that in the experiment conducted by Pezzarossa et al. [12] lasted from the beginning of May
9 to the end of July, whereas in the current experiment it lasted from February to June.

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14 Foliar application of 1 mg Se L^{-1} to tomato plants prior to fruit development resulted in an increased
15 fruit selenium content of 0.6 mg Se kg^{-1} [32]. This content is much lower compared to what reported
16 in the current experiment suggesting that the addition of Se to the nutrient solution is likely more
17 effective than foliar application to produce Se-enriched tomatoes.

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19
20 In this study the addition of selenium to the nutrient solution did not affect either plant yield or the
21 qualitative parameters of tomato, i.e. fruit dry matter content, soluble solid content, titratable
22 acidity, maturity and taste index (Table 2). This is in agreement with previous studies conducted on
23 tomato plants grown under similar experimental conditions [11, 12]. The herein reported mean
24 value of taste index was about 1, indicating that the tomatoes were of good quality. Tomatoes are
25 considered as having little taste when the taste index is lower than 0.7 [24].

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30 Ascorbate peroxidase (APX) and Catalase (CAT) activities were lower in red fruit of Se-enriched
31 plants, 1.9 and 1.5 fold respectively, compared to control fruit. Instead, a significantly higher
32 superoxide dismutase (SOD) activity was detected in fruit of treated plants. No differences were
33 detected in glutathione peroxidase (GSH-Px) activity between control and treated plants (Table 3).
34 GPX activity follows the ripening trend and generally decreases during ripening. The fact that it
35 remained steady in selenium treated fruit, which have showed a delay in ripening, might represent
36 somehow a rise. Thus, selenium might have induced a reduction of APX and CAT activity because
37 GPX increased.

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43 As far as the increase of SOD activity is concerned, plant might have perceived the increase of
44 selenium content as a mild stress. Selenium may increase the antioxidant enzyme activity of SOD
45 and GSH-Px [10] and decrease various reactive oxygen species, such as H_2O_2 and superoxide,
46 during fruit storage [8]. Selenium has proven effective in increasing the oxidative status and
47 improving the content of reduced glutathione and ascorbate of tomato fruit, thus delaying fruit
48 ripening [8, 13].

49 50 51 52 53 54 **Effects of selenium on post-harvest ripening**

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3 Delayed post-harvest ripening was detected in tomatoes harvested from Se-treated plants following
4 the visual evaluation of colour development (Fig. 1). The timing of the delay in fruit ripening varied
5 across trusses, and was more noticeable in fruit derived from the second and third truss compared to
6 the first. This delay was also confirmed by physiological parameters. Indeed, the addition of
7 selenium to the nutrient solution was effective in postponing (2 days) the ethylene climacteric peak
8 in fruit from all trusses (Fig. 2), and in general resulted in a reduced respiration rate at the
9 climacteric peak (Fig. 3), as previously reported [12]. Zhu et al. [8] found that, in tomato fruit, Se
10 suppressed the transcription of *ACO1*, *ACS2* and *ACS4*, genes involved in ethylene biosynthesis,
11 with beneficial effects in terms of prolonged commercial life. The effects of Se on the postharvest
12 ripening were also evident by data on fruit elasticity (Table 4). Fruit elasticity is inversely related to
13 fruit softening. Thus, the higher values of fruit elasticity detected in treated fruit compared to
14 control may indicate that the ripening-related loss of firmness was indeed retarded by Se. A similar
15 result was reported by Pezzarossa et al. [15] in flesh firmness of Se-enriched peaches.

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17 Interestingly, the addition of selenium to the nutrient solution, either at 1 and 1.5 mg Se L⁻¹, reduced
18 the fruit weight loss during the post-harvest ripening, especially after 9 and 12 days of storage
19 (Figure 4). The reduced weight loss could be related to delayed ripening or be the result of Se-
20 induced changes in the cuticle thickness and composition. Golob et al. [33] reported that wheat
21 plants treated with selenium had thicker cuticles for both the upper and lower leaf surface. Thicker
22 cuticles represent a barrier to the water movement from inside the tissue/organ to the external
23 atmosphere.

