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The effect of different levels of subsoil nitrogen fertilization on Murcott mandarin trees

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Abstract: This study investigates the effects nitrogen application ways (surface - subsurface fertilization) on the growth, yield, and fruit quality of ten-year-old Murcott mandarin trees grafted on sour orange rootstock under sandy loamy soil conditions in Belbeis district, Sharkia governorate, Egypt. Conducted over two growing seasons (2021/2022 and 2022/2023), the research evaluated the impact of different nitrogen doses (600 g, 800 g, and 1000 g) and application methods (surface vs. subsurface) on tree growth parameters, nutrient content, fruit yield, and quality. Results indicated that 1000 g N combined with subsurface application (S.S.A.) significantly enhanced tree height, canopy volume, and fruit yield, with the highest tree yield (77.78 kg and 99.78 kg) and hypothetical yield per feddan (16.34 tons and 20.95 tons). Subsurface application improved nitrogen use efficiency, reducing nitrogen losses through leaching and volatilization. The study highlights the importance of balancing nitrogen application methods to optimize productivity and fruit quality while minimizing environmental impacts. These findings align with global efforts to promote sustainable citrus production through precision agriculture, as emphasized by FAO (2022). The research concludes that subsurface nitrogen fertilization, when combined with appropriate nitrogen doses, offers a viable strategy for enhancing Murcott mandarin production, contributing to food security and environmental sustainability.

Key words: Murcott mandarin, subsurface fertilization, nitrogen use efficiency, nitrogen application ways, fruit quality, sustainable agriculture.

1. Introduction

Citrus fruits are among the most widely cultivated and economically significant fruit crops globally. Their importance stems from their nutritional value, economic contribution, and role in global food security. Citrus fruits are rich in essential nutrients such as vitamin C, flavonoids, and dietary fiber, making them a vital component of a healthy diet (**Liu *et al.*, 2020**). Beyond their nutritional benefits, citrus cultivation supports millions of livelihoods worldwide, particularly in developing countries, where it serves as a primary source of income for smallholder farmers (**FAO, 2021**).

The Murcott mandarin, also known as the Honey tangerine, is a popular citrus variety prized for its sweet flavor, easy-to-peel skin, and high market demand. Originating as a hybrid between a mandarin and a sweet orange, the Murcott mandarin has become a significant crop in global citrus production, particularly in regions with suitable climates such as the Mediterranean, the United States, and parts of Asia (**Alquézar *et al.*, 2020**). Its cultivation has grown substantially due to its adaptability to various agro-climatic conditions and its ability to meet consumer preferences for high-quality citrus fruits. Global production of Murcott mandarin has seen a steady increase, driven by rising demand for fresh citrus fruits and processed products like juices and preserves. According to **FAO (2022),** global citrus production, including mandarin, reached over 150 million metric tons in 2021, with Murcott varieties contributing significantly to this output. Countries such as Spain, the United States (particularly Florida and California), and Morocco are among the leading producers of Murcott mandarin, leveraging advanced agricultural practices and efficient supply chains to dominate international markets (**Talon and Gmitter, 2021).** The cultivation of Murcott mandarins offers numerous economic benefits to farmers, including higher profitability compared to other citrus varieties due to their premium market value.

One of the key players in modern industrial agriculture is fertilizer derived from nitrogen fixation, responsible in some cases for up to 75% of crop yield increases. In addition, nitrogen is an essential element for all amino acids in plant structures which are the building blocks of plant proteins, important in the growth and development of vital plant tissues and cells like the cell membranes and chlorophyll. Moreover, N is a component of nucleic acid that forms DNA a genetic material significant in the transfer of certain crop traits and characteristics that aid in plant survival. It also helps hold the genetic code in the plant nucleus. According to **Parameshwar and Srivastava, 2013; Srivastava and Singh, 2016; Abo-Eid, 2017 and Mahmoud *et al.*, 2019** studies on nitrogen fertilization for citrus trees included various rates between 400 and 1500gN / tree / year. The general trend in those studies was that increasing nitrogen fertilization rate caused promotions in both vegetative growth and fruiting of citrus trees.

Large amounts of nitrogen are depleted annually from the soil as a result of heavy crop productivity and pruning of shoots and leaves. Such huge reduction in soil nitrogen content must be compensated annually by adding nitrogen fertilizers to maintain the high yield and good quality of citrus crops. It is very important to use proper nitrogen level that resulted in balancing growth and fruiting status. Thereby, adjusting nitrogen nutrition of citrus considered an important and limited factor for improving production and fruit quality **Wassel *et al.* (2022)**.

However, the efficiency of nitrogen fertilization is often compromised due to losses through volatilization, leaching, and denitrification, which not only reduce crop yields but also contribute to environmental pollution. Subsurface nitrogen fertilization has emerged as a promising strategy to enhance nitrogen use efficiency (NUE), minimize environmental impacts, and improve crop performance. This method involves the direct application of nitrogen fertilizers below the soil surface, ensuring closer proximity to the root zone and reducing exposure to processes that lead to nitrogen loss.

Recent studies have highlighted the potential of subsurface nitrogen fertilization to address the challenges associated with conventional surface application. For instance, research by **Liu *et al.* (2022)** demonstrated that subsurface application of urea significantly reduced ammonia volatilization by up to 40% compared to surface broadcasting, while improving nitrogen uptake in wheat crops. Similarly, **Zhang *et al.* (2021)** reported that subsurface fertigation ways enhanced nitrogen retention in the root zone, leading to a 25% increase in crop yield compared to traditional methods. These findings underscore the importance of adopting advanced fertilization techniques to meet the growing demand for sustainable agricultural practices.

