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Mitigation of Alternate Bearing in Balady Mandarin by Winter Pruning or Fruit Thinning

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Abstract: Alternate bearing is a major phenomenon limiting the sustainable production of 'Balady' mandarin (*Citrus reticulata Blanco*), leading to inconsistent yields and fluctuating fruit quality. This three-season study (2021–2023) in Nubaria region, Egypt, evaluated various pruning intensities (25, 50, and 75%) and thinning applications (manual and chemical) at different stages on 20-year-old trees to stabilize yields. Combined analysis across three seasons revealed that all pruning levels increased tree volume by 78.46%, 62.98%, and 32.13% respectively, above the control. Early and late chemical thinning enhanced leaf nutrient accumulation, including nitrogen and boron under early application, and iron and zinc under late application. The control recorded higher fruitlet and fruit retention percentages, which logically responds to removing fruiting shoots during pruning and the direct removal of fruitlets during thinning. However, early chemical thinning and moderate pruning (50%) achieved a superior balance between vegetative growth and reproductive potential by improving shoot C: N ratios (12.58 and 12.39, respectively) over the control; thus, establishing enhanced yield (kg/tree and ton/feddan) and yield efficiency (kg/m^3) while minimizing the biennial bearing index. Furthermore, fruit weight, Vitamin C, and TSS: acid ratio was markedly improved under these treatments. Overall, adopting either early chemical thinning or moderate pruning is recommended as an effective horticultural practice to ensure consistent, high-quality production and maintain tree longevity under experimental conditions.

Key words: *Citrus reticulata*, Alternate bearing, Crop load, Fruit thinning, Pruning severity, Fruit quality

1. Introduction

Mandarin (*Citrus reticulata* Blanco) constitutes one of the most important fruit crops in Egypt, contributing significantly to both local consumption and export revenues due to its nutritional value and strong market demand. Recent reports indicate that the sector generates approximately $1.5 billion annually from citrus exports **(FAO, 2024)**. According to 2024 statistics from **Egypt Ministry of Agriculture, mandarin** is cultivated on more than 50,000 feddans, yielding over 1.2 million tons per year. Nevertheless, 'Balady' mandarin is highly susceptible to the alternate bearing phenomenon, which leads to marked year-to-year variations in crop load. In heavy "on-years", excessive fruit set often results in smaller fruit size and increased risk of branch breakage under mechanical stress. Such heavy cropping inhibits floral initiation in the following season, primarily due to elevated gibberellin levels from developing seeds and depletion of stored carbohydrates, ultimately causing substantial yield decline in "off-years" **(Monselise and Goldschmidt, 1982; Stander *et al*., 2018; Agustí *et al*., 2026)**.

Pruning and fruit thinning represent two important and complementary cultural practices in citrus management. These techniques selectively eliminate vegetative growth and excess fruitlets to improve canopy structure, control crop load, and achieve better resource distribution within the tree **(Mika, 1986; Greene, 2010)**.

Pruning increases light interception and photosynthetic efficiency by removing overcrowded, shaded, and non-productive branches and shoots. Meanwhile, thinning- whether performed manually by removing 40–50% of fruitlets or chemically using NAA at 200 - 400 ppm, enhances fruit size, overall quality, and reduces the risk of mechanical damage.

Both practices help alleviate alternate bearing through the restoration of carbohydrate reserves and the stimulation of return bloom in the following season. In years with heavy fruit load (on-years), severe pruning is usually carried out in late winter (February–March) to avoid branch breakage and reduce physiological stress **(Salem *et al*., 2008)**. This is typically followed by targeted thinning during the early fruitlet stage, either through manual removal during the second week of June when fruit diameter reaches 25–30 mm **(Mostafa and Abdel-Aal, 2009)** or via chemical application in mid-May during the physiological June drop period **(El-Sayed *et al*., 2017)**

Therefore, this study evaluates the independent effects of pruning and fruit thinning (manual and chemical) on mitigating alternate bearing, enhancing yield stability, and improving fruit quality in Balady mandarin orchards under Nubaria climatic conditions.

2. Material and Methods

2.1. Experimental Site and Plant Material

The experiment was conducted in a commercial orchard of local mandarin trees located in Ahmed Badawi village, Nubaria region, Beheira Governorate, Egypt. Twenty-year-old mandarin trees (Citrus reticulata Blanco) budded on sour orange (*Citrus aurantium* L.) rootstock used. The trees were planted at a spacing of 3.5 × 3.5 m under drip irrigation, in good health and free from major pests and diseases.

The study aimed to investigate the effects of different pruning and fruit thinning treatments in an attempt to mitigate the alternate bearing phenomenon. The experiment spanned three consecutive seasons (2021, 2022 and 2023). Considering that the first experimental season (2021) represented an "on-year" with heavy crop load, followed by an "off-year" with light crop load in 2022 and then another "on-year" with heavy crop load in 2023.

Treatments and Experimental Design

The trees under study were subjected to different pruning and fruit thinning treatments in the "on-year" seasons (2021 and 2023). Pruning severities were defined as percentages of the previous season's vegetative growth (current-year shoots and water sprouts) removed, without cutting any primary scaffold branches. Pruning was performed manually using hand shears on 15 February following harvest, after which all trees were sprayed with copper oxychloride (Kupfer Kavaro 8%) at 300 g/100 L water to prevent fungal infections at cut sites. Fruit thinning was applied independently at two timings: early on 29 May (~55 days after full bloom, coinciding with physiological drop onset) and late on 20 June (~75 days after full bloom, post-June drop phase). Manual thinning achieved a 40% reduction in developing fruitlets by selecting 10 branches per quadrant (north, south, east, west; total 40 branches/tree). Fruitlets on each branch were counted, and exactly 40% - prioritizing small, deformed, or densely clustered ones- were hand-removed using pruning shears. Chemical thinning was applied at the same timings via a single foliar spray of NAA at 350 ppm with 0.1% Tween 20 as a surfactant, using a motorized knapsack sprayer (15 L/tree) until runoff. No treatments were applied in the "off-year" (2022).

The treatments were as follows:

- T1: severe pruning (75%): extensive removal of 75% of excess current-season vegetative growth, focusing on water sprouts and interior shoots to open the canopy while preserving the main structural framework.
- T2: moderate pruning (50%): removal of 50% of crossed, shaded, and non-productive current-season shoots.
- T3: light pruning (25%): selective removal of 25% of current-season shoots and weakly attached water sprouts.
- T4: control (no treatment).
- T5: early manual thinning (29 May): hand-removal of 40% fruitlets.
- T6: early chemical thinning (29 May): NAA spray at 350 ppm.
- T7: late manual thinning (20 June): hand-removal of 40% fruitlets.
- T8: late chemical thinning (20 June): NAA spray at 350 ppm.

2.2. Experimental design

The experiment was conducted using a randomized complete block design (RCBD) with three blocks. Eight treatments were randomly allocated within each block, with one tree per treatment per block serving as a single replicate. This arrangement resulted in 24 trees in total (3 blocks × 8 treatments × 1 tree) and provided three independent replicates per treatment for statistical analysis

1- Physiological studies:

a. Canopy volume

Tree height (H, m) and canopy diameter (D, m); were measured immediately after pruning (late February) and at the end of each season (December). Canopy volume (V, m³) was calculated using the following formula **(Castle, 1983):** $V = 0.524\ H \times D^2$. The percentage increase in canopy volume was then computed as: where V initial is the volume post-pruning and V final is the volume in December

$$\%increase = \frac{V_{\{final\}} - V_{\{initial\}}}{V_{\{initial\}}} X100$$

b. Flowering and fruit set

At full bloom (early April), flowers count was conducted on three randomly selected 3-4 cm diameter branches per tree, distributed around the canopy. Fruit set was assessed on the same labeled shoots for all treatments at three time points: (1) ten days after early thinning (May 29), when fruitlet diameter averaged 1.60 cm; (2) ten days after late thinning (June 20), when fruitlet diameter averaged 2.32 cm; and (3) at pre-harvest in mid-December. Remaining fruitlets were manually counted on each shoot. Fruit set percentage was calculated as:

$$Fruit\ set(\%) = \frac{number\ of\ retained\ fruitlets}{initial\ number\ of\ flowers} X100$$

c. Yield assessment

At harvest in mid-December, the total number of fruits was counted on each individual tree. A random sample of 15 fruits per replicate was collected to determine average fruit weight in grams. Tree yield was calculated as

$$Tree\ yield\ (kg) = \frac{No.of\ fruit \times fruit\ weight}{1000}$$

Productivity was expressed as tons per feddan based on a planting density of 340 trees per feddan which are at 3.5 by 3.5 meter spacing. Yield efficiency was calculated as kilograms per cubic meter by dividing tree yield by the corresponding canopy volume measured in December.

d. Biennial bearing index (BBI)

The biennial bearing index (BBI) was calculated across three consecutive seasons (2021, 2022, and 2023) using the formula of **Pearce and Doberšek-Urbanc (1967):**

$$\text{BBI} = \frac{1}{n-1}\sum_{i=1}^{n-1} \frac{ai+1-ai}{ai+1+ai}$$

Where, n = number of seasons (3), ai = tree yield (kg/tree) in season. The index was computed for each treatment using yield data from the three replicates. A BBI value of 0 indicates no alternation, while 1 represents complete biennial bearing.

2. Leaf nutrient analysis

In mid-October, twenty fully expanded spring-cycle leaves were sampled from non-fruiting shoots, and eight one-year-old shoots were collected from around each tree canopy. Samples were washed, dried at 70 °C to constant weight, ground, and digested according to **Chapman and Pratt, (1961)**. Total nitrogen (N) in both leaves and shoots was determined using the Kjeldahl method **(Bremner, 1965)**, while phosphorus (P) and potassium (K) in leaves were quantified via colorimetry **(Jackson, 1958)** and flame photometry, respectively. Calcium (Ca) and magnesium (Mg) were determined by EDTA titration, and micronutrients (Fe, Zn, Mn, and Cu) were measured colorimetrically **(Chapman and Pratt, 1961)**. Total carbon (C) in the one-year-old shoots was analyzed using the Walkley–Black method to calculate the shoots C: N ratio **(Walkley and Black, 1934**).

3. Fruit quality

Fifteen fruits were randomly selected from each replicate at commercial maturity in late December for some physical and chemical characteristic

a. Physical fruit quality attributes

Fruit weight (g) and dimensions were measured on fifteen randomly selected fruits per replicate. Polar length and equatorial diameter (cm) were recorded using a manual caliper, and the shape index was calculated as the length: diameter ratio. After manual separation, the weights of juice, pulp, and peel were determined. These components were expressed as a percentage of the total fruit weight (w/w) using the following formula

$$(\%) = \frac{(juice, pulp\ or\ peel\ \ weight)}{fruit\ weight} \times 100$$

B. Chemical fruit quality attributes

Juice extracted from the 15-fruit sample was filtered and used for chemical analysis. Total soluble solids (TSS) were measured as °Brix using a digital refractometer. Titratable acidity (TA) was determined by titrating 5 mL of juice with 0.1 N NaOH and expressed as % citric acid. The TSS: TA ratio was then calculated. Vitamin C (ascorbic acid) content was quantified using the 2, 6-dichlorophenolindophenol (DCPIP) dye method and expressed as mg/100 mL juice. All determinations were performed according to **AOAC, (2005).**

4- Statistical analysis

The experiment was conducted using a randomized complete block design (RCBD) with three replications over three growing seasons. Data for each season were analyzed separately. A combined analysis of variance over the three seasons was also performed. Treatment means were compared using the least significant difference (LSD) test at the 5% probability level **(Steel and Torrie, 1980)**. All statistical analyses were carried out using MSTAT- C Package (1996).