24
25 Se-enriched fruit showed also a delayed accumulation of reducing sugars (glucose and fructose)
26 during the postharvest phases (Fig. 5). This seems to indicate that Se may affect the carbohydrate
27 metabolism (sugar interconversion, starch residues degradation) in the early stages of ripening when
28 also ethylene biosynthesis is affected (Fig 2).

29
30 As above reported, the visual evaluation of fruit after harvest indicated a different colour
31 development in Se-treated fruit (Fig. 1). Indeed, the analysis of pigments content confirmed this
32 data (Fig. 6): lycopene and beta-carotene accumulations were delayed in Se-treated fruit through
33 postharvest, even if no differences were detected between Se-treated and control fruit at the end of
34 the experiment (Fig. 6 A and B). In addition, chlorophylls degradation rates were slower in Se-
35 enriched fruit compared to control (Fig. 6 C and D).

36
37 In the current experiment, the activity of antioxidant enzymes and the lipid peroxidation level
38 detected in red fruit were in agreement with the delayed ripening of Se-treated fruit. During
39 ripening, the antioxidant capacity decreases, and the lipid peroxidation consistently increases [34].
40 The antioxidant enzymes behave differently during fruit ripening: SOD activity decreases whereas
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CAT [35] and APX [36] activity increase. Therefore, a lower lipid peroxidation, CAT and APX activities and a higher SOD activity, as detected in Se-treated fruit, may indicate a delay in fruit ripening that is not possible to discern only from the fruit color, since from the outside all fruit were at the red ripe stage. Se has an antioxidant function as a cofactor of glutathione peroxidase [16]. Since in the present experiment differences in GSH-Px activity between treatments were not detected, it can be argued that Se could affect the oxidative status of fruit also in others ways.

The reduction in respiration rate has been already detected in tomato fruit treated with Se [8], and can induce a delay of fruit ripening, as found in banana by Srivastava and Dwivedi [37]. A lower respiration during storage has a positive effect in improving post-harvest shelf-life of fruit.

The evaluation of tomato fruit ripening on the basis of the fruit color showed a slower color change in fruit of plants treated with Se compared to the control. This was associated with a delayed lycopene and b-carotene synthesis and chlorophylls degradation during postharvest. This could be the result of a delayed ripening, since lycopene and b-carotene concentrations increase, whereas the concentration of chlorophylls decreases during tomato ripening [38, 39].

As the final issue, the effect of the consumption of Se-enriched tomatoes on health was taken into consideration. Since the estimated values for Se daily intake are 60 µg for women and 70 µg for men [40], the consumption of 100 g of the Se-enriched tomatoes obtained in this experiment, with an average total Se content of 23.7 µg, could provide a good Se diet supplementation. The consumption of 200 g of fresh Se-enriched tomato could provide the recommended daily intake of Se. On the basis of the results obtained in the present experiment, and in accordance to previous studies [12], the hydroponic cultivation of tomato plants using a nutrient solution enriched in Se could represent a viable way to produce Se-enriched tomatoes.

Conclusions

The results of the present experiment support the hypothesis that Se affects specific ripening-related processes and may have a positive effect in delaying fruit ripening, thus positively affecting the postharvest shelf life of tomatoes. Selenium-treated fruit showed in fact lower respiration rate and ethylene production that slowed the postharvest ripening process. This was associated with a delayed lycopene and b-carotene synthesis, and chlorophylls degradation. The consumption of Se-enriched fruit may contribute to the daily supplementation of selenium, thus improving human health. Further studies are needed to fully understand how Se affects the molecular and biochemical processes involved in fruit ripening and post-harvest storage, in order to optimize the Se-enrichment technique and the combination with post-harvest storage conditions.