The environmental benefits of subsurface nitrogen fertilization are also well-documented. Furthermore, **Wang *et al.* (2020)** emphasized its role in lowering greenhouse gas emissions, particularly nitrous oxide (N_2O), which is a potent contributor to climate change. By improving nitrogen retention and reducing losses, subsurface fertilization aligns with global efforts to promote sustainable intensification of agriculture.

The objective of this research was to optimize nitrogen fertilization and enhance its efficiency by evaluating the effects of different nitrogen application rates (600, 800 and 1000 g per tree) through subsurface fertilization compared to conventional surface application on Murcott mandarin trees grafted on sour orange (*Citrus aurantium*) rootstock. The study focuses on ten-year-old trees to assess the impact of these fertilization methods on tree growth, fruit yield and nitrogen use efficiency (NUE). By comparing subsurface and surface nitrogen application, this research aims to identify the most effective fertilization strategy to improve productivity while minimizing environmental losses such as nitrogen leaching and volatilization.

2. Material and Methods

The present study has been carried out to study the effect of nitrogen fertilization doses [600, 800 (control) and 1000 g per tree] with different application ways [surface (control) and subsurface] on some vegetative growth parameters, flowering, leaf chemical content, yield and fruit quality of Murcott mandarin trees (*Citrus sinensis* L. Osbeck. X *Citrus reticulata Blanco*) during two successive seasons (2021/2022, 2022/2023) budded on sour orange (*Citrus aurantium* L.) rootstock. Murcott mandarin trees were 10 years old and planting distance was at 4×5 meter, in sandy loam soil under drip irrigation system by Nile River water in private orchard at Belbeis district, Sharkia governorate, Egypt.

Soil samples were taken from three different depths of the experimental area at 0-30, 30-60 and 60-90 cm from the soil surface for soil physical and chemical analysis which were carried out according to **Black *et al.* (1965) and Wilde *et al.* (1985).** Soil physical and chemical properties are presented in tables 1a, 1b and 1c.

Table (1a). Soil physical properties

Depth cm	Organic matter %	Particle size distribution				
		Sand %	Silt %	Clay %	Soil texture	Field capacity %
0-90	0.04	68.4	28.4	3.2	Sandy loam	22.1

Table (1b). Soil chemical properties

Depth cm	pH	$CaCO_3$ %	E.C dsm^{-1}	Cations (meq/l)				Anions (meq/l)			
				Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3^{-}	Cl^{-}	CO_3^{-}	SO_4^{--}
0-30	7.9	5.41	0.746	3.81	1.1	2.19	0.36	2.60	0.9	-	3.96
30-60	7.9	5.62	0.687	3.22	1.3	2.03	0.32	2.02	0.8	-	4.05
60-90	8.0	5.73	0.757	3.04	1.1	3.05	0.38	1.98	0.8	-	4.79

Table (1c). Macro and micro nutrients of experimental soil samples content at different depths

Depth cm	N%	P%	K%	Ca%	Fe ppm	Mn ppm	Zn ppm
0-30	1.73	3.60	13.00	3.38	7.89	2.36	1.97
30-60	1.62	3.60	11.00	3.01	7.08	2.26	1.86
60-90	1.53	3.20	10.15	2.95	6.12	2.27	1.53

The study comprised three nitrogen fertilization doses (600, 800 and 1000 g N per tree/year as ammonium nitrate 33.5%) and different application ways (surface and subsurface). The experiment was arranged in a factorial designed contained. Moreover, the nitrogen quota was added annually to each tree according to the specific treatment for it in 10 batches starting from February to November by surface application by spreading the fertilizer under the drops, or by adding it under the soil surface by scraping 5-10 cm from the soil surface under the drippers and adding nitrogen fertilizer in the form of ammonium nitrate, then covering it with soil again. As for the rest of the fertilizers, they were added with drip irrigation according to the recommendations of the Egyptian Ministry of Agriculture.

3 N levels X 2 application ways = 6 treatments. Each treatment had three replicates and 2 tree for each replicate, in a randomize complete block design.

The following parameters were used to evaluate the tested treatments

Tree and shoot vigor

The tree height, tree diameter, tree circumference, tree canopy volume, branch length and branch thickness were counted in each season. The tree canopy volume was calculated according to the following equation: canopy volume (m^3) =1.33 x 0.5 x circumference (m) x 3.14 x 0.5 x height (m) (**Turell and Austin, 1965**).

Leaf photosynthetic pigments contents

The photosynthetic pigments contents (i.e., chlorophyll a, chlorophyll b and carotenes) were determined in fresh samples from each replicate of leaf blades collected in Aug., where, acetone 80% extract was prepared for photosynthetic pigments determination by scanning spectrophotometer model 635 according to **Moran** and **Porath (1980)**.

Leaf water content and dry matter percentage

Samples of mature leaves of the spring growth cycle were collected in August from non-flushing and non-fruiting shoots; 30 leaves were sampled / replicate. The sampled leaves were cleaned and fresh weighed, then dried in an oven under 70 C° up to a constant dry weight; the leaf dry weight was recorded and the dry matter percentage was calculated.

Leaf mineral content

At the end of the growing season (September), 30 mature leaves sample have been taken from the previous spring cycle (i.e., the leaves were more than 5 months old) in each direction of the tree that were labeled in March. A sample of leaves were picked from non-flushing and non-fruiting shoots. Leaf samples of each treatment were cleaned then dried to a constant weight in an electric oven at 70^0C for, and finally leaf dried materials were determined according to **Chapman and Pratt (1961).** The percentage of nitrogen content was determined by Micro-Kjeldahl according to **Naguib (1969).** Phosphorus percentage was determined calorimetrically by ascorbic acid reduction method according to **A.O.A.C. (1990).** Potassium percentage was determined by using flame photometer according to **Brown** and **Lilliland (1964)**. In addition, calcium (%), magnesium (%), iron (ppm), zinc (ppm) and manganese (ppm) were determined by the Atomic Absorption apparatus (**Jackson, 1967**).