3. Results and Discussion

3.1 Tree Vegetative Growth Percentage of Increment of tree volume

Table (1) revealed three distinct response groups for percentage increase in tree volume across the three seasons. Pruning treatments (75, 50 and 25%) showed markedly higher vegetative growth than thinning treatments and the control, with severe pruning (T1) recording the highest values every season and the greatest overall mean (56.69%), followed by moderate T2 (32.98%) and light T3 (17.99%). This response is attributed to reduced reproductive sink demand, which redirected photoassimilates toward new shoot growth, along with improved light penetration and photosynthetic activity in the remaining canopy (**Tucker *et al*., 1994**; **Wheaton *et al*., 1995**; **Matias *et al*., 2023**; **Al-Saif *et al*., 2023**).

Fruit-thinning treatments (T5–T8), regardless of method or timing, showed significantly lower responses (7.32–9.73%). The untreated control (T4) had an intermediate overall mean (12.21%) but fluctuated markedly across seasons (4.53%, 14.50%, 17.60%), reflecting the natural alternate-bearing pattern in which unthinned trees shift carbohydrate allocation between fruiting and vegetative growth (**El-Sayed *et al*., 2017**; **Khurshid and Sanderson, 2023**).

Late thinning (T7, T8; applied 20 June) gave the weakest vegetative response, as most photoassimilates were already committed to fruit development after the main shoot-growth flush had ended—consistent with carbohydrate-partitioning models showing that delaying crop-load adjustment beyond the fruit-drop window limits its effect on new growth (**Guardiola and García-Luis, 2000**; **Stander *et al*., 2018**).

The exceptionally high vegetative growth of T1 in the first season (96.68%) coincided with winter pruning after a light-crop year, when low fruit demand allowed reserve accumulation. In later seasons, heavier crop loads and stronger fruit competition (**Matias *et al*., 2023**; **Stander *et al*., 2018**) reduced the vegetative growth of T1 to 34.20% and 39.20%, though it remained the highest among all treatments.

3.2 Fruitlet Retention (%)

3.2.1 Post-early thinning fruitlet retention (May 29)

Table (1) showed that pruning treatments significantly reduced fruitlet retention after early thinning (May 29) during the heavy "on-year" seasons (first and third). In the first season, retention was lowest under severe pruning T1 (22.80%), followed by T2 (23.16%) and T3 (23.27%), compared to 24.99% in the control, with a similar trend in the third season. This decline reflects the direct removal of flower-bud-bearing shoots and the indirect stimulation of vegetative regrowth, which draws down carbohydrate reserves needed for reproductive sinks **(Iglesias *et al*., 2007; Al-Saif *et al*., 2023)**, consistent with the increased carbohydrate draw down by vigorous vegetative regrowth, which creates strong sink competition during early fruitlet establishment, a response supported by the significant negative correlation observed between shoot C:N ratio and fruitlet retention (Fig. 2).

In contrast, pruning had a positive effect in the second, light-cropping season, where enhanced carbohydrate accumulation and flower bud formation from the previous season raised retention in T2 (18.63%), T3 (17.14%), and T1 (15.57%) above the control (14.19%) **(Goldschmidt, 1982; Stander *et al*., 2018)**.

As expected, early thinning treatments (T5, T6) gave the lowest retention on May 29, since late thinning (T7, T8, scheduled for June 20) had not yet been applied and thus resembled the control at this stage. Overall means were 14.66% for T5 and 15.78% for T6, well below the control (21.30%) and late thinning treatments (T7: 21.34%; T8: 21.05%). Early intervention can remove some healthy fruitlets before natural selection stabilizes final crop load **(El-Sayed *et al*., 2017; Agustí *et al*., 2026)**; nonetheless, in citrus, timely early thinning reduces prolonged sink competition ahead of the natural June drop more effectively than delayed regulation, which limits optimal resource partitioning **(Guardiola and García-Luis, 2000)**.

Table (1). Effect of pruning and thinning treatments on percentage of tree growth increment and fruitlet retention of Balady mandarin over three seasons and their overall mean

Season	1st	2nd	3rd	Overall Mean	1st	2nd	3rd	Overall Mean
Treat	**Increment of tree volume (%)**				**Post-early thinning fruitlet retention (%) (May 29)**			
Pruning75%	96.68^{a}	34.20^{a}	39.20^{a}	56.69^{a}	22.80^{b}	15.57^{c}	20.66^{cd}	19.68^{b}
Pruning50%	53.44^{b}	15.00^{c}	30.50^{b}	32.98^{b}	23.16^{b}	18.63^{a}	22.68^{bc}	21.49^{a}
Pruning25%	22.10^{c}	13.46^{d}	18.40^{c}	17.99^{c}	23.27^{b}	17.14^{b}	22.04^{c}	20.82^{a}
control	4.53^{d}	14.5^{c}	17.60^{d}	12.21^{d}	24.99^{a}	14.19^{d}	24.72^{ab}	21.30^{a}
early man.thinning	4.51^{d}	16.59^{b}	8.10^{e}	9.73^{e}	17.47^{d}	7.91^{f}	18.61^{d}	14.66^{d}
early chem. Thinning	4.38^{d}	13.64^{d}	8.10^{e}	8.71^{f}	19.24^{c}	8.63^{e}	19.48^{d}	15.78^{c}
late man. thinning	4.41^{d}	13.45^{d}	4.10^{f}	7.32^{h}	24.58^{a}	14.00^{d}	25.43^{a}	21.34^{a}
late chem. thinning	4.59^{d}	15.46^{c}	4.10^{f}	8.05^{g}	24.35^{a}	13.92^{d}	24.88^{ab}	21.05^{a}
Treat	**Post-late thinning fruitlet retention (%) (June 20)**				**fruitlet retention on pre-harvest (%) (mid-Dec)**			
Pruning75%	3.97^{f}	3.38^{de}	4.70^{c}	4.01^{c}	3.54^{e}	2.93^{d}	4.23^{b}	3.57^{e}
Pruning50%	4.72^{cd}	3.70^{c}	5.20^{ab}	4.54^{b}	4.46^{b}	3.25^{b}	4.71^{a}	4.14 ^{b}
Pruning25%	4.82^{c}	3.58^{cd}	5.08^{b}	4.49^{b}	4.49^{b}	3.13^{bc}	4.62^{a}	4.08^{bc}
control	5.69^{a}	3.31^{de}	5.36^{a}	4.79^{a}	5.00^{a}	3.08^{d}	4.75^{a}	4.30 ^{a}
early man.thinning	4.54^{de}	3.40^{de}	3.53^{e}	3.83^{d}	3.70^{d}	3.22^{bc}	3.20^{d}	3.40 ^{f}
early chem. Thinning	5.15^{b}	4.04^{b}	4.46^{d}	4.55^{b}	4.00^{c}	3.38^{a}	3.98^{c}	3.80 ^{d}
late man. thinning	4.44^{e}	4.37^{a}	2.84^{f}	3.89^{cd}	3.94^{cd}	3.10^{c}	2.59^{e}	3.21 ^{g}
late chem. thinning	5.30^{b}	3.22^{e}	5.33^{a}	4.62^{ab}	4.87^{a}	2.71^{e}	4.41^{b}	4.00 ^{c}

Means followed by the same letter(s) within each column are not significantly different at $P \leq 0.05$

3.2.2 Post-late thinning fruitlet retention (June 20)

On June 20 (Table 1), moderate and light pruning (50%, 25%) achieved higher retention means (4.54%, 4.49%) than severe pruning (75%; 4.01%). This advantage reflects the smaller reduction in vegetative growth under lighter pruning, which maintains a more balanced source–sink relationship and reduces physiological stress, whereas severe pruning removes a greater share of leaves and shoots, leading to carbohydrate loss and higher fruitlet drop **(Goldschmidt, 1999; Iglesias *et al*., 2007)**.

Late chemical thinning gave a comparably high mean (4.62%) to the control (4.79%), as delayed NAA application (350 ppm) targeted well-developed fruitlets more resistant to abscission **(Guardiola and García-Luis, 2000)**. In the off-year (second season), early chemical thinning (T6) exceeded the control (4.04% vs. 3.31%), likely by reducing the intensity of the natural June drop through improved nutrient supply to the remaining fruitlets, while late manual thinning (T7) showed reduced retention in the third season. Overall, these results support combining moderate pruning with well-timed chemical thinning to achieve more stable fruitlet retention and better mitigation of alternate bearing **(Stander *et al*., 2018)**.

3.2.3 Pre-harvest fruit retention (mid-December)

Pre-harvest fruit retention was significantly affected by pruning and thinning treatments across the three seasons (Table 1). Moderate and light pruning consistently showed higher retention than severe pruning, with combined means of 4.14%, 4.08%, and 3.57%, respectively. Chemical thinning with NAA (350 ppm), whether early (T6: 3.80%) or late (T8: 4.00%), generally outperformed manual thinning (T5: 3.40%; T7: 3.21%) in the combined analysis. Timing effects were most evident during the off-year (second season), where early chemical thinning (T6) achieved the highest retention among thinning treatments (3.38%), significantly exceeding the control (3.08%), while late chemical thinning (T8) dropped to 2.71%, suggesting that early intervention in the preceding on-year helped preserve carbohydrate reserves and reduce pre-harvest fruit drop in the following season **(Matias *et al*., 2023)**.

Conversely, the marked decline in late manual thinning (T7) during the third season (2.59%) confirmed its limited effectiveness in sustaining fruit persistence during heavy-yielding cycles **(Stander *et al*., 2018)**. Overall, moderate and light pruning gave relatively higher retention, while the untreated control preserved a natural crop load, achieving a balance between initial fruit set and minimized physiological drop **(Hmmam *et al*., 2023)**.

3.3 Leaf Nutritional Status

3.3.1 Leaf Macro-nutrients

Leaf nutritional status in **Table (2)** reflects how effectively treatments manage internal reserves to reduce alternate bearing. For nitrogen (N), early thinning - manual (T5) and chemical (T6) - gave the highest combined means (2.41%, 2.35%), as early removal of competing reproductive sinks redirected nitrogenous compounds to leaves and buds rather than fruit growth **(Nartvaranant, 2016; Martínez-Fuentes *et al*., 2010; Guardiola and García-Luis, 2000)**. Severe pruning (T1) raised N in the second season (2.32%), a compensatory "concentration effect" from reduced canopy volume **(Jarrell and Beverly, 1981; Al-Saif *et al*., 2023)**, whereas moderate pruning (T2: 1.99%), light pruning (T3: 1.93%), and late chemical thinning (T8: 1.99%) showed the lowest levels, reflecting dilution from larger canopy size and crop load, and continued nutrient drain under delayed intervention **(Jarrell and Beverly, 1981; Guardiola and García-Luis, 2000)**.