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Table 1

Se concentration in red fruit of tomato plants (cv. Red Bunch) grown in nutrient solution supplied with 0, 1 and 1.5 mg Se L⁻¹.

Se (mg L ⁻¹)	Se concentration (mg kg ⁻¹ DW)			Se concentration (µg 100 g ⁻¹ FW)		
	Truss			Truss		
	1 st	2 nd	3 rd	1 st	2 nd	3 rd
0	0.00 ± 0 c	0.00 ± 0 c	0.00 ± 0 c	0.0 ± 0 c	0.0 ± 0 c	0.0 ± 0 c
1	2.76 ± 0.18b	1.82 ± 0.02b	0.94 ± 0.05b	22.0 ± 1.8 b	14.6 ± 0.3 b	7.5 ± 0.5 b
1.5	3.54 ± 0.07a	3.14 ± 0.02a	2.08 ± 0.09a	28.2 ± 1.6 a	25.7 ± 1.6 a	17.0 ± 1.3 a
	Significance					
Se (mg L ⁻¹)	***	***	***	***	***	***

Values followed by different letters in the same column differ significantly at 5% level by the LSD test. Significance level: *** P ≤ 0.001; ** P ≤ 0.01; * P ≤ 0.05; ns = not significant.

Table 2

Yield and qualitative characteristics of red fruit of tomato plants (cv. Red Bunch) grown in nutrient solution supplied with 0, 1 and 1.5 mg Se L⁻¹. Data are the means of 3 replicates.

Parameters		Se added (mg L ⁻¹)			Significance
		0	1	1.5	
Total yield	g FW m ⁻²	2471 ± 310	2517 ± 290	2522 ± 204	ns
Commercial yield	g FW m ⁻²	1768 ± 155	1739 ± 124	1753 ± 139	ns
Solid content	%	6.78 ± 0.80	6.72 ± 0.72	6.61 ± 0.53	ns
Solid soluble content (SSC)	°Brix	8.30 ± 0.74	8.11 ± 0.86	8.17 ± 0.79	ns
Titrate acidity	g citric acid 100 ml ⁻¹	0.70 ± 0.06	0.69 ± 0.04	0.71 ± 0.08	ns
Maturity index		12	11.8	11.5	ns
Taste index		0.98	0.97	1.00	ns

Significance at 5% level by the LSD test. ns = not significant.

Table 3

Activity of antioxidant enzymes [Ascorbate peroxidase (APX), Catalase (CAT), Superoxide dismutase (SOD), Glutathione peroxidase (GSH-Px)] and lipid peroxidation expressed as malondialdehyde (MDA) content in red fruit of the first truss of tomato plants (cv. Red Bunch) grown in nutrient solution supplied with 0, 1 and 1.5 mg Se L⁻¹.

Se added mg L ⁻¹	APX activity μmoli ASA g ⁻¹ FW min ⁻¹	CAT activity μmol H ₂ O ₂ g ⁻¹ FW min ⁻¹	SOD activity SOD Units g ⁻¹ FW	GSH-Px activity μmoli GSH g ⁻¹ FW min ⁻¹	MDA content mmol MDA EQ g ⁻¹ FW
0	0.634±0.090 a	0.412±0.037 a	59.4±0.5 c	0.094±0.004	156±6 a
1	0.316±0.023 b	0.270±0.026 b	67.1±1.8 b	0.090±0.008	138±4 b
1.5	0.348±0.040 b	0.279±0.016 b	83.6±1.6 a	0.089±0.009	126±4 b
Significance	**	**	***	ns	*

Values followed by different letters in the same column differ significantly at 5% level by the LSD test. Significance level: *** P ≤ 0.001; ** P ≤ 0.01; * P ≤ 0.05; ns = not significant.