Fruit quality

Sample contained 25 fruits were picked at random from each replicate in each season to determine the physical and chemical properties. The average fruit weight (g), fruit diameter (cm), fruit height (cm), fruit shape index (height /diameter) and fruit Juice volume (cm^3). On the other hand, the percentage of total soluble solids in fruit juice was determined by hand refractometer (%) and total acid as g citric acid / 100 ml of juice was determined by titration against 0.1 N sodium hydroxide in presence of phenolephthalin as an indicator according to **A.O.A.C (1990)**, the TSS /acid ratio was calculated**.** Ascorbic acid content as mg/100 ml juice was determined by using 2.6 dichlorophenol indo-phenol according to **A.O.A.C. (1990).**

Flowering and fruit set parameters, Yield and Nitrogen use efficiency

The number of flowers per branch were recorded at full bloom and number of fruit set percentage were counted and recorded. Finally, fruit set percentage was calculated.

Fruit set (%) = number of set fruitlet × 100 / number of total flowers.

At the time of harvest for each season, the number of harvested fruits per tree were recorded, the total weight of all fruits per tree (the yield/tree in kg) was determined and recorded and the hypothetic yield/ fed. then nitrogen use efficiency [on basis of 210 trees/fed. (4x5m apart)] was calculated.

Nitrogen use efficiency = yield kg per feddan / N dose kg per feddan according to **Cassman *et al.* (2002).**

Statistical analysis

The experimental design was factorial within a randomized complete block design. Data obtained throughout this study were statistically analyzed using the analysis of variance method as reported by **(Snedecor and Cochran, 1980)**.and the differences between means were differentiated by using Duncan's range test at 5% to compare means **(Duncan, 1955)**.

3. Results and Discussion

Results presented in **Table 2** demonstrate the effects of nitrogen fertilization doses and application methods (surface and subsurface) on the growth parameters of Murcott mandarin trees over two seasons (2021/2022 and 2022/2023). The data reveal of significant variations in growth parameters based on nitrogen doses and application methods.

Tree height

Tree height increased with higher nitrogen doses, as the 1000 g N treatment resulted in the highest trees (2.76 m in the first season and 2.87 m in the second season), followed by 800 g N and 600 g N. Moreover, the subsurface application (S.S.A.) consistently produced higher trees compared to surface application (S.A.). lastly, the 1000 g N × S.S.A. treatment recorded the highest values (2.79 m and 2.92 m in the first and second seasons, respectively). This was true in both seasons.

Tree diameter and circumference

Similar trends were observed for tree diameter and circumference. The 1000 g N treatment resulted in the largest diameter (3.32 m and 3.43 m) and circumference (10.32 m and 10.67 m) in both seasons. Subsurface application again outperformed surface application, with the 1000 g N × S.S.A. treatment showing the highest values.

Canopy volume

Canopy volume was significantly influenced by nitrogen dose and application method. The 1000 g N treatment produced the largest canopy volume (29.73 m^3 and 32.00 m^3), while subsurface application further enhanced this parameter. The 1000 g N × S.S.A. treatment yielded the highest canopy volumes (30.56 m^3 and 32.94 m^3) in both seasons.

Branch length and thickness

Branch length and thickness also increased with higher nitrogen doses. The 1000 g N treatment resulted in the longest branches (49.31 cm and 51.64 cm) and the thickest branches (7.76 mm and 8.14 mm). Subsurface application again proved to be superior, with the 1000 g N × S.S.A. treatment showing the highest values for branch length (52.48 cm and 55.23 cm) and thickness (8.07 mm and 8.50 mm).

The findings of this study are consistent with previous research papers on nitrogen fertilization in citrus trees**. Quaggio *et al.* (2019)** highlighted that nitrogen is a critical nutrient for citrus growth, and its application significantly enhances tree height, canopy volume, and branch development. The higher growth parameters observed with the 1000 g N treatment align with their findings, as increased nitrogen availability improves photosynthetic efficiency and biomass production.

The superiority of subsurface application (S.S.A.) over surface application (S.A.) can be attributed to reduced nitrogen losses through volatilization and leaching, as well as improved root uptake efficiency. **Alva *et al.* (2018)** demonstrated that subsurface application minimizes environmental losses and maximizes nutrient use efficiency in citrus orchards. This is further supported by **Morgan *et al.* (2018)**, who emphasized that subsurface fertilization ensures better nitrogen availability to the roots, leading to enhanced tree growth.

The interaction between nitrogen doses and application methods highlights the importance of optimizing fertilization strategies. The combination of high nitrogen doses (1000 g N) with subsurface application (S.S.A.) resulted in the highest growth parameters, suggesting that this approach maximizes nutrient availability and uptake. **Mattos *et al.* (2021)** also reported similar findings, emphasizing the synergistic effects of nitrogen dose and application method on citrus tree performance.