For phosphorus (P), the control (T4) and early manual thinning (T5) recorded the highest means (0.33%, 0.30%), as early fruit-load reduction spared P from seed development for tree vigor **(Guardiola and García-Luis, 2000)**, while moderate pruning (T2) and late manual thinning (T7) recorded the lowest levels (≈0.20%) due to macronutrient competition under heavy cropping **(Bangerth, 1989)**. Late chemical thinning (T8) showed relatively higher P (0.26%) than T7 (0.20%), which may be related to the reduction in crop load after NAA application and the subsequent improvement in nutrient availability to the remaining tissues.

For potassium (K), the control (T4) consistently recorded the highest levels (overall mean 2.32%), reflecting low sink demand in the off-year and stable canopy in on-years, versus dilution from vegetative flushes in other treatments, particularly severe pruning **(Marschner, 2012)**. Early manual (T5) and late chemical thinning (T8) recorded the lowest K, with T8 dropping to 1.19%, reflecting strong K mobilization from leaves to developing fruit under heavy crop load **(Wu *et al*., 2024; Zekri and Obreza, 2013)**.

For calcium (Ca), which accumulates via the transpiration stream rather than phloem transport, the control (T4) and early chemical thinning (T6) retained the highest levels (5.18%, 4.74%) - the former from a large, stable canopy sustaining transpiration, while severe pruning (T1) recorded the lowest Ca (3.33%) due to reduced leaf surface weakening the transpiration stream and limited Ca transport **(Saure, 2005).**

For magnesium (Mg), the control again showed superiority, as unthinned fruits exerted less sink strength, limiting Mg export from leaves and reducing dilution from vegetative flushes **(Marschner, 2012)**. Light pruning (T3) followed closely due to a balanced source–sink ratio favoring photosynthetic efficiency **(Jiao *et al*., 2023)**, whereas severe pruning (T1) and late thinning (T7, T8) showed the lowest Mg through distinct mechanisms, dilution from vigorous shoot growth versus prolonged fruit-driven Mg export before removal **(Goldschmidt and Koch, 1996).**

Table (2). Effect of pruning and thinning treatments on leaf macro-nutrients (N, P, K, Ca, and Mg %) and shoot C: N ratio of Balady mandarin over three seasons and their overall mean

Season	1st	2nd	3rd	Overall Mean	1st	2nd	3rd	Overall Mean
Treat	**Leaf content of N (%)**				**Leaf content of P (%)**			
Pruning75%	2.19b^{c}	2.32^{ab}	2.14^{bcd}	2.22^{b}	0.24^{bcd}	0.23^{cd}	0.25^{c}	0.24^{cd}
Pruning50%	1.90^{d}	1.95^{c}	2.12^{cd}	1.99^{c}	0.19^{d}	0.20^{b}	0.20^{d}	0.20^{e}
Pruning25%	1.91^{d}	1.94^{c}	1.95^{d}	1.93^{c}	0.23^{cd}	0.20^{d}	0.25^{c}	0.23^{d}
control	2.19^{ab}	2.26^{ab}	2.22^{bc}	2.23^{b}	0.33^{a}	0.33^{a}	0.33 ^{a}	0.33^{a}
early man. thinning	2.46^{a}	2.33^{ab}	2.43^{a}	2.41^{a}	0.29^{ab}	0.32^{a}	0.30^{ab}	0.30^{b}
early chem. thinning	2.35^{ab}	2.37^{a}	2.33^{ab}	2.35^{ab}	0.22^{cd}	0.29^{ab}	0.24^{cd}	0.25^{cd}
late man. thinning	2.27^{ab}	2.30^{ab}	2.27^{abc}	2.28^{ab}	0.19^{d}	0.22^{cd}	0.20^{d}	0.20^{e}
late chem. thinning	1.93^{cd}	2.05^{bc}	1.97^{d}	1.99^{c}	0.25^{bc}	0.26^{bc}	0.28^{bc}	0.26^{c}
Treat	**Leaf content of K (%)**				**Leaf content of Ca (%)**			
Pruning75%	1.93^{abc}	1.94^{bc}	1.93^{b}	1.93^{bc}	3.29^{f}	3.43^{f}	3.27^{e}	3.33^{e}
Pruning50%	2.03^{ab}	2.07^{b}	2.07^{b}	2.06^{b}	4.44^{bcd}	4.55^{bcd}	4.42^{bc}	4.47^{c}
Pruning25%	1.95^{ab}	1.91^{bc}	1.98^{b}	1.94^{bc}	3.84^{e}	3.91^{ef}	3.88^{d}	3.88^{d}
control	2.14^{a}	2.37^{a}	2.44^{a}	2.32^{a}	5.19^{a}	5.23^{a}	5.12^{a}	5.18^{a}
early man. thinning	1.72^{c}	1.75^{c}	1.78^{b}	1.75^{d}	4.61^{bc}	4.60^{b}	4.51^{bc}	4.57^{bc}
early chem. thinning	1.90^{bc}	1.90^{bc}	1.92^{b}	1.91^{c}	4.79^{ab}	4.73^{b}	4.70^{ab}	4.74^{b}
late man. thinning	1.84^{bc}	1.79^{c}	1.87^{b}	1.83^{cd}	4.09^{cde}	4.13^{cde}	4.17^{cd}	4.13^{d}
late chem. thinning	1.19^{bc}	1.89^{bc}	1.88^{b}	1.89^{bc}	3.97^{de}	4.07^{de}	4.05^{cd}	4.03^{d}
Treat	**Leaf content of Mg (%)**				**Shoot C: N ratio**			
Pruning75%	0.37^{c}	0.39^{b}	0.37^{c}	0.38^{cd}	13.37^{b}	13.75^{b}	9.74^{b}	12.29^{b}
Pruning50%	0.40^{c}	0.39^{b}	0.39^{c}	0.39^{c}	14.09^{a}	13.49^{b}	9.57^{b}	12.39^{b}
Pruning25%	0.49^{b}	0.45^{b}	0.50^{b}	0.48^{b}	13.08^{c}	13.05^{c}	9.28^{c}	11.81^{c}
control	0.86^{a}	0.79^{a}	0.88^{a}	0.84^{a}	12.22^{ef}	12.52^{d}	8.94^{d}	11.23^{e}
early man. thinning	0.37^{c}	0.38^{b}	0.38^{c}	0.38^{cd}	12.39^{de}	13.14^{c}	9.34^{c}	11.62^{d}
early chem. thinning	0.37^{c}	0.38^{b}	0.38^{c}	0.38^{cd}	12.62^{d}	14.74^{a}	10.38^{a}	12.58^{a}
late man. thinning	0.38^{c}	0.41^{b}	0.40^{c}	0.39^{c}	11.93^{g}	12.07^{e}	8.64^{e}	10.88^{g}
late chem. thinning	0.35^{c}	0.34^{b}	0.34^{c}	0.35^{d}	12.11^{fg}	12.32^{de}	8.81^{de}	11.08^{f}

Means followed by the same letter(s) within each column are not significantly different at $P \leq 0.05$

3.3.2 Leaf Micro-nutrients

For iron (Fe) and zinc (Zn) in Table (3), late chemical thinning (T8) consistently recorded the highest levels (Fe: 119.86 ppm; Zn: 28.86 ppm), attributed to reduced fruit sink demand and the beneficial effects of NAA on metabolic activity, senescence delay, and nutrient retention **(Pestana *et al*., 2005; Fernández *et al*., 2013)**. Light pruning (25%) recorded a lower mean Fe concentration (81.51 ppm), likely reflecting dilution across the larger retained canopy volume, where a greater proportion of vegetative growth remained compared to the more drastically reduced canopy under severe pruning. The control recorded the lowest Zn concentration, consistent with intensive phloem-mediated translocation to fruit under high sink demand, similar to the patterns observed for K and Mg, while severe pruning also showed low Zn, mirroring its parallel decline in boron; both reductions are attributed to dilution from vigorous vegetative regrowth outpacing root uptake and xylem translocation to mature leaves **(Goldschmidt and Koch, 1996).**

Manganese (Mn) and boron (B) followed contrasting patterns. Mn, transpiration-dependent like Ca, was highest under the control and light pruning (39.17–39.40 ppm) due to a larger, stable canopy, and lowest under severe pruning (17.49 ppm) from reduced leaf area and weakened transpiration. B, by contrast, accumulated most under early thinning (T5, T6: 54.11, 52.89 ppm) through luxury consumption favored by an optimized source–sink ratio **(Marschner, 2012)**, while late thinning and light pruning recorded the lowest levels. Overall, these results confirm that strategic source–sink manipulation through pruning and thinning shapes the foliar micronutrient profile in citrus, with moderate interventions generally favoring better nutrient reserves.

Table (3). Effect of pruning and thinning treatments on leaf micro-nutrients (Fe, Zn, Mn, and B, ppm) of Balady mandarin over three seasons and their overall mean

Season	1st	2nd	3rd	Overall Mean	1st	2nd	3rd	Overall Mean
Treat	**Leaf- Fe (ppm)**				**Leaf- Zn (ppm)**			
Pruning75%	97.35^{c}	95.42^{c}	98.36^{c}	97.04^{d}	18.07^{c}	18.24^{c}	18.18^{e}	18.16^{e}
Pruning50%	86.36^{d}	92.39^{c}	93.63^{c}	90.80^{e}	23.30^{b}	23.77^{b}	23.33^{bc}	23.47^{cd}
Pruning25%	81.35^{d}	80.00^{d}	83.18^{d}	81.51^{f}	23.03^{b}	23.86^{b}	23.27^{bc}	23.39^{cd}
control	115.16^{ab}	108.89^{b}	114.15^{ab}	112.73^{bc}	18.53^{c}	19.39^{c}	20.40^{de}	19.44^{e}
early man. thinning	105.71^{bc}	109.35^{b}	110.12^{b}	108.40^{c}	22.33^{b}	24.49^{b}	22.43^{cd}	23.09^{d}
early chem .thinning	112.37^{ab}	112.37^{ab}	118.95^{ab}	114.56^{b}	24.37^{b}	25.70^{ab}	24.53^{bc}	24.87^{b}
late man. thinning	117.79^{a}	118.57^{ab}	118.80^{ab}	118.39^{a}	24.26^{b}	24.17^{b}	24.96^{b}	24.46^{bc}
late chem. thinning	119.34^{a}	119.72^{a}	120.50^{a}	119.86^{a}	29.00^{a}	27.58^{a}	30.00^{a}	28.86^{a}
Treat	**Leaf – Mn (ppm)**				**% Leaf- B (ppm)**			
Pruning75%	16.97^{d}	17.93^{d}	17.57^{e}	17.49^{e}	41.67^{e}	46.00^{b}	50.00^{b}	45.89^{b}
Pruning50%	30.33^{b}	31.09^{b}	30.77^{b}	30.73^{b}	47.33^{c}	47.00^{b}	46.00^{c}	46.78^{b}
Pruning25%	38.50^{a}	39.63^{a}	40.07^{a}	39.40^{a}	36.67^{h}	40.33^{de}	40.67^{d}	39.22^{c}
control	38.32^{a}	39.48^{a}	39.72^{a}	39.17^{a}	43.67^{d}	44.00^{bc}	45.33^{c}	44.33^{b}
early man. thinning	26.50^{bc}	27.08^{bc}	27.87^{bc}	27.15^{c}	54.67^{a}	54.67^{a}	53.00^{a}	54.11^{a}
early chem. thinning	21.23^{cd}	22.90^{cd}	22.23^{de}	22.12^{d}	51.33^{b}	52.33^{a}	55.00^{a}	52.89^{a}
late man. thinning	22.27^{cd}	23.60^{c}	22.35^{d}	22.74^{d}	38.67^{g}	37.67^{e}	38.67^{d}	38.33^{c}
late chem. thinning	25.22^{bc}	26.30^{bc}	$25,63^{cd}$	25.72^{c}	39.00^{f}	41.33^{cd}	40.33^{d}	40.22^{c}

Means followed by the same letter(s) within each column are not significantly different at $P \leq 0.05$

3.3.3 Shoot C: N Ratio and Alternate Bearing Regulation

The shoot carbon-to-nitrogen (C: N) ratio (Table 2 & Figure 1) provided the physiological explanation for breaking the biennial cycle. Moderate pruning (T2) and severe pruning (T1, 75%) achieved significantly higher overall C: N ratios than light pruning (T3, 25%), while early chemical thinning (T6: NAA 350 ppm) showed clear superiority over its manual counterpart (T5) and all late thinning treatments.