Table 4

Firmness during post-harvest ripening of fruit from the first, second and third truss of tomato plants (cv Red Bunch) grown in nutrient solution supplied with 0, 1 and 1.5 mg Se L⁻¹.

Se (mg L ⁻¹)	Firmness (Shore %)					
	Days after harvest					
	First truss					
	0	4	6	8	11	13
0	86.4 ± 0.7	71.9 ± 0.1 c	60.3 ± 0.7 c	55.8 ± 0.5 b	51.0 ± 0.6 b	45.2 ± 0.4 b
1	84.8 ± 0.5	76.8 ± 0.9 b	63.8 ± 0.6 b	57.5 ± 0.5 ab	52.1 ± 0.6 ab	50.4 ± 0.4 a
1.5	86.0 ± 0.5	79.3 ± 0.8 a	66.1 ± 0.6 a	58.6 ± 0.7 a	53.4 ± 0.1 a	50.9 ± 0.4 a
Significance	ns	***	**	*	*	***
	Second truss					
	Days after harvest					
	Second truss					
	0	2	7	9	11	14
0	90.6 ± 0.9	82.7 ± 0.8 b	67.8 ± 2.1 b	57.6 ± 0.7 b	53.4 ± 1.8 b	49.2 ± 0.8 b
1	92.0 ± 0.2	88.5 ± 0.4 a	78.0 ± 2.5 ab	67.7 ± 0.5 a	57.4 ± 2.1 ab	56.2 ± 2.2 a
1.5	89.9 ± 0.9	90.7 ± 0.9 a	81.4 ± 4.3 a	71.9 ± 4.1 a	64.2 ± 2.0 a	56.5 ± 1.4 a
Significance	ns	***	*	*	*	*
	Third truss					
	Days after harvest					
	Third truss					
	0	3	6	10	12	
0	94.1 ± 0.8	78.3 ± 0.4 c	69.6 ± 0.7 b	53.6 ± 0.7 c	50.6 ± 0.1 b	
1	95.0 ± 0.5	82.2 ± 0.8 b	75.1 ± 0.3 a	57.3 ± 1.2 b	53.9 ± 1.2 ab	
1.5	94.9 ± 0.7	86.9 ± 1.3 a	79.0 ± 2.0 a	64.8 ± 1.1 a	58.0 ± 1.2 a	
Significance	ns	**	**	***	**	

Values followed by different letters in the same column differ significantly at 5% level by the LSD test. Significance level: *** P ≤ 0.001; ** P ≤ 0.01; * P ≤ 0.05; ns = not significant.