Table (2). The effects of nitrogen fertilization doses with different application ways (surface and subsurface) on the tree and branch growth parameters of Murcott mandarin trees during the 2021/2022 and 2022/2023 seasons

Season	Factor	Treatments	Tree Height (m)	Tree Diameter (m)	Tree Circumference (m)	Canopy Volume (m^3)	Branch length	Branch Thickness (mm)
First season	Nitrogen fertilization doses	600gN	2.48 C	2.92 C	9.33 C	24.21 C	36.13 C	6.14 C
		800gN(control)	2.65 B	3.10 B	9.83 B	27.22 B	40.50 B	6.74 B
		1000gN	2.76 A	3.32 A	10.32 A	29.73 A	49.31 A	7.76 A
	Application ways	S.A.(control)	2.56 B	3.02 B	9.58 B	25.66 B	39.15 B	6.54 B
		S.S.A.	2.70 A	3.21 A	10.07 A	28.44 A	44.81 A	7.22 A
	interaction	600gN×S.A.	2.34 d	2.82 d	8.98 d	21.95 d	33.85 d	5.77 d
		600gN×S.S.A.	2.62 c	3.03 c	9.67 c	26.46 c	38.40 c	6.51 c
		800gN×S.A.(control)	2.60 c	3.03 c	9.62 c	26.14 c	37.46 c	6.41 c
		800gN×S.S.A.	2.70 b	3.17 b	10.04 b	28.31 b	43.55 b	7.08 b
		1000gN×S.A	2.73 b	3.22 b	10.15 b	28.90 b	46.15 b	7.46 b
		1000gN×S.S.A.	2.79 a	3.42 a	10.49 a	30.56 a	52.48 a	8.07 a
Second season	Nitrogen fertilization doses	600gN	2.55 C	3.02 C	9.62 C	25.66 C	36.99 C	6.29 C
		800gN(control)	2.74 B	3.21 B	10.18 B	29.19 B	41.83 B	6.98 B
		1000gN	2.87 A	3.43 A	10.67 A	32.00 A	51.64 A	8.14 A
	Application ways	S.A.(control)	2.64 B	3.12 B	9.89 B	27.33 B	40.33 B	6.75 B
		S.S.A.	2.81 A	3.33 A	10.42 A	30.57 A	46.64 A	7.52 A
	interaction	600gN×S.A.	2.40 d	2.89 d	9.21 d	23.03 d	34.45 d	5.88 d
		600gN×S.S.A.	2.70 c	3.15 c	10.03 c	28.29 c	39.52 c	6.71 c
		800gN×S.A.(control)	2.69 c	3.13 c	9.95 c	27.90 c	38.51 c	6.59 c
		800gN×S.S.A.	2.80 b	3.29 b	10.42 b	30.47 b	45.15 b	7.36 b
		1000gN×S.A	2.83 b	3.34 b	10.51 b	31.07 b	48.04 b	7.78 b
		1000gN×S.S.A.	2.92 a	3.53 a	10.82 a	32.94 a	55.23 a	8.50 a

S.A. = Surface application and S.S.A. = Subsurface application.
Mean followed by the same letter\s within each column are not significantly different from each other at 0.5% level.

Table 3 investigated the effects of nitrogen fertilization doses applied through surface (S.A.) and subsurface (S.S.A.) application methods on leaf photosynthetic pigments, water content, and dry matter percentage of Murcott mandarin trees during the 2021/2022 and 2022/2023 seasons.

Leaf chlorophyll content

Chlorophyll a: The highest chlorophyll a content was observed in the 1000 g N treatment with subsurface application (S.S.A.) in both seasons (0.239 mg/100 g in the first season and 0.251 mg/100 g in the second season). This was significantly higher than the 600 g N treatment, which had the lowest chlorophyll a content (0.166 mg/100 g in the first season and 0.170 mg/100 g in the second season). The subsurface application method consistently resulted in higher chlorophyll a content compared to surface application across all nitrogen doses.

Chlorophyll b: Similar trends were observed for chlorophyll b, with the 1000 g N + S.S.A. treatment showing the highest values (0.110 mg/100 g in the first season and 0.115 mg/100 g in the second season). The lowest values were recorded in the 600 g N + S.A. treatment (0.079 mg/100 g in the first season and 0.080 mg/100 g in the second season).

Carotenoids content

Carotenoids content was inversely related to nitrogen dose, with the 600 g N treatment showing the highest carotenoids content (0.157 mg/100 g in the first season and 0.165 mg/100 g in the second season). The 1000 g N treatment had the lowest carotenoids content (0.134 mg/100 g in the first season and 0.137 mg/100 g in the second season). Subsurface application slightly reduced carotenoids content compared to surface application.

Water content and dry matter percentage

Total water content: The 1000 g N + S.S.A. treatment resulted in the highest water content (71.76% in the first season and 74.15% in the second season), while the 600 g N + S.A. treatment had the lowest water content (68.25% in the first season and 69.70% in the second season).

Dry matter percentage: Dry matter percentage followed an inverse trend to water content. The 600 g N + S.A. treatment had the highest dry matter percentage (31.76% in the first season and 30.30% in the second season), while the 1000 g N + S.S.A. treatment had the lowest (28.24% in the first season and 25.86% in the second season).

The results indicate that higher nitrogen doses (1000 g N) combined with subsurface application significantly enhance chlorophyll content and water retention of Murcott mandarin leaves. This is consistent with findings by **Zhang *et al.*, (2021)**, who reported that subsurface nitrogen application improves nutrient uptake efficiency and promotes chlorophyll synthesis. However, the reduction in carotenoids content with increasing nitrogen doses suggests a trade-off between chlorophyll production and carotenoids accumulation, as noted by **Li *et al.*, (2022)**.

The higher water content and lower dry matter percentage in the 1000 g N treatment may be attributed to improved nitrogen availability, which enhances cell expansion and water retention. This aligns with the observations of **Wang *et al.*, (2020)**, who found that nitrogen fertilization increases leaf water content by promoting osmotic adjustment and cell turgor.

The superiority of subsurface application over surface application in enhancing photosynthetic pigments and water content can be explained by reduced nitrogen losses through volatilization and leaching, as highlighted by **Kumar *et al.*, (2023)**. This method ensures more efficient nitrogen utilization, leading to better physiological responses in plants.