Notably, T6 during the off-year (second season) showed a physiological response similar to moderate pruning during on-years, with the C:N ratio rising to 14.74, suggesting that chemical intervention at the appropriate phenological stage can compensate for natural fluctuations in carbohydrate reserves -consistent with source–sink dynamics reviewed by **Agustí *et al*. (2026)** and with **García-Luis *et al*. (1995)**, who identified early crop-load regulation as the primary driver of an elevated C:N balance and improved subsequent flowering.

The contrast between T6 (12.58) and T8 (11.08) further revealed the critical role of thinning timing in carbohydrate preservation: in T8, fruits remained on the trees longer, acting as strong carbohydrate sinks that depleted starch reserves in leaves and shoots, whereas early intervention in T6 eliminated this sink competition at a critical developmental stage, preventing carbohydrate exhaustion and supporting the Nutritional Balance Hypothesis (**Goldschmidt, 1999)**. This favorable biochemical profile enabled trees to develop robust floral buds for the following season despite a heavy current crop, achieving a better balance between vegetative and reproductive growth as part of the adaptation strategy of citrus trees in alternating environments (**Bustan *et al*., 2011**).

Regression analysis (Figure 2) using season-adjusted ANCOVA (n = 72) demonstrated a significant negative correlation between shoot C: N ratio and fruitlet retention on May 29 (R^2 = 0.694, P = 0.022, Slope = -1.105). It should be noted that "early thinning" here refers to the earlier of our two thinning schedules (29 May, relative to the later 20 June application) rather than to early post-anthesis timing.

Fruitlet abscission in citrus has been reported to become increasingly carbohydrate-dependent as fruitlets develop, with flower and early-stage abscission largely independent of carbohydrate shortage, while later stages are more closely tied to sucrose limitation and inter-fruitlet competition for photoassimilates **(Ruiz *et al*., 2001)**.

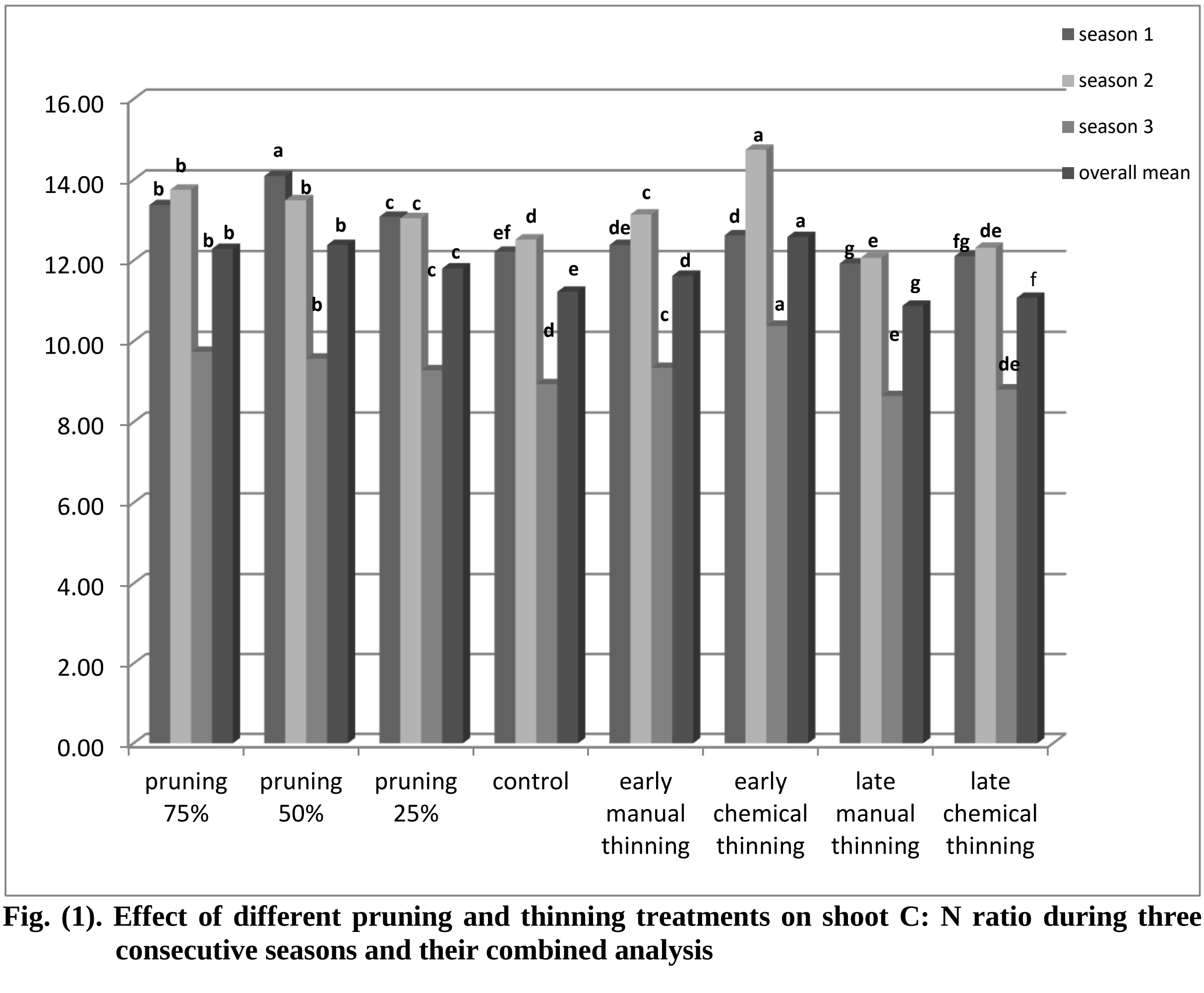

Fig. (1). Effect of different pruning and thinning treatments on shoot C: N ratio during three consecutive seasons and their combined analysis

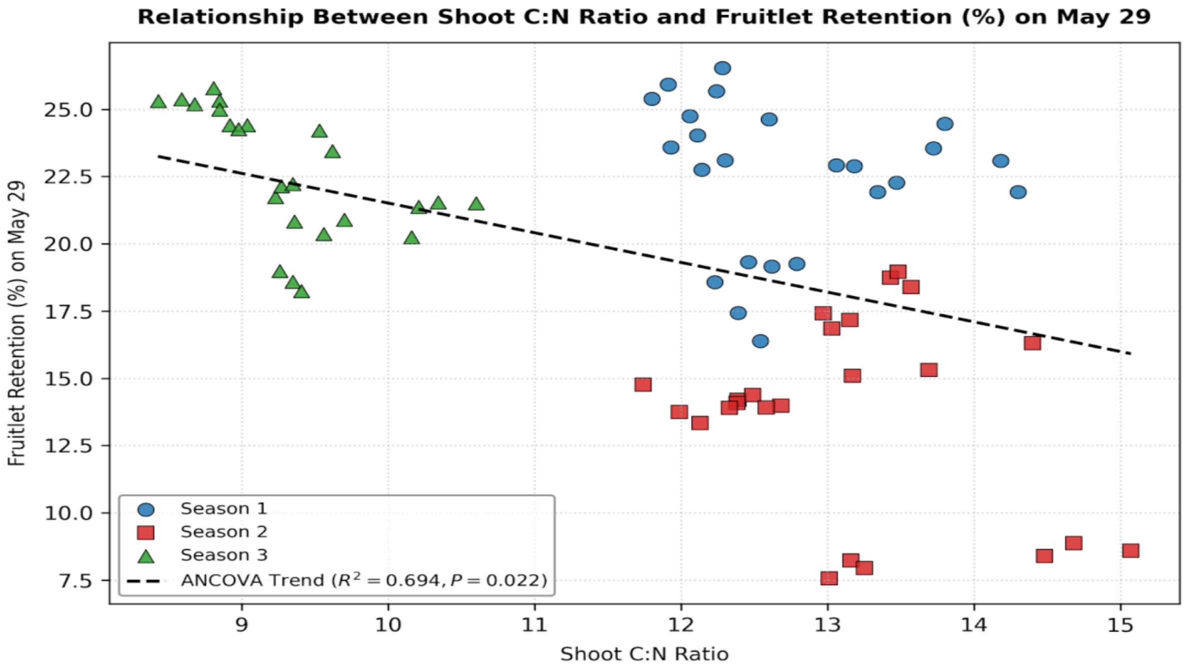

Fig. (2). Relationship between shoot C: N ratio and post-early thinning fruitlet retention (%) on 29 May across three seasons, as affected by different pruning and thinning treatments. The regression line indicates a significant negative correlation (R^2 = 0.694, P = 0.022)

The lowest retention values coincided with early manual and chemical thinning (T5, T6), which combined elevated C: N ratios with reduced retention. This negative relationship reflects the primary influence of deliberate, early fruitlet removal rather than carbon limitation at this specific date; the early reduction in sink demand allowed carbohydrate accumulation (elevated C: N), while naturally resulting in lower remaining fruitlet percentages. Conversely, pruning-only treatments and control maintained higher retention percentages under moderate C: N levels, indicating that the overall regression line captures both treatment-induced fruitlet removal and early seasonal drop dynamics acting together at this stage **(Gómez-Cadenas *et al*., 2000; Talon *et al*., 1998)**.

3.4 Fruit Yield

1. Yield as number of fruits per tree

Fruit number per tree was significantly influenced by canopy management and thinning across the three seasons (Table 4). The control (T4) recorded the highest overall mean (492 fruits) but showed severe alternate-bearing fluctuations, declining sharply in the off-year—consistent with **Bustan *et al*. (2011)**, who linked excessive on-year fruit load to depleted reserves and a suppressed subsequent cycle. Moderate pruning (T2: 459 fruits) outperformed light (T3) and severe (T1) pruning, reflecting a better balance between vegetative growth and floral-bud preservation, whereas severe pruning reduced fruit number through bud removal and vigorous regrowth **(Abobatta, 2019)**. Chemical thinning (T6, T8) generally exceeded manual thinning (T5, T7) in fruit number, reflecting the more selective nature of NAA-induced abscission; early chemical thinning (T6) achieved the highest off-year stability (381 fruits), linked to its elevated C:N ratio (Figure 1), while late chemical thinning (T8) dropped to the lowest value (270 fruits). Across seasons, treatments sustaining high fruitlet and fruit retention consistently produced the highest total counts, consistent with the role of source–sink regulation in yield stability **(Stander *et al*., 2018; Martínez-Cuenca *et al*., 2016).**

2. Yield as Fruit Weight per Tree (kg)

Average fruit yield per tree (Table 4) was markedly affected by pruning and thinning treatments across the three seasons. Early chemical thinning (T6) consistently delivered the greatest yield in every season, attaining the highest combined mean (60.68 kg), while severe pruning (T1) and the control (T4) yielded the lowest values.