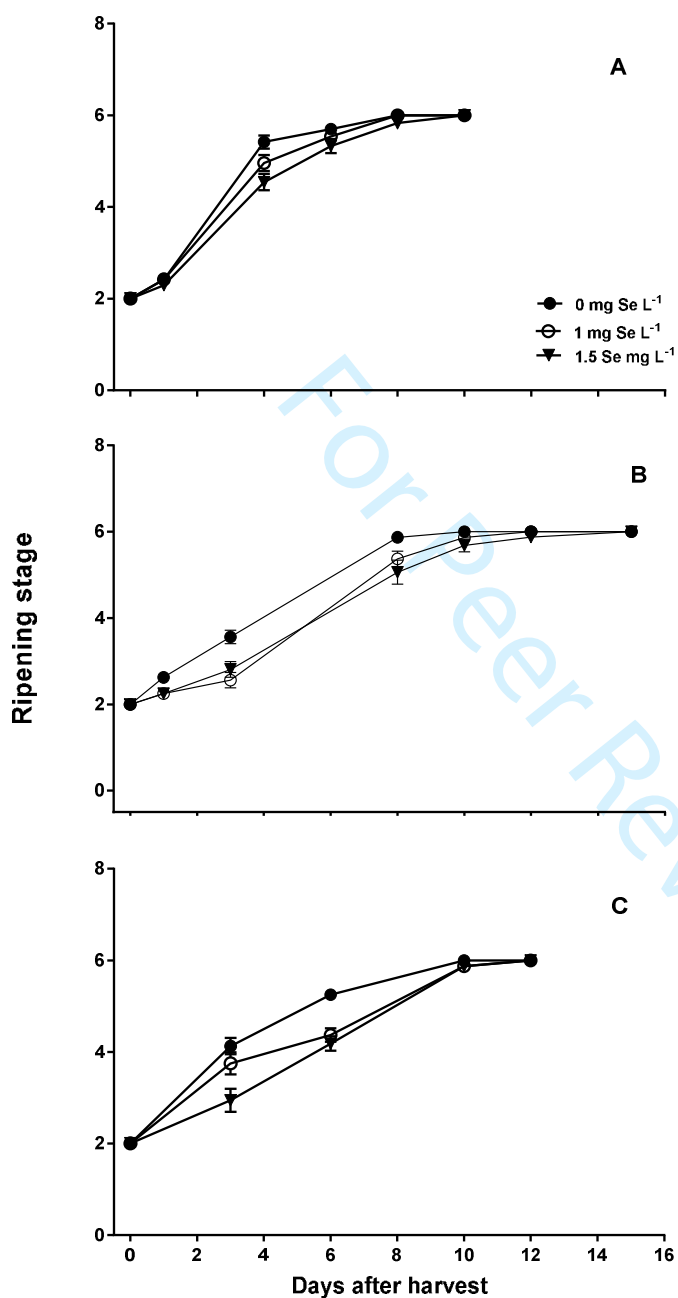


Figure 1. Post-harvest ripening process in fruit of the first (A), second (B) and third (C) truss of tomato plants (cv. Red Bunch) grown in nutrient solution supplied with 0, 1 and 1.5 mg Se L⁻¹, on the basis of visual color appearance. Values are means with standard errors (n=4).