Table (3). The effects of nitrogen fertilization doses with different application ways (surface and subsurface) on leaf photosynthetic pigments, water content and dry matter percentage of Murcott mandarin trees during the 2021/2022 and 2022/2023 seasons

Season	Factor	Treatments	Leaf chlorophyll a content (mg/100 g of leaf F. W.)	Leaf chlorophyll b content (mg/ 100 g of leaf F. W.)	Carotenoids content (mg/ 100 g of leaf F. W.)	Total water content per leaf (%)	Dry matter %
First season	Nitrogen fertilization doses	600gN	0.166 C	0.085 C	0.157 A	68.72 C	31.28 A
		800gN(control)	0.194 B	0.095 B	0.149 B	69.69 B	30.31 B
		1000gN	0.239 A	0.110 A	0.134 C	71.17 A	28.83 C
	Application ways	S.A.(control)	0.183 B	0.091 B	0.153 A	69.31 B	30.69 A
		S.S.A.	0.216 A	0.102 A	0.141 B	70.41 A	29.59 B
	interaction	600gN×S.A.	0.147 d	0.079 d	0.164 a	68.25 d	31.76 a
		600gN×S.S.A.	0.184 c	0.091 c	0.151 b	69.20 c	30.80 b
		800gN×S.A.(control)	0.175 c	0.088 c	0.156 b	69.10 c	30.90 b
		800gN×S.S.A.	0.214 b	0.101 b	0.141 c	70.27 b	29.73 c
		1000gN×S.A	0.228 b	0.106 b	0.138 c	70.59 b	29.41 c
		1000gN×S.S.A.	0.251 a	0.114 a	0.129 d	71.76 a	28.24 d
Second season	Nitrogen fertilization doses	600gN	0.170 C	0.087 C	0.165 A	70.92 C	29.09 A
		800gN(control)	0.201 B	0.098 B	0.154 B	72.25 B	27.76 B
		1000gN	0.251 A	0.115 A	0.137 C	73.52 A	26.48 C
	Application ways	S.A.(control)	0.189 B	0.094 B	0.159 A	71.43 B	28.57 A
		S.S.A.	0.225 A	0.106 A	0.145 B	73.02 A	26.98 B
	interaction	600gN×S.A.	0.150 d	0.080 d	0.172 a	69.70 d	30.30 a
		600gN×S.S.A.	0.189 c	0.094 c	0.157 b	72.13 c	27.87 b
		800gN×S.A.(control)	0.180 c	0.091 c	0.162 b	71.69 c	28.31 b
		800gN×S.S.A.	0.222 b	0.105 b	0.145 c	72.80 b	27.20 c
		1000gN×S.A	0.237 b	0.110 b	0.142 c	72.89 b	27.11 c
		1000gN×S.S.A.	0.264 a	0.120 a	0.131 d	74.15 a	25.86 d

S.A. = Surface application and S.S.A. = Subsurface application.
Mean followed by the same letter\s within each column are not significantly different from each other at 0.5% level.

Table 4 presents the effects of nitrogen fertilization doses and application methods (surface and subsurface) on the leaf nutrient content of Murcott mandarin trees during the 2021/2022 and 2022/2023 seasons. The parameters evaluated include nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), and manganese (Mn) content in leaves. The data reveal significant variations in nutrient content based on nitrogen doses and application methods.

Table (4). The effects of nitrogen fertilization doses with different application ways (surface and subsurface) on leaf nutrition content of Murcott mandarin trees during the 2021/2022 and 2022/2023 seasons

Season	Factor	Treatments	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Fe (ppm)	Zn (ppm)	Mn (ppm)
First season	Nitrogen fertilization doses	600gN	2.126 C	0.136 A	1.363 C	4.519 A	0.395 A	106.67 A	63.91 A	62.73 A
		800gN(control)	2.359 B	0.130 B	1.479 B	4.427 B	0.383 B	101.85 B	60.58 B	57.98 B
		1000gN	2.667 A	0.122 C	1.633 A	4.305 C	0.368 C	96.41 C	56.84 C	52.62 C
	Application ways	S.A.(control)	2.261 B	0.133 A	1.430 B	4.469 A	0.389 A	104.19 A	62.20 A	60.29 A
		S.S.A.	2.507 A	0.126 B	1.554 A	4.365 B	0.376 B	99.09 B	58.68 B	55.26 B
	interaction	600gN×S.A.	1.977 d	0.139 a	1.289 d	4.582 a	0.403 a	110.01 a	66.21 a	66.02 a
		600gN×S.S.A.	2.275 c	0.133 b	1.438 c	4.457 b	0.387 b	103.33 b	61.61 b	59.44 b
		800gN×S.A.(control)	2.235 c	0.134 b	1.418 c	4.477 b	0.390 b	104.55 b	62.45 b	60.64 b
		800gN×S.S.A.	2.482 b	0.127 c	1.541 b	4.376 c	0.377 c	99.15 c	58.72 c	55.32 c
		1000gN×S.A	2.569 b	0.125 c	1.585 b	4.347 c	0.373 c	98.03 c	57.95 c	54.21 c
		1000gN×S.S.A.	2.764 a	0.119 d	1.682 a	4.264 d	0.363 d	94.80 d	55.72 d	51.03 d
Second season	Nitrogen fertilization doses	600gN	2.177 C	0.142 A	1.396 C	4.581 A	0.403 A	108.37 A	65.08 A	64.40 A
		800gN(control)	2.441 B	0.135 B	1.531 B	4.472 B	0.389 B	103.01 B	61.38 B	59.12 B
		1000gN	2.796 A	0.125 C	1.713 A	4.334 C	0.372 C	97.06 C	57.29 C	53.26 C
	Application ways	S.A.(control)	2.332 B	0.138 A	1.475 B	4.523 A	0.395 A	105.65 A	63.20 A	61.72 A
		S.S.A.	2.610 A	0.130 B	1.617 A	4.402 B	0.380 B	99.98 B	59.29 B	56.13 B
	interaction	600gN×S.A.	2.016 d	0.147 a	1.314 d	4.656 a	0.412 a	112.12 a	67.67 a	68.10 a
		600gN×S.S.A.	2.337 c	0.138 b	1.477 c	4.507 b	0.393 b	104.61 b	62.49 b	60.70 b
		800gN×S.A.(control)	2.300 c	0.139 b	1.459 c	4.532 b	0.397 b	105.98 b	63.44 b	62.05 b
		800gN×S.S.A.	2.582 b	0.131 c	1.603 b	4.411 c	0.381 c	100.03 c	59.33 c	56.19 c
		1000gN×S.A	2.680 b	0.129 c	1.653 b	4.381 c	0.378 c	98.84 c	58.51 c	55.01 c
		1000gN×S.S.A.	2.912 a	0.122 d	1.772 a	4.288 d	0.366 d	95.29 d	56.06 d	51.52 d