This performance was reflected in the Biennial Bearing Index (BBI, Figure 3): the control and late chemical thinning (T8) showed the highest BBI values (~0.27 and 0.33, respectively), indicating severe yield instability, whereas T6 achieved one of the lowest BBI scores (~0.18), demonstrating that it not only maximized yield but also stabilized it across seasons—a direct result of the optimal C:N ratio and stable nitrogen reserves previously achieved under T6, which ensured consistent floral induction even after a heavy crop year **(Martínez-Fuentes *et al*., 2013)**.

Yield performance across treatments was largely governed by the inverse relationship between fruit number and fruit weight. In the control, the high fruit number (492) led to strong resource competition, resulting in smaller fruits (106.33 g) and a marked yield decline in the second season (35.29 kg). Late chemical thinning, by contrast, failed to mitigate the biennial habit: despite reducing crop load, the intervention came too late (June), when the tree had already committed its energy to the current load, resulting in the lowest off-year yield (32.04 kg) and the highest BBI (0.325) **(Iglesias *et al*., 2007)**.

Early chemical thinning and moderate pruning achieved a more favorable physiological balance by reducing crop load at a critical timing; preventing nutrient dilution and maintaining high sink strength in the remaining fruit **(Agustí *et al*., 2026)**. This balance ensured adequate fruit-size compensation while preserving overall fruit numbers, enhancing cumulative yield and reducing BBI **(Agustí *et al*., 2002)**, consistent with evidence that early crop-load adjustment is essential for canopy efficiency and citrus productivity **(Abobatta, 2019)**.

Table (4). Effect of pruning and thinning treatments on fruit number per tree, total yield (per tree and per feddan), and yield efficiency (kg/m³) of Balady mandarin over three seasons and their overall mean

Season	**1st**	**2nd**	**3rd**	**Overall Mean**	**1st**	**2nd**	**3rd**	**Overall Mean**
Treat	**Fruit No./ tree**				**Yield of tree (Kg)**			
Pruning75%	415^{h}	319^{f}	435^{g}	390^{g}	55.06^{g}	39.99^{e}	57.96^{g}	51.00^{f}
Pruning50%	511^{c}	346^{b}	520^{c}	459^{c}	65.02^{b}	42.07^{c}	66.91^{b}	58.00^{b}
Pruning25%	508^{d}	342^{cd}	503^{d}	451^{d}	59.95^{e}	37.99^{f}	62.04^{d}	53.33^{d}
control	594^{a}	335^{e}	548^{a}	492^{a}	62.97^{c}	35.29^{g}	59.01^{f}	52.42^{e}
early man. thinning	444^{g}	345^{bc}	463^{f}	417^{f}	60.98^{d}	44.94^{b}	64.72^{c}	56.88^{c}
earlychem. thinning	502^{e}	381^{a}	523^{b}	469^{b}	67.05^{a}	46.95^{a}	68.05^{a}	60.68^{a}
late man. thinning	487^{f}	339^{d}	499^{e}	442^{e}	57.05^{f}	40.99^{d}	58.97^{f}	52.34^{e}
late chem. thinning	560^{b}	270^{g}	521^{bc}	450^{d}	64.96^{b}	32.04^{h}	61.03^{c}	52.68^{e}
Treat	**Yield of Feddan (ton)**				**Yield efficiency(kg/m3)**			
Pruning75%	18.72^{f}	13.59^{e}	19.70^{f}	17.34^{e}	2.70^{g}	1.99^{d}	2.903^{d}	2.53^{e}
Pruning50%	22.11^{b}	14.30^{b}	22.75^{b}	19.72^{b}	3.70^{d}	2.25^{c}	4.30^{b}	3.41^{c}
Pruning25%	20.38^{d}	12.92^{bcd}	21.09^{d}	18.13^{c}	3.48^{ef}	2.45^{c}	4.20^{bc}	3.37^{c}
control	21.13^{c}	12.00^{d}	20.06^{e}	17.73^{d}	3.45^{f}	1.97^{d}	4.08^{c}	3.17^{d}
early man. thinning	21.32^{c}	15.28^{bc}	22.00^{c}	19.53^{b}	3.57^{e}	2.45^{c}	4.26^{b}	3.43^{c}
early chem. Thinning	22.80^{a}	15.96^{a}	23.14^{a}	20.63^{a}	4.47^{a}	3.13^{a}	5.16^{a}	4.25^{a}
late man. thinning	19.40^{e}	13.94^{cd}	20.05^{ef}	17.79^{d}	4.18^{b}	2.79^{b}	4.21^{bc}	3.73^{b}
late chem. thinning	22.09^{b}	10.90^{f}	20.75^{d}	17.91^{d}	4.02^{c}	1.97^{d}	4.28^{b}	3.42^{c}

Means followed by the same letter(s) within each column are not significantly different at $P \leq 0.05$

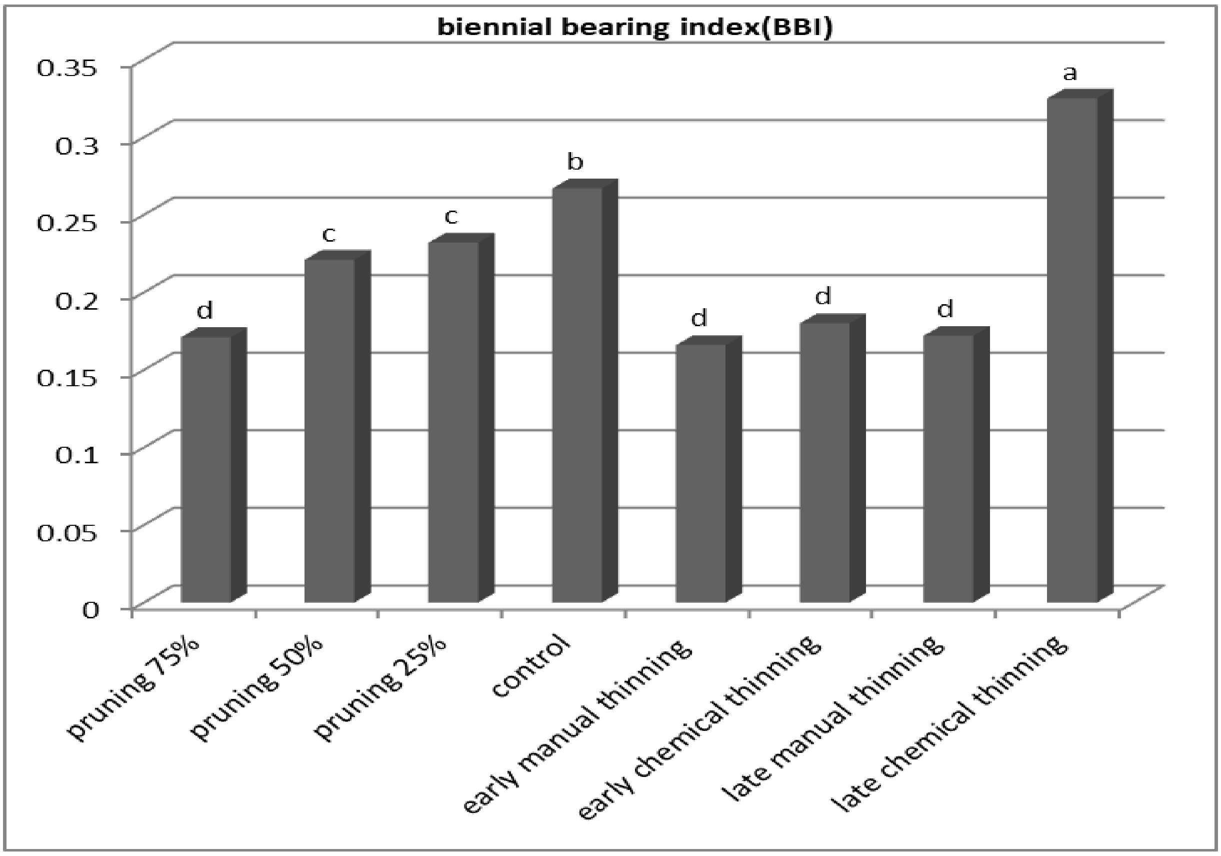

Fig. (3). Effect of different pruning and thinning treatments on Biennial Bearing Index (BBI) during three consecutive seasons

3. Biennial Bearing Index (BBI)

The Biennial Bearing Index (BBI), developed by **Pearce and Doberšek-Urbanc (1967)** to assess alternate bearing in perennial fruit trees, ranges from near 0 (yield stability) to near 1 (strong alternation), making it a key metric for evaluating treatments aimed at stabilizing production and reducing economic risk in citrus.

Combined analysis across the three seasons (Figure 3; $LSD_{0.05}$ = 0.0157) revealed significant differences among treatments. Late chemical thinning (T8) showed the highest BBI (0.325a), indicating pronounced alternation, while the control (T4) recorded a relatively high value (0.267b), reflecting noticeable natural yield fluctuation in the absence of intervention. Moderate (T2: 0.22c) and light pruning (T3: 0.232c) showed intermediate values, whereas early manual thinning (T5: 0.166d), late manual thinning (T7: 0.172d), early chemical thinning (T6: 0.180d), and severe pruning (T1: 0.171d) achieved the lowest, most stable BBI values.

The stability under severe pruning is mainly attributed to the drastic reduction in initial crop load and vegetative growth, which minimizes carry-over inhibitory effects between on- and off-years and limits the physiological feedback loop driving alternate bearing **(Samach and Smith, 2013)**, by removing a large proportion of potential bearing wood, severe pruning breaks the typical high–low yield cycle, producing more uniform output despite lower absolute yield—consistent with reports that severe pruning reduces BBI through aggressive load and canopy management **(Matias *et al*., 2023)**. Manual and early chemical thinning (T5, T6, T7) achieved comparable stability through precise crop-load control and improved carbohydrate and nitrogen reserves **(Ahmadpoor *et al*., 2022; Abobatta, 2019)**, whereas late chemical thinning (T8) tended to worsen yield fluctuation, likely because delayed intervention failed to adequately offset the carry-over inhibitory effects of a heavy fruit load **(Agustí *et al*., 2022)**.

4. Yield as Ton/Feddan

Yield per feddan (Table 4) responded strongly and consistently to pruning and thinning treatments across the three seasons. Early chemical thinning (T6) achieved the highest yield in every season, attaining the highest combined mean (20.63 ton/fed), closely followed by moderate pruning (T2: 19.72 ton/fed) and early manual thinning (T5: 19.53 ton/fed), both at the same significance level. Late manual (T7: 17.79 ton/fed) and chemical thinning (T8: 17.91 ton/fed), along with the control (T4: 17.73 ton/fed), produced lower overall yields, while severe pruning (T1: 17.34 ton/fed) recorded the significant minimum.

The economic value of early intervention was most evident in the off-year (second season): while T8 and the control suffered sharp declines (10.90 and 12.00 ton/fed, respectively), T6 maintained significantly higher productivity (15.96 ton/fed), limiting off-year losses to 30% and ensuring more acceptable returns for growers during the low-yielding cycle. This superiority reflects the timely reduction of crop load during early fruit development, which reduced competition among developing fruits, enhanced source–sink assimilate distribution (carbohydrates, water, nutrients), and supported better retention, size, and final fruit weight.