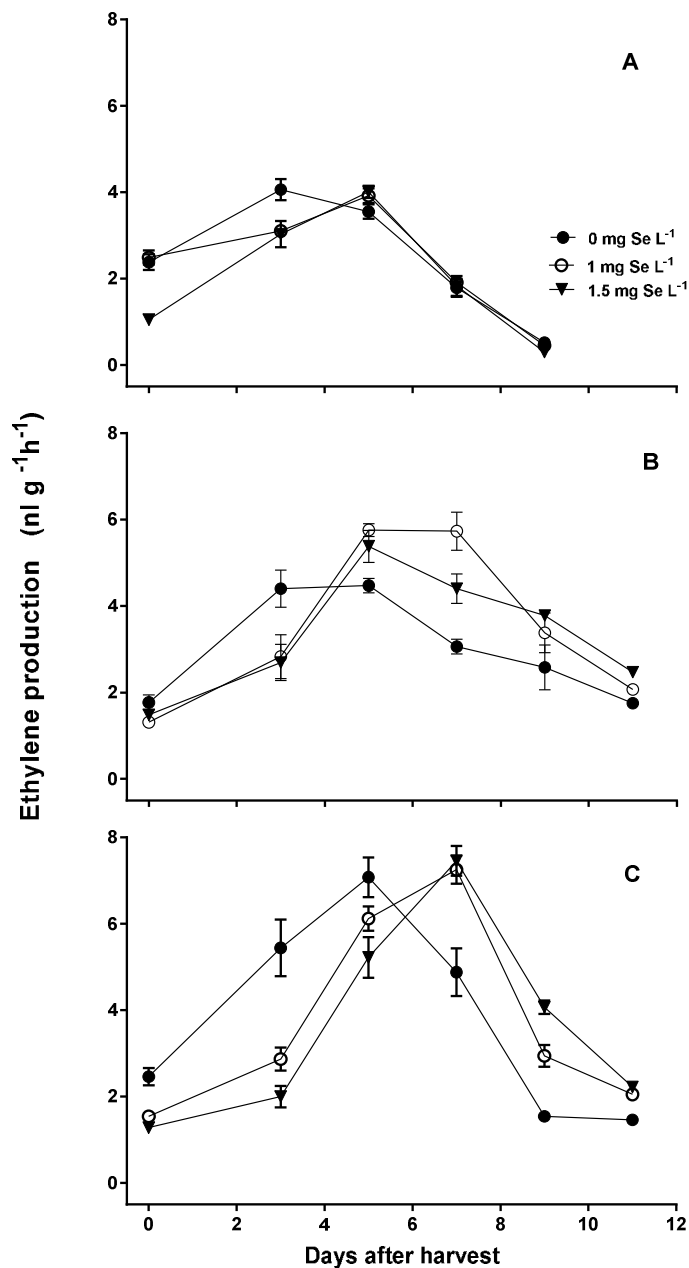


Figure 2. Ethylene production during post-harvest ripening in fruit of the first (A), second (B) and third (C) truss in tomato plants (cv. Red Bunch) grown in nutrient solution supplied with 0, 1 and 1.5 mg Se L⁻¹. Values are means with standard errors (n=4).

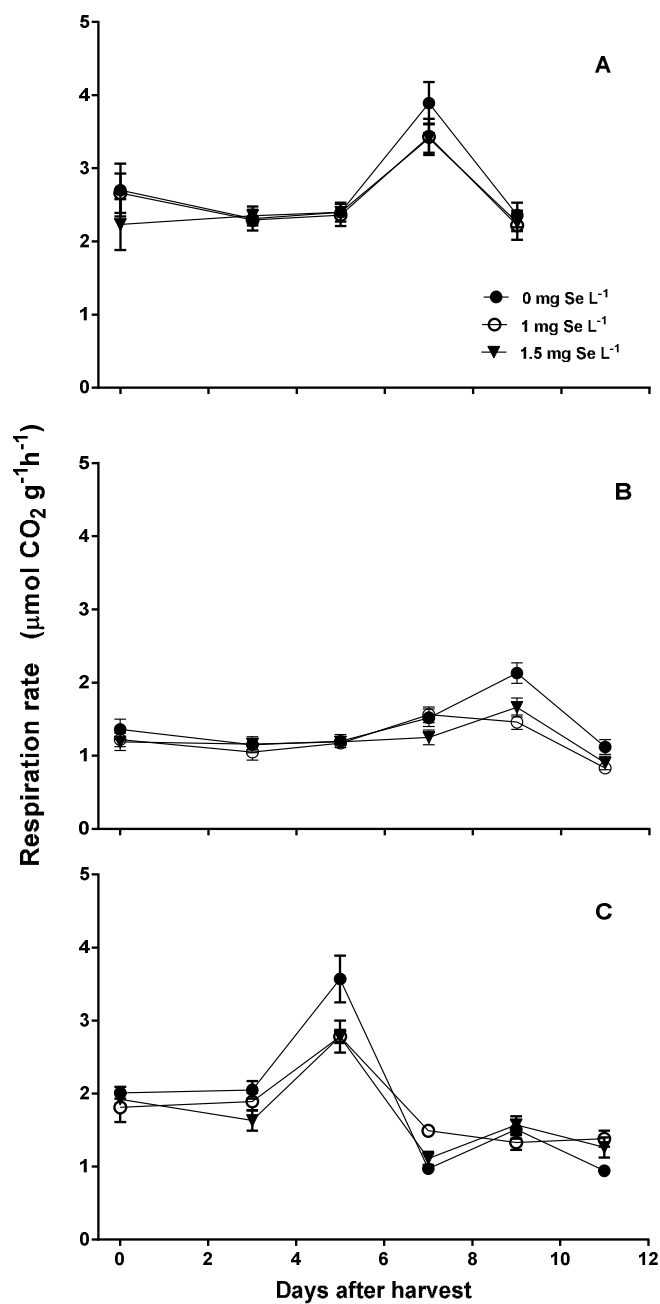


Figure 3. Respiration rate during post-harvest ripening in fruit of first (A), second (B) and third (C) truss of tomato plants (cv. Red Bunch) subjected to different Se treatments. Values are means with standard errors (n=4).

