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Crop load management in high density apple plantation

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Abstract

Aim of the study: To optimize the best thinning method and elucidate its effect on fruit size, quality, yield and return bloom in apple under high density plantation in sub-temperate zone of India.

Area of study: Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh, India.

Material and methods: The experiment consisted of 30 combinations of 10 thinning (chemical and manual) treatments (T_1: 10 mg L^{-1} NAA; T_2: 20 mg L^{-1} NAA; T_3: 100 mg L^{-1} BA; T_4: 200 mg L^{-1} BA; T_5: 100 mg L^{-1} Metamitron; T_6: 200 mg L^{-1} Metamitron; T_7: crop load of 4 fruits cm^{-2} TCSA; T_8: crop load of 6 fruits cm^{-2} TCSA; T_9: crop load of 8 fruits cm^{-2} TCSA and T_{10}: control - no thinning) and 3 cultivars treatments ('Jeromine', 'Redlum Gala' and 'Super Chief'), replicated five times over three growing seasons (2020 to 2022).

Main results: The highest return bloom, fruit size, red skin color (RSC), sugars content, and anthocyanin content were produced due to manual thinning while maintaining a crop load of 4-6 fruits cm^{-2} TCSA (trunk cross sectional area). 'Jeromine' cultivar produced fruits with better yields, productivity, and RSC. 'Redlum Gala' had fruits with a better extent of thinning, return bloom, and sugar content. The extent of thinning showed a significant positive correlation with return bloom, fruit quality and physicochemical parameters, and growth in apples under high-density plantations.

Research highlights: A possible threshold for optimal fruit quality and consistent return bloom is around 4-6 fruits cm^{-2} TCSA in apple under high density plantation in India.

Additional key words: *Malus* × *domestica*; return bloom; thinning; yield.

Abbreviations used: BA (6- benzyladenine); GA (gibberellic acid); LAI (leaf area index); L/D (length:diameter ratio); NAA (1-naphthalene acetic acid); PCA (principal component analysis); RSC (red skin colour); SSC (soluble solids content); TCSA (trunk cross sectional area); TSS (total soluble solids).

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Introduction

High-density apple cultivation is characterized by intense bloom and fruit set, which has a number of detrimental effects on overall profitability, including undersized, subpar-quality fruits and limited return bloom (Wünsche et al., 2005). Crop load management (CLM) is one of the key technologies used in apple farming to assure regular fruit production and high fruit quality, particularly in terms of fruit size, flavour, and colour (Bound, 2018; Peifer et al., 2018). Crop load, a quantitative measure frequently used in industry, is typically defined as the quantity of fruits produced by each tree (Wünsche et al., 2005; Racsko, 2006) and is frequently expressed as the number of fruits per trunk cross-sectional area (TCSA) (Jimenez & Diaz, 2004; Racsko, 2006; Wright et al., 2006).

One of the key elements of "precision" crop load management techniques in apple under high density plantation is chemical and manual thinning (Robinson et al., 2014). The most widely utilised chemical thinning agents in apple products are 6-benzyladenine (BA) and 1-naphthalene acetic acid (NAA) (Greene, 2002; Pesteanu, 2013; 2015; Keserovic et al., 2016). Metamitron, a photosystem II inhibitor from the triazinone chemical family (Gabardo et al., 2017; Botton et al., 2020; Penzel & Kroling, 2020), is a novel thinning agent. However, the reaction to chemical thinning is strongly influenced by the weather, and cultivars differ significantly in their susceptibility to thinning chemicals (Bound, 2001). Hand thinning can improve pest control by exposing clustered fruit, increase fruit size and colour by singling out fruit within the cluster, balance the number of resting spurs with fruitful ones to ensure return bloom, and fill out the canopy in young trees by balancing continued growth with cropping. Apple tree hand thinning can be quite accurate, but it is very expensive and requires specialized labour inputs (Costa et al., 2001). High density plantations are a relatively new concept in India, and effective crop load standardisation and optimization is not yet done but is needed to ensure high-quality fruit production and regular bearing. Keeping in view these facts, the present study aims to optimize the best thinning method and elucidate its effect on fruit size, quality, yield and return bloom in apple under high density plantation in sub-temperate zone of India.

Material and methods

Experimental site

The experiment was carried out in the high-density apple orchard of Department of Fruit Science, Dr. Y. S. Parmar University of Horticulture and Forestry, Nauni, Solan (Himachal Pradesh), India, which is situated at a height of 1,250 m above mean sea level and is situated between 30º-51' N latitude and 76º-11' E longitude. This is located in the sub-humid mid-hill agro-climatic zone-II, which has a typical sub-temperate climate. The average annual rainfall is between 1000 and 1300 mm, with the monsoons responsible for 70 % of the entire amount (July-August). The soil is sandy loam texture, free of stone, and deep, with 1.50% organic matter content and a bulk density of 1.35 g cm^{-3}.