S.A. = Surface application and S.S.A. = Subsurface application.
Mean followed by the same letter\s within each column are not significantly different from each other at 0.5% level.

Nitrogen (N) content

Nitrogen content in leaves increased with higher nitrogen doses. The 1000 g N treatment resulted in the highest N content (2.667% in the first season and 2.796% in the second season), followed by 800 g N and 600 g N. Subsurface application (S.S.A.) consistently produced higher N content compared to surface application (S.A.), with the 1000 g N × S.S.A. treatment yielding the highest values (2.764% and 2.912% in the first and second seasons, respectively).

Phosphorus (P) and Potassium (K) content

Phosphorus content decreased with higher nitrogen doses, with the 600 g N treatment showing the highest P content (0.136% and 0.142% in the first and second seasons). Conversely, potassium content increased with higher nitrogen doses, with the 1000 g N treatment resulting in the highest K content (1.633% and 1.713%). Subsurface application generally improved K content, particularly in the 1000 g N × S.S.A. treatment.

Calcium (Ca) and Magnesium (Mg) content

Calcium and magnesium content decreased with higher nitrogen doses. The 600 g N treatment showed the highest Ca (4.519% and 4.581%) and Mg (0.395% and 0.403%) content. Surface application resulted in slightly higher Ca and Mg content compared to subsurface application.

Micronutrients (Fe, Zn, Mn)

Iron, zinc, and manganese content decreased with higher nitrogen doses. The 600 g N treatment resulted in the highest Fe (106.67 ppm and 108.37 ppm), Zn (63.91 ppm and 65.08 ppm), and Mn (62.73 ppm and 64.40 ppm) content. Surface application generally produced higher micronutrient content compared to subsurface application.

The findings align with recent studies on nitrogen fertilization in citrus trees. **Quaggio *et al.* (2020)** found that higher nitrogen doses improve nitrogen uptake but may reduce the availability of other nutrients due to nutrient imbalances. Similarly, **Mattos *et al.* (2021)** reported that subsurface application enhances nitrogen use efficiency but may lead to reduced uptake of immobile nutrients like phosphorus and micronutrients.

The reduction in phosphorus and micronutrient contents with higher nitrogen doses supports the findings of **Morgan *et al.* (2020)**, who demonstrated that excessive nitrogen can inhibit the uptake of other essential nutrients. The higher calcium and magnesium contents with surface application agree with the observations of **Legaz *et al.* (2022)**, who noted that surface application improves the availability of these nutrients in the root zone.

Table 5 presents the effects of nitrogen fertilization doses and application methods (surface and subsurface) on the fruit quality parameters of Murcott mandarin fruits during the 2021/2022 and 2022/2023 seasons. The data reveal significant variations in fruit quality based on nitrogen doses and application methods.

Fruit weight

Fruit weight increased with higher nitrogen doses. The 1000 g N treatment resulted in the heaviest fruits (194.51 g in the first season and 198.87 g in the second season), followed by 800 g N and 600 g N. Subsurface application (S.S.A.) consistently produced heavier fruits compared to surface application (S.A.), with the 1000 g N × S.S.A. treatment yielding the highest values (197.34 g and 201.62 g in the first and second seasons, respectively).

Fruit shape index

The fruit shape index (length/diameter) was not significantly affected by nitrogen doses or application methods, with all treatments showing similar values (1.43–1.33 in the first season and 1.37–1.31 in the second season).

Juice volume

Juice volume per fruit increased with higher nitrogen doses. The 1000 g N treatment resulted in the highest juice volume (115.48 cm^3 and 112.22 cm^3), while subsurface application further enhanced this parameter. The 1000 g N × S.S.A. treatment yielded the highest juice volumes (119.04 cm^3 and 124.08 cm^3) in both seasons.

Total soluble solids (TSS) and acidity

TSS content decreased with higher nitrogen doses, with the 600 g N treatment showing the highest TSS (18.41% and 18.97%). Conversely, juice acidity increased with higher nitrogen doses, with the 1000 g N treatment resulting in the highest acidity (1.10% and 1.13%). Subsurface application generally reduced TSS and increased acidity compared to surface application.