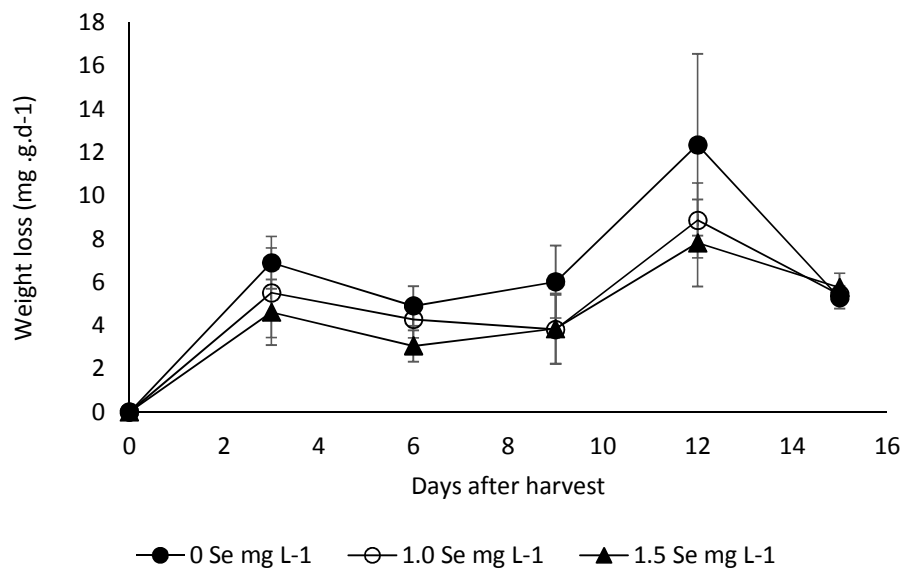


Figure 4. Post-harvest weight loss, expressed as mg/g per day, in fruit of tomato plants (cv. Red Bunch) grown in nutrient solution supplied with 0, 1 and 1.5 mg Se L⁻¹ and stored for 15 days. Values are means of the three trusses with standard errors (n=4).