Moderate pruning similarly provided a balanced reduction in vegetative growth and crop load, enhancing canopy efficiency and photosynthetic capacity without excessive vegetative stress, whereas severe pruning, late manual thinning, and the control either reduced fruit number without sufficient compensation in fruit weight or maintained an excessively high natural load, resulting in greater physiological drop, smaller fruit size, and lower overall productivity. These findings align with citrus literature showing that early chemical thinning maximizes yield through effective crop-load management **(Matias *et al*., 2023; Abobatta, 2019)**, moderate pruning improves productivity by enhancing canopy light interception, resource-use efficiency, and carbohydrate accumulation in branches **(Ahmadpoor *et al*., 2022; Guardiola and García-Luis, 2000)**, and severe pruning or delayed manual thinning limits yield through carbohydrate depletion or non-selective fruit loss **(Ladaniya, 2008)**.

5. Yield efficiency as (kg/m^3)

Yield efficiency (kg fruit per m³ canopy volume) differed markedly among treatments across the three seasons (Table 4). Regression analysis (Figure 4), using season-adjusted ANCOVA on replicate-level data (n = 72), demonstrated a significant negative correlation between tree volume increment and yield efficiency (**slope = -0.0149, R^2 = 0.795, P < 0.0001**), reflecting competition between vegetative vigor and reproductive development. Early chemical thinning (T6) achieved the highest efficiency (4.25 kg/m³), followed by late manual thinning (T7: 3.73 kg/m³), then early manual thinning (T5: 3.43), late chemical thinning (T8: 3.42), moderate pruning (T2: 3.41), and light pruning (T3: 3.37), which formed comparable intermediate values. The control (T4) and severe pruning (T1) showed the lowest efficiencies (3.17 and 2.53 kg/m³, respectively).

This physiological contrast is especially clear between T1 and T6: severe pruning triggered vigorous vegetative expansion, recording the highest tree volume increment (56.69%, Table 1), yet failed to convert this structural growth into yield, confirming that available resources were directed toward canopy regrowth rather than reproductive organs. Early chemical thinning, by contrast, minimized volume increment (8.71%) while redirecting metabolic energy toward fruit biomass, achieving a more favorable balance between vegetative and reproductive sinks.

This ranking revealed clear differences in the productive use of canopy volume, consistent with citrus research showing that early chemical thinning maximizes efficiency by reducing initial fruit load at a critical stage and lowering intra-fruit competition **(Matias *et al*., 2023; Abobatta, 2019)**, moderate pruning maintains a functional photosynthetic capacity while balancing efficiency **(Ahmadpoor *et al*., 2022)**, and selective crop-load adjustment based on canopy volume supports stable cumulative yield across seasons **(Khurshid and Sanderson, 2023)**. Severe pruning and the untreated control, in contrast, reduced efficiency through excessive removal of fruiting surface (T1) or an overburdened canopy that induced resource dilution and elevated natural fruit drop **(**T4; **Abobatta, 2019**).

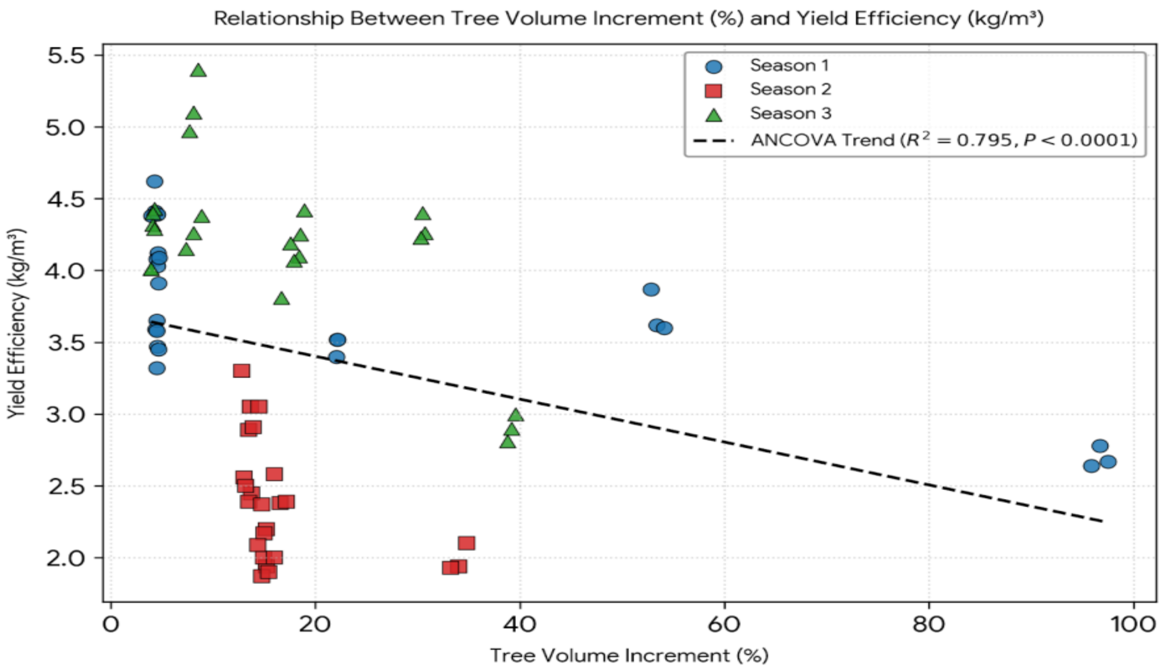

Fig. (4). Relationship between tree volume increment (%) and yield efficiency (kg/m³) across three seasons, as affected by different pruning and thinning treatments. The regression line indicates a significant negative correlation ($R^2 = 0.795$, P < 0.0001)

3.5 Fruit quality

3.5.1 Fruit Physical Components

Fruit weight (gm)

Fruit weight was significantly influenced by pruning and thinning treatments across all seasons and in the combined analysis (Table 5). Early manual thinning (T5) achieved the highest combined mean (135.79 g), followed by severe pruning (T1: 130.41 g) and early chemical thinning (T6: 128.96 g), while moderate pruning (T2: 125.80 g), late manual thinning (T7: 118.73 g), light pruning (T3: 117.47 g), and late chemical thinning (T8: 117.27 g) recorded significantly lower values, with the untreated control (T4) producing the smallest fruit overall (106.33 g).

This pattern reflects source–sink dynamics governing individual fruit growth. The superior fruit weight under early load-regulation (T5, T6) is attributed to the prompt reduction of competing sinks during the initial stages of fruit development, which refined the leaf-to-fruit ratio and promoted more efficient distribution of photoassimilates, including carbohydrates, water, and nutrients, toward a smaller number of developing fruit (**Agustí *et al*., 2002**). Severe pruning (T1) achieved a comparable effect on individual fruit size through a different route: by drastically reducing the number of bearing sites, it increased the assimilates available per remaining fruit (promoted individual fruit weight), even though most synthesized resources were allocated to structural canopy regrowth rather than overall yield efficiency **(Ahmadpoor *et al*., 2022).** By contrast, delaying crop-load adjustment in late thinning (T7, T8), applied after the natural window for cell division had largely closed, failed to induce meaningful resource reallocation, while the unregulated, overloaded canopy of the control intensified competitive pressure and assimilate dilution, restricting individual fruit expansion, consistent with reports linking delayed thinning to reduced fruit-size compensation from earlier nutrient depletion **(Abobatta, 2019**).

Table (5). Effect of pruning and thinning treatments on fruit physical characteristics (weight, length, diameter, and L: D ratio) of Balady mandarin over three seasons and their overall mean

Season	1st	2nd	3rd	Overall Mean	1st	2nd	3rd	Overall Mean
Treat	**Fruit weight (g)**				**Fruit length (cm))**			
Pruning75%	132.67b	125.33b	133.22b	130.41b	6.38a	5.86ab	6.33a	6.19a
Pruning50%	127.22c	121.56d	128.67c	125.8d	6.28ab	5.86ab	6.18ab	6.10ab
Pruning25%	118.00d	111.08f	123.33d	117.47f	5.85c	5.57bc	6.04bc	5.82de
control	106.00f	105.33g	107.67f	106.33g	5.08e	5.15d	5.00f	5.08g
early man. thinning	137.33a	130.25a	139.78a	135.79a	5.41d	5.10d	5.53e	5.34f
early chem. thinning	133.56b	123.22c	130.11c	128.96c	6.07bc	5.39cd	5.78de	5.75e
late man. thinning	117.11de	120.89d	118.17e	118.73e	5.81c	6.05a	5.85cd	5.91cd
late chem. thinning	116.00e	118.67e	117.13e	117.27f	5.97c	6.00a	6.07abc	6.02bc
Treat	**Fruit diameter (cm)**				**Fruit L:D ratio**			
Pruning75%	3.97f	3.38de	4.70c	4.01c	1.11bc	1.11cd	1.19ab	1.14c
Pruning50%	4.72cd	3.70c	5.20ab	4.54b	1.16b	1.13bc	1.16a	1.15bc
Pruning25%	4.82c	3.58cd	5.08b	4.49b	1.15b	1.20a	1.17b	1.17b
control	5.69a	3.31de	5.36a	4.79a	1.04d	1.07d	1.06d	1.06e
early man. thinning	4.54de	3.40de	3.53e	3.83d	1.14bc	1.18ab	1.15bc	1.15bc
early chem. Thinning	5.15b	4.04b	4.46d	4.55b	1.24a	1.18ab	1.24a	1.22a
late man. thinning	4.44e	4.37a	2.84f	3.89cd	1.10c	1.08cd	1.11c	1.10d
late chem. thinning	5.30b	3.22e	5.33a	4.62ab	1.12bc	1.14bc	1.14bc	1.13c

Means followed by the same letter(s) within each column are not significantly different at P ≤ 0.05

Fruit Length (L), Diameter (D), and L: D Ratio

Pruning and thinning treatments significantly affected fruit physical dimensions and shape (Table 5). Severe pruning (T1) recorded the highest length (6.19 cm) and diameter (5.46 cm), followed by moderate pruning (T2), while the control (T4) produced the smallest fruit in both dimensions (5.08 cm, 4.80 cm). Early chemical thinning (T6), despite relatively smaller fruit size, achieved the highest shape index (L: D = 1.22), reflecting more elongated fruit.

These differences relate to intervention timing and its effect on carbohydrate distribution: severe pruning increases assimilate availability, stimulating cell division and enlargement and yielding larger fruit, while late thinning promotes rapid cell expansion through water uptake, increasing external dimensions. Early chemical thinning, by contrast, reduces crop load during the cell-division phase, producing denser fruit tissue and a superior shape despite moderate dimensions **(Iglesias *et al*., 2007; Agustí *et al*., 2002)**. Overall, early chemical thinning optimized fruit morphology, while heavy pruning maximized absolute fruit size in Balady mandarin, underscoring the value of timed crop-load management as a practical tool for shaping fruit quality outcomes in citrus orchards.

Pulp, Peel, and Juice %

The data presented in Figures (6–9) illustrate the significant impact of pruning and thinning treatments on the physical quality of Balady mandarin fruits across three successive seasons. A consistent inverse relationship between pulp and peel percentages was observed, reflecting the differential partitioning of assimilates within the fruit under varying crop load.