The experiment was carried out using a randomised block design (factorial), which was replicated five times over three growing seasons (2020 to 2022). It included 30 treatment combinations of 10 thinning (chemical and manual) treatments (T_1: 10 mg L^{-1} NAA; T_2: 20 mg L^{-1} NAA; T_3: 100 mg L^{-1} BA; T_4: 200 mg L^{-1} BA; T_5: 100 mg L^{-1} Metamitron; T_6: 200 mg L^{-1} Metamitron; T_7: crop load of 4 fruits cm^{-2} TCSA; T_8: crop load of 6 fruits cm^{-2} TCSA; T_9: crop load of 8 fruits cm^{-2} TCSA and T_{10}: control - no thinning) and 3 cultivars treatment (C_1: 'Jeromine', C_2: 'Redlum Gala' and C_3: 'Super Chief'). Metamitron, a new chemical that is basically a triazine-type herbicide, is also an effective apple thinning agent, inhibits photosynthesis by blocking electron transport in apple photosystem II for 7–18 days, further reducing the carbon supply to the tree and potentially causing fruit thinning when used once or twice between petal fall and 20 mm in fruit diameter (Kopcke, 2004; Stern, 2014; Gonzalez et al., 2019; Penzel & Korling, 2020; Verjans et al., 2020).

Plant material

For the study, 150 uniform five-year-old apple trees of three cultivars ('Jeromine', 'Redlum Gala', and 'Super Chief') planted at a spacing of 2.5 m × 1.0 m and trained as tall spindle systems were chosen. Fertigation was applied at 15 split doses starting from green tip until fruit maturity at a dose of 175:87.50:175 g $tree^{-1}$ yr^{-1} (N:P:K) for the year 2020; 210:105:210 g $tree^{-1}$ yr^{-1} in 2021 and 245:122.50:245 g $tree^{-1}$ yr^{-1} in 2022.

Thinning treatments

Chemical thinning

NAA, BA and Metamitron were used to induce chemical thinning. They were applied only once at 10 days after petal fall. Required quantity of spray solution was prepared for each chemical treatment and was applied by using Knapsack sprayer to wet the fruits and foliage of tree under different chemical treatments without causing runoff.

Manual (hand thinning)

First, following fruit set (full bloom in 'Jeromine' on 4/04/2020; 03/04/2021 and 03/4/2022; in 'Redlum Gala' on 29/03/2020; 27/03/2021 and 29/3/2022; in 'Super Chief' on 2/04/2020; 03/04/2021 and 03/4/2022), the total number of fruits on each tree in each replication was counted. The manual thinning was done on the basis of TCSA. Before the trees were thinned, the diameter of each tree's trunk was measured with a digital vernier calliper 15 cm above the graft union. From tree trunk diameter (d = 2r), radius (r) was calculated and then TCSA (cm^2) was determined as TCSA = πr^2. The average TCSA was 10±2 cm^2; 12±2 cm^2 and 14±2 cm^2 in the year 2020, 2021 and 2022, respectively, for the selected trees. Trees were then thinned to the closest possible target crop load category after the fruitlets had attained the diameter of 10 to 12 mm (10 days of petal fall) at 4, 6, and 8 fruits cm^{-2} TCSA under various manual treatments using Oumefar Stainless Steel Forging Apple Tree Scissors. In general, we preferred to keep king blooms and fruits that had more direct sunshine exposure and all lateral fruitlets on spurs were removed manually.

Cropping parameters

The initial fruit set of each experimental tree was noted prior to administering thinning treatments in order to gauge the degree of thinning (caused by chemical, manual, and natural means). When the fruits were harvested, the ultimate fruit retention was noted. The amount of fruits gathered from each experimental tree was used to calculate the ultimate fruit retention. The extent of thinning (%) was calculated by using the following formula: Extent of thinning (%) = [(No. of initial fruit set – No. of fruits harvested) / (No. of initial fruit set) × 100]. The number of fruits after thinning was determined by the fruits kept up until harvest. To determine the fruit yield (kg tree^{-1}) basis, the total weight of fruits gathered from each experimental tree under various thinning procedures was recorded. The productivity (Mt ha^{-1}) was calculated by multiplying the average fruit yield per tree by the total number of trees accumulated per hectare of the planting density (i.e. with 2.5 m× 1.0 m total trees were 4,000 trees ha^{-1}). By counting the flower clusters on each tree and multiplying the total by 5, the return bloom (flowering in 2021, 2022 and 2023) of each tree was calculated. The return bloom i.e. the number of flowers per TCSA of tree in the next year, was calculated by dividing the quantity of blooms by the respective TCSA of each experimental tree (Anthony et al., 2019).

Fruit