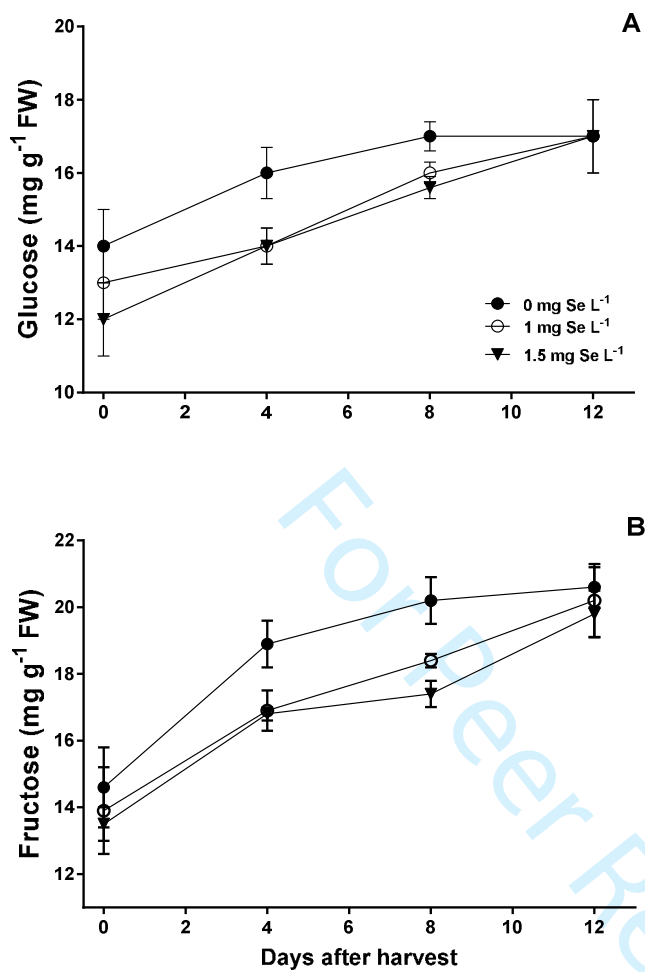


Figure 5. Non-structural carbohydrates, glucose (A) and fructose (B), concentration in fruit of tomato plants (cv. Red Bunch) subjected to different Se treatments. Values are means with standard errors (n=4).

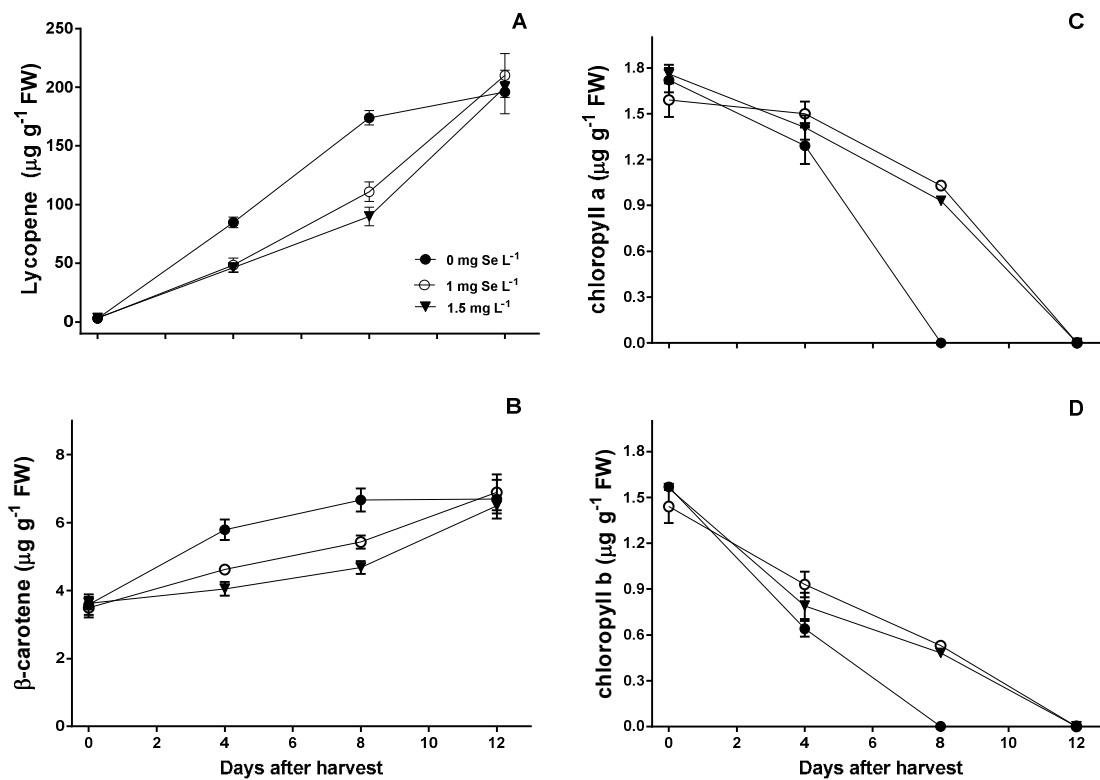


Figure 6. Lycopene (A), β -carotene (B), chlorophyll a (C) and chlorophyll b (D) concentration in fruit of tomato plants (cv. Red Bunch) subjected to different Se treatments during post-harvest. Values are means with standard errors (n=4).