Table (5). The effects of nitrogen fertilization doses with different application ways (surface and subsurface) on fruit weight, fruit shape index, juice volume, juice TSS, juice acidity, TSS/acid ratio and ascorbic acid of Murcott mandarin fruits during the 2021/2022 and 2022/2023 seasons

Season	Factor	Treatments	Fruit weight (g)	Fruit shape index (length/diameter)	Juice volume/ fruit (cm^3)	Juice TSS (%)	Juice acidity (%)	TSS/acid ratio	Ascorbic acid (mg/100 ml)
First season	Nitrogen fertilization doses	600gN	180.34 C	1.43 A	92.83 C	18.41 A	0.73 A	25.99 A	35.98 C
		800gN(control)	185.94 B	1.42 A	102.92 B	16.12 B	0.88 B	18.96 B	36.91 B
		1000gN	194.51 A	1.38 A	115.48 A	13.29 C	1.10 C	12.20 C	38.38 A
	Application ways	S.A.(control)	184.08 B	1.42 A	100.16 B	17.15 A	0.82 A	22.31 A	36.55 B
		S.S.A.	189.79 A	1.40 A	107.01 A	14.73 B	0.98 B	15.79 B	37.63 A
	interaction	600gN×S.A.	177.79 d	1.42 a	89.22 e	19.63 a	0.65 d	30.22 a	35.45 d
		600gN×S.S.A.	182.89 c	1.44 a	96.51 d	17.19 b	0.81 c	21.76 b	36.50 c
		800gN×S.A.(control)	182.75 c	1.44 a	99.85 d	17.64 b	0.78 c	23.06 b	36.28 c
		800gN×S.S.A.	189.13 b	1.41 a	106.03 c	14.59 c	0.99 b	14.85 c	37.54 b
		1000gN×S.A	191.68 b	1.40 a	111.98 b	14.18 c	1.04 b	13.64 c	37.91 b
		1000gN×S.S.A.	197.34 a	1.36 a	119.04 a	12.40 d	1.15 a	10.76 d	38.85 a
Second season	Nitrogen fertilization doses	600gN	188.06 C	1.37 A	98.76 C	18.97 A	0.76 A	25.73 A	37.35 C
		800gN(control)	192.05 B	1.37 A	107.69 B	16.64 B	0.91 B	18.90 B	38.05 B
		1000gN	198.87 A	1.33 A	120.55 A	13.89 C	1.13 C	12.35 C	39.14 A
	Application ways	S.A.(control)	190.45 B	1.37 A	105.53 B	17.75 A	0.85 A	22.26 A	37.80 B
		S.S.A.	195.54 A	1.35 A	112.22 A	15.25 B	1.02 B	15.73 B	38.56 A
	interaction	600gN×S.A.	186.00 d	1.36 a	95.68 e	20.36 a	0.68 d	30.10 a	37.00 d
		600gN×S.S.A.	190.14 c	1.38 a	101.90 d	17.58 b	0.84 c	21.35 b	37.71 c
		800gN×S.A.(control)	189.23 c	1.38 a	104.28 d	18.10 b	0.81 c	22.82 b	37.63 c
		800gN×S.S.A.	194.86 b	1.36 a	111.15 c	15.19 c	1.02 b	14.97 c	38.47 b
		1000gN×S.A	196.12 b	1.36 a	117.06 b	14.80 c	1.07 b	13.84 c	38.77 b
		1000gN×S.S.A.	201.62 a	1.31 a	124.08 a	12.97 d	1.20 a	10.86 d	39.50 a

S.A. = Surface application and S.S.A. = Subsurface application.
Mean followed by the same letter\s within each column are not significantly different from each other at 0.5% level.

TSS/acid ratio

The TSS/acid ratio decreased with higher nitrogen doses, with the 600 g N treatment showing the highest ratio (25.99 and 25.73). Subsurface application further reduced the TSS/acid ratio, particularly in the 1000 g N × S.S.A. treatment (10.76 and 10.86).

Ascorbic acid content

Ascorbic acid content increased with higher nitrogen doses. The 1000 g N treatment resulted in the highest ascorbic acid content (38.38 mg/100 ml and 39.14 mg/100 ml), while subsurface application further enhanced this parameter. The 1000 g N × S.S.A. treatment yielded the highest ascorbic acid content (38.85 mg/100 ml and 39.50 mg/100 ml) in both seasons.

The findings align with recent studies on nitrogen fertilization in citrus fruits. **Quaggio *et al.* (2020)** found that higher nitrogen doses improve fruit size and juice volume but may reduce TSS and increase acidity due to dilution effects. Similarly, **Mattos *et al.* (2021)** reported that subsurface application enhances nitrogen use efficiency, leading to better fruit growth but potentially altering juice quality.

The reduction in TSS and TSS/acid ratio with higher nitrogen doses supports the findings of **Morgan *et al.* (2020)**, who demonstrated that excessive nitrogen can dilute soluble solids and increase acidity in citrus fruits. The increase in ascorbic acid content with higher nitrogen doses aligns with the observations of **Legaz *et al.* (2022)**, who noted that nitrogen plays a critical role in the biosynthesis of ascorbic acid.

Table 6 presents the effects of nitrogen fertilization doses and application methods (surface and subsurface) on the yield and nitrogen use efficiency (NUE) of Murcott mandarin during the 2021/2022 and 2022/2023 seasons. The parameters evaluated include fruit set percentage per twig, number of fruits per tree, tree yield, hypothetical yield per feddan, and nitrogen use efficiency. The data reveal significant variations in yield and NUE based on nitrogen doses and application methods.

Fruit set percentage

Fruit set percentage increased with higher nitrogen doses. The 1000 g N treatment resulted in the highest fruit set percentage (6.36% in the first season and 7.95% in the second season), followed by 800 g N and 600 g N. Subsurface application (S.S.A.) consistently produced higher fruit set percentages compared to surface application (S.A.), with the 1000 g N × S.S.A. treatment yielding the highest values (6.45% and 8.07% in the first and second seasons, respectively).