During the On-years (Seasons 1 and 3), all treatments recorded higher pulp percentages compared to the off-year. The control (T4) achieved the highest pulp weight percentage (69.22% in Season 1 and 67.51% in Season 3) and correspondingly the lowest peel percentages (30.78% and 32.49%). The decline in peel proportion is explained by the great sink demand generated under heavy fruit load, intensifies competition for carbohydrates among developing fruits and preferring allocation toward pulp development **(Monselise, 1986)**.

On the opposite side, a pronounced shift occurred under low crop load during the Off-year (Season 2). The control (T4) exhibited a sharp increase in peel percentage (70.27%) accompanied by a marked decrease in pulp percentage (29.73%). When fruit numbers were low, assimilates were mainly directed toward peel tissues. **(Agustí *et al*., 2026)**. During the Off-year (Season 2), T3 maintained remarkably high juice content (59.32%), whereas T4 saw a decline in juice-bearing tissues relative to the rind (Fig. 7).

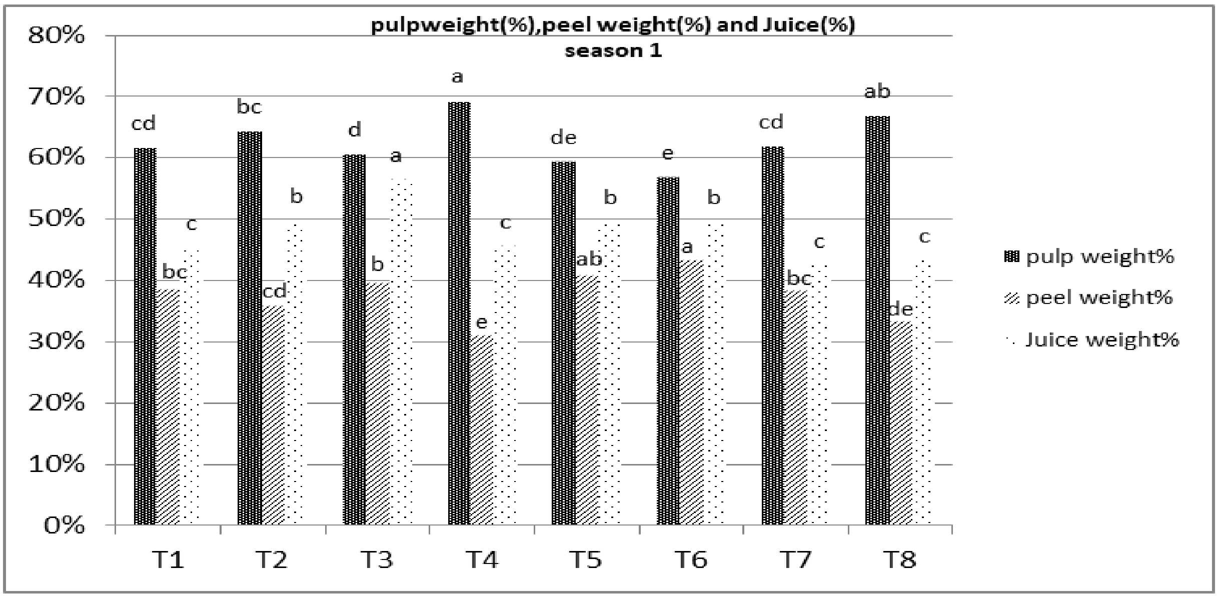

Fig. (6). Changes in fruit physical components (pulp, peel, and juice percentages) of "Balady" mandarin as affected by different pruning and thinning treatments during Season 1 (On-year)

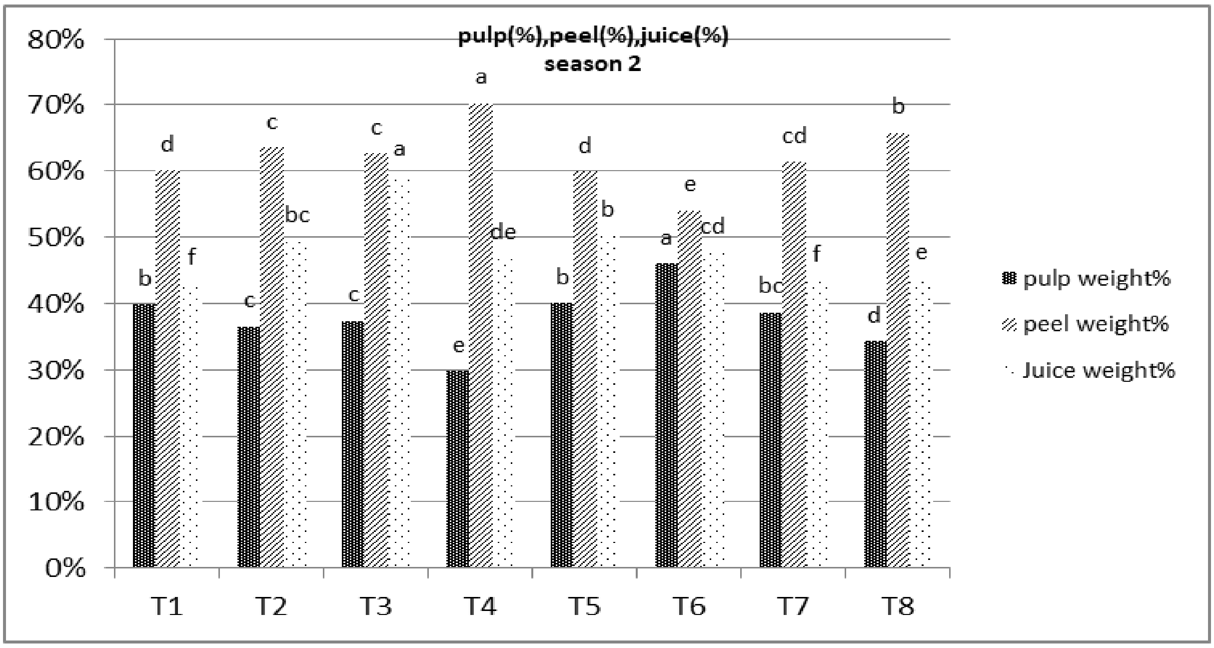

Fig. (7). Changes in fruit physical components (pulp, peel, and juice percentages) of "Balady" mandarin as affected by different pruning and thinning treatments during Season 2 (Off-year)

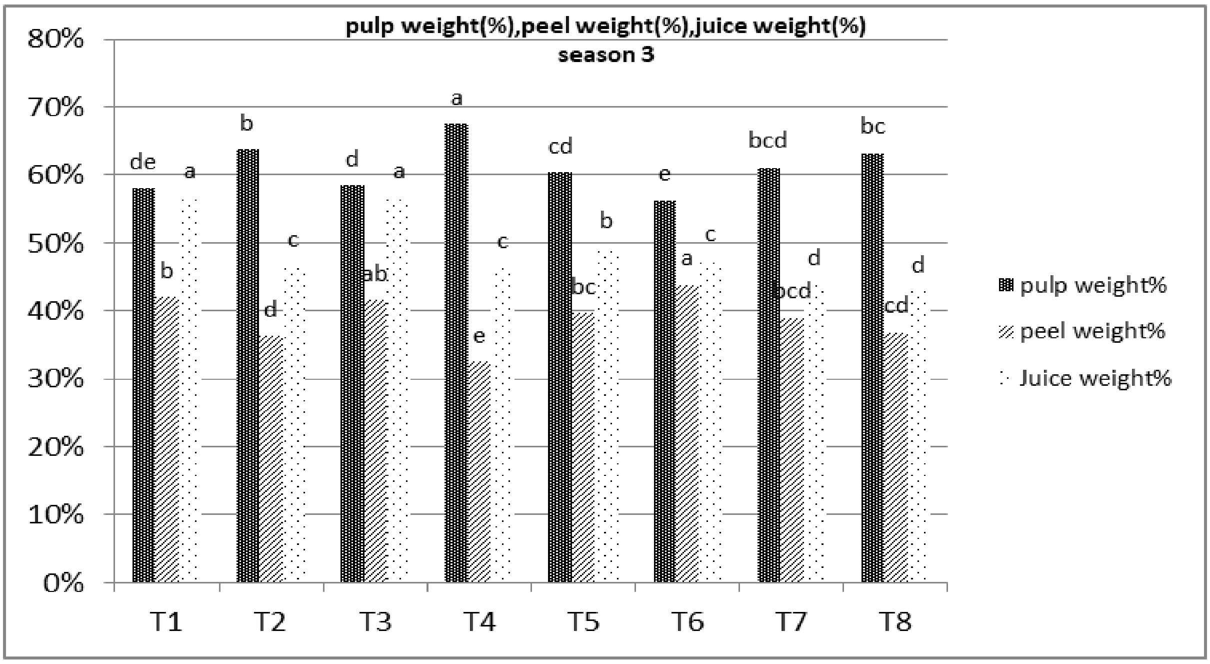

Fig. (8). Changes in fruit physical components (pulp, peel, and juice percentages) of "Balady" mandarin as affected by different pruning and thinning treatments during Season 3 (On-year)

Juice Content: Juice percentage varied significantly among treatments and seasons. In the combined analysis, light pruning (T3) achieved the highest overall juice mean (57.47%), maintaining elevated juiciness even during the off-year (59.32%). Early chemical thinning (T6) also demonstrated strong stability, recording a markedly lower peel proportion (53.99%) compared with the control (70.27%). By stabilizing cell division and expansion phases under reduced crop load, T6 preserved both internal chemical quality and pericarp balance, whereas unthinned trees diverted excess assimilates toward peel thickening rather than balanced pulp and juice accumulation.