Number of fruits per tree

The number of fruits per tree increased with higher nitrogen doses. The 1000 g N treatment resulted in the highest number of fruits (374.19 and 469.02 in the first and second seasons, respectively), while subsurface application further enhanced this parameter. The 1000 g N × S.S.A. treatment yielded the highest number of fruits (394.11 and 494.88) in both seasons.

Tree yield and hypothetical yield per feddan

Tree yield and hypothetical yield per feddan increased with higher nitrogen doses. The 1000 g N treatment resulted in the highest tree yield (72.87 kg and 93.37 kg) and hypothetical yield per feddan (15.30 tons and 19.61 tons). Subsurface application consistently produced higher yields compared to surface application, with the 1000 g N × S.S.A. treatment yielding the highest values (77.78 kg and 99.78 kg for tree yield, and 16.34 tons and 20.95 tons for hypothetical yield per feddan).

Nitrogen use efficiency (NUE)

Nitrogen use efficiency (NUE) was highest in the 800 g N and 1000 g N treatments (72.81–72.87 kg fruit/kg N) and (94.11–93.37 kg fruit/kg N) in the first and the second season, respectively. Subsurface application significantly improved NUE compared to surface application, with the interaction the treatments 1000, 800 and 600 g N under S.S.A. showing the highest NUE (77.78 - 79.69 -76.61 and 99.78 -102.70 -99.64 kg fruit/kg N) in the first and the second season, respectively.

Table (6). The effects of nitrogen fertilization doses with different application ways (surface and subsurface) on yield and Nitrogen use efficiency of Murcott mandarin during the 2021/2022 and 2022/2023 seasons

Season	Factor	Treatments	fruit set percentage per twig	Number of fruits per tree	Tree yield (kg)	Hypothetic yield per feddan (ton)	Nitrogen use efficiency (kg fruit /N Kg)
First season	Nitrogen fertilization doses	600gN	4.41 C	230.37 C	41.62 C	8.74 C	69.36 B
		800gN(control)	5.93 B	312.58 B	58.25 B	12.23 B	72.81 A
		1000gN	6.36 A	374.19 A	72.87 A	15.30 A	72.87 A
	Application ways	S.A.(control)	5.30 B	284.10 B	52.66 B	11.06 B	65.33 B
		S.S.A.	5.84 A	327.33 A	62.50 A	13.12 A	78.02 A
	interaction	600gN×S.A.	3.93 e	209.58 f	37.26 e	7.83 f	62.10 b
		600gN×S.S.A.	4.90 d	251.16 e	45.97 d	9.66 e	76.61 a
		800gN×S.A.(control)	5.69 c	288.45 d	52.75 c	11.08 d	65.94 b
		800gN×S.S.A.	6.16 b	336.71 c	63.75 b	13.39 c	79.69 a
		1000gN×S.A	6.27 b	354.28 b	67.96 b	14.27 b	67.96 b
		1000gN×S.S.A.	6.45 a	394.11 a	77.78 a	16.34 a	77.78 a
Second season	Nitrogen fertilization doses	600gN	5.52 C	287.98 C	54.23 C	11.39 C	90.38 B
		800gN(control)	7.41 B	391.35 B	75.28 B	15.81 B	94.11 A
		1000gN	7.95 A	469.02 A	93.37 A	19.61 A	93.37 A
	Application ways	S.A.(control)	6.62 B	355.42 B	68.02 B	14.29 B	84.54 B
		S.S.A.	7.30 A	410.15 A	80.57 A	16.92 A	100.71 A
	interaction	600gN×S.A.	4.92 e	261.69 f	48.67 e	10.23 f	81.12 c
		600gN×S.S.A.	6.12 d	314.26 e	59.78 d	12.55 e	99.64 a
		800gN×S.A.(control)	7.12 c	361.40 d	68.43 c	14.37 d	85.53 b
		800gN×S.S.A.	7.70 b	421.31 c	82.15 b	17.26 c	102.70 a
		1000gN×S.A	7.83 b	443.17 b	86.96 b	18.27 b	86.96 b
		1000gN×S.S.A.	8.07 a	494.88 a	99.78 a	20.95 a	99.78 a

S.A. = Surface application and S.S.A. = Subsurface application.
Mean followed by the same letter\s within each column are not significantly different from each other at 0.5% level.

The findings align with recent studies on nitrogen fertilization in citrus production. **Quaggio *et al.* (2020)** found that higher nitrogen doses improve fruit set and yield but emphasized the importance of efficient nitrogen management to maximize NUE. Similarly, **Mattos *et al.* (2021)** reported that subsurface application enhances nitrogen availability and uptake, leading to improved yield and NUE.

The increase in fruit set and yield with higher nitrogen doses supports the findings of **Morgan *et al.* (2020)**, who demonstrated that nitrogen is a critical nutrient for flower initiation and fruit development in citrus trees. The improvement in NUE with subsurface application aligns with the observations of **Legaz *et al.* (2022)**, who noted that subsurface application reduces nitrogen losses and improves nutrient use efficiency.

4. Conclusion

The study concludes that subsurface nitrogen fertilization, particularly at higher doses (1000 g N), is an effective strategy for enhancing Murcott mandarin production. It improves tree growth, fruit yield, and nitrogen use efficiency while minimizing environmental impacts. However, the trade-offs in fruit quality, such as increased acidity and reduced TSS, highlight the need for balanced nitrogen management to optimize both productivity and fruit quality. These findings contribute to sustainable citrus production and align with global efforts to promote precision agriculture and environmental conservation.

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