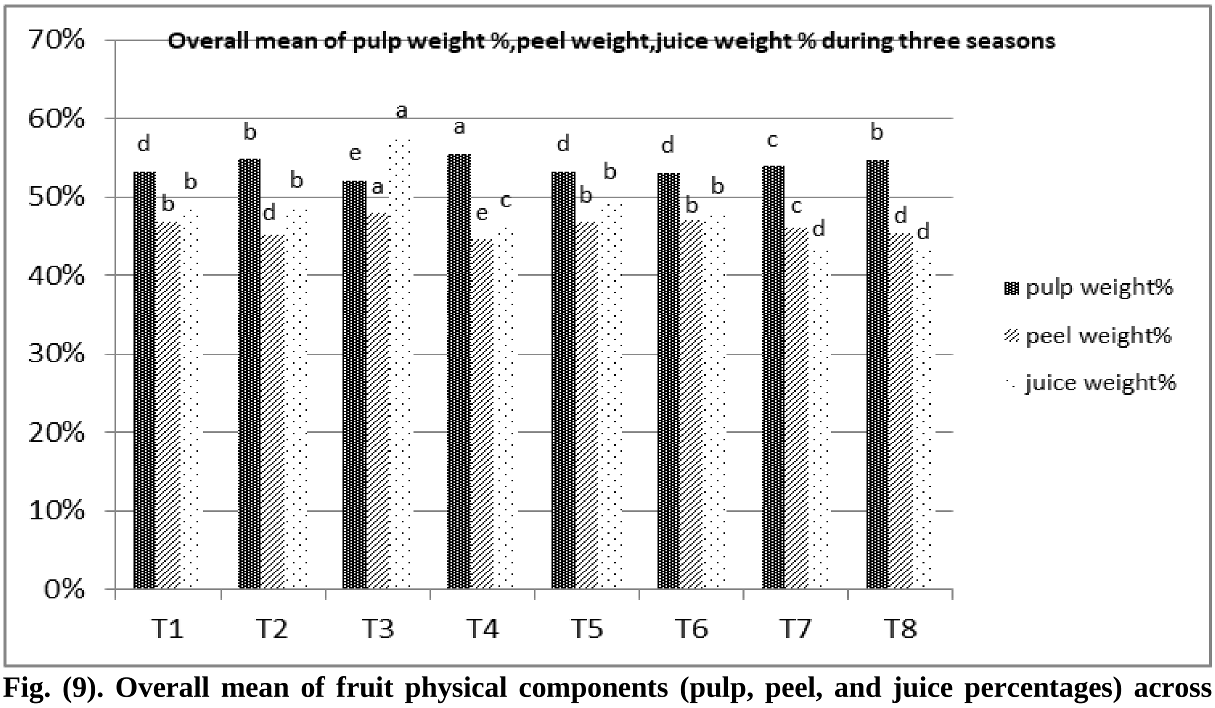

Fig. (9). Overall mean of fruit physical components (pulp, peel, and juice percentages) across three successive seasons as affected by different pruning and thinning treatments

Overall, light pruning and early chemical thinning emerged as the most effective strategies for stabilizing fruit quality across seasons, albeit through distinct physiological routes: T3 enhanced juice content, while T6 promoted consistency in internal fruit composition via optimized assimilate partitioning. In contrast, the control (T4) exhibited the highest pulp weight percentage but suffered pronounced seasonal fluctuations. Collectively, these findings underscore the regulatory role of pruning and thinning in modulating source–sink dynamics and endogenous hormonal balance that govern citrus fruit growth and development **(Agustí *et al*., 2026; Samach and Smith, 2013)**.

3.5.2 Fruit Chemical Components

Vitamin C content (mg/100 ml juice)

Table (6) shows that vitamin C (ascorbic acid) content was markedly affected by canopy management and crop-load regulation. Severe pruning (T1) outperformed moderate (T2) and light pruning (T3), consistent with **Sakhidin *et al*. (2021) and Al-Saif *et al*. (2023)**, who linked increased pruning intensity to greater ascorbic acid accumulation through reduced canopy shading and enhanced solar interception—a primary driver of vitamin C biosynthesis. Chemical thinning (T6, T8) also recorded significantly higher values than manual thinning (T5, T7), supported by **Agustí *et al*. (2002)** and **Farinha *et al*. (2020)**, who showed that chemical thinning agents trigger metabolic adjustments that increase vitamin C accumulation in the juice.

Among all treatments, early chemical thinning (T6) was superior overall, achieving the highest value in the second season (45.77 mg/100 mL) and the highest combined mean (42.41 mg/100 mL), while the untreated control (T4) recorded the lowest values across all seasons (mean 34.06 mg/100 mL)—consistent with reports that excessive fruit load increases competition for carbohydrates and nutrients, reducing final fruit quality **(Stander *et al*., 2018).**

Vitamin C levels were generally higher in the off-year (season 2) than in the on-years (seasons 1 and 3) across all treatments, consistent with the known effect of crop load on fruit quality, whereby lower fruit density improves the source–sink balance and allows greater accumulation of photoassimilates and antioxidants, including ascorbic acid, per fruit **(Monselise and Goldschmidt, 1982; Agustí *et al*., 2026)**.

Table (6). Effect of pruning and thinning treatments on chemical characteristics of fruit juice (vitamin C, TSS %, acidity, and TSS: acidity ratio) of Balady mandarin over three seasons and their overall mean

Season	1st	2nd	3rd	Overall Mean	1st	2nd	3rd	Overall Mean
Treat	**Vitamin C content (mg/100 ml juice)**				**TSS%**			
Pruning75%	36.39^{d}	43.05^{d}	39.09^{c}	39.51^{d}	12.50^{b}	11.80^{cd}	11.50^{bc}	11.93^{c}
Pruning50%	35.29^{e}	41.03^{f}	38.03^{d}	38.12^{e}	12.50^{b}	12.20^{ab}	11.83^{ab}	12.18^{b}
Pruning25%	34.17^{f}	40.80^{f}	36.80^{e}	37.26^{f}	12.70^{ab}	12.40^{a}	12.33^{a}	12.48^{a}
control	31.16^{g}	38.01^{g}	33.01^{f}	34.06^{g}	13.00^{a}	11.47^{de}	11.83^{ab}	12.10^{bc}
early man. thinning	37.78^{b}	43.78^{c}	40.24^{b}	40.60^{b}	12.80^{ab}	12.40^{a}	12.17^{a}	12.46^{a}
early chem. Thinning	39.78^{a}	45.77^{a}	41.67^{a}	42.41^{a}	12.50^{b}	12.00^{bc}	11.80^{ab}	12.10^{bc}
late man. thinning	35.00^{e}	42.00^{e}	38.00^{d}	38.33^{e}	11.50^{c}	11.17^{e}	11.00 ^{c}	11.22^{e}
late chem. thinning	36.94^{c}	43.94^{b}	39.33^{c}	40.07^{c}	11.67^{c}	11.50^{de}	11.33^{bc}	11.50^{d}
Treat	**Acidity %**				**TSS: Acid ratio**			
Pruning75%	1.24^{b}	1.28^{a}	1.33^{b}	1.28^{b}	10.06^{de}	9.22^{d}	8.64^{e}	9.31^{de}
Pruning50%	1.10^{C}	1.19^{e}	1.25^{c}	1.18^{d}	11.37^{c}	10.25^{b}	9.44^{c}	10.35^{c}
Pruning25%	1.00^{d}	1.10^{f}	1.23^{c}	1.11^{e}	12.71^{a}	11.28^{a}	9.78^{b}	11.26^{b}
control	1.33^{a}	1.26^{b}	1.37^{a}	1.32^{a}	9.80^{ef}	9.12^{d}	8.62^{e}	9.18^{e}
early man. thinning	1.00^{d}	1.10^{f}	1.15^{d}	1.08^{e}	12.80^{a}	11.28^{a}	10.59^{a}	11.56^{a}
early chem. thinning	1.04^{d}	1.21^{d}	1.25^{c}	1.17^{d}	11.98^{b}	9.95^{b}	9.47^{c}	10.47^{c}
late man. thinning	1.12^{c}	1.24^{c}	1.32^{b}	1.23^{c}	10.33^{d}	9.00^{d}	8.34^{f}	9.22^{e}
late chem. Thinning	1.21^{b}	1.20^{de}	1.25^{c}	1.22^{c}	9.64^{f}	9.59^{c}	9.07^{d}	9.43^{d}

Means followed by the same letter(s) within each column are not significantly different at $P \leq 0.05$

TSS%

Table (6) showed that canopy management and crop-load regulation significantly modulated fruit TSS accumulation across bearing cycles. Light pruning (T3) and early manual thinning (T5) were the most effective, recording the highest overall means (12.48%, 12.46%). The control (T4) maintained a high TSS in the heavy-crop phase (season 1: 13.00%) but declined sharply in the off-year (11.47%), whereas T3 and T5 stabilized TSS across seasons, maintaining high values (12.40%) even under low crop load. Severe pruning (T1) and early chemical thinning (T6) ranked intermediate, with T1 mostly below T3 and dropping to 11.80% in the second season, while late thinning (T7, T8) recorded the lowest values overall, reaching a critical low of 11.17% for T7 in season 2.

Acidity %

Juice acidity (Table 6) showed no consistent trend among pruning intensities or late thinning across bearing seasons. Light pruning (T3) recorded the lowest overall acidity (1.11%) compared to moderate (T2: 1.18%) and severe pruning (T1: 1.28%). Early manual thinning (T5) achieved significantly lower acidity (1.08%) than its chemical counterpart (T6: 1.17%), a pattern consistent across the second and third seasons. The control recorded the highest acidity in the on-years and overall mean (1.33%, 1.37%, 1.32%), while severe pruning showed the highest acidity during the off-year (1.28%).

TSS: Acidity Ratio

The TSS: acid ratio, an indicator of fruit maturity and taste balance, varied significantly among treatments across seasons (Table 6). Light pruning (T3) outperformed moderate (T2) and severe pruning (T1) in all seasons, achieving the highest mean among pruning treatments (11.26 vs. 10.35 and 9.31). Early manual thinning (T5) showed clear superiority over its chemical counterpart and all other treatments, achieving the highest overall mean (11.56), ahead of T3 (11.26), while early chemical thinning (T6) was intermediate (10.47).

The chemical quality of citrus fruit -TSS, acidity, and maturity ratio- is governed by source–sink interactions and assimilate partitioning within the canopy **(Hmmam *et al*., 2023)**, closely linked to how carbon movement into the fruit regulates sugar accumulation and citric acid storage in juice-sac vacuoles **(Sadka *et al*., 2019)**. During the heavy-crop phase, intense fruit competition for limited assimilates in the control delayed ripening, trapping organic acids and limiting sugar accumulation; the sharp TSS decline in the following off-year confirmed that the absence of canopy management depletes carbohydrate reserves and drives alternate bearing **(Hmmam *et al*., 2023)**.

By contrast, the optimized source–sink balance achieved through light pruning or early manual thinning enhanced both carbohydrate translocation and acid metabolism, consistent with **Mostafa and Abdel-Aal (2009)** on Balady mandarin and **El-Sayed *et al*. (2017)** on Murcott mandarin, who showed that reducing fruit competition in high-yield seasons increases the carbohydrate pool per fruit. By regulating crop load early, these treatments improved light interception and canopy microclimate efficiency, providing a continuous, luxury carbohydrate supply that stabilized TSS even under low crop load **(Al-Saif *et al*., 2023)**; similarly, Mostafa and **Abdel-Aal (2009)** confirmed that higher manual thinning rates (40–50%) maximize juice TSS and total sugars through improved source–sink dynamics. Early intervention (T5) also triggered premature metabolic redirection from citric acid storage toward soluble sugar deposition **(Farinha *et al*., 2020)**, yielding the highest maturity ratio and confirming that early crop-load adjustment accelerates commercial maturity through reduced sink competition.

Severe pruning, in contrast, induced a negative physiological response: despite the reduced fruit load, the drastic 75% canopy removal compromised photosynthetic source strength, depriving fruit of the baseline carbohydrate supply needed for both sugar synthesis and acid-degrading respiratory enzymes **(Monselise, 1986)**, explaining the elevated acidity and reduced TSS observed under T1 in the second season. Late thinning (T7, T8) likewise failed to improve fruit quality over the control, reflecting the importance of intervention timing: prolonged inter-fruit competition before thinning had already depleted the stored carbon pool, leaving remaining fruit without sufficient time or resources to rebalance sugar and acid content before harvest **(Farinha *et al*., 2020)**.

4. Conclusion

Based on the results presented above, it is evident that early chemical thinning emerged as the most effective treatment, while moderate pruning (50%) offered a comparatively balanced alternative for 'Balady' mandarin, achieving a favorable balance between fruit yield and quality. These interventions improved the tree nutritional status and shoot C: N ratio, ensuring superior productivity. Therefore, adopting either early chemical thinning or moderate pruning (50%) is recommended as an effective horticultural practice for sustainable high-quality production, under experimental conditions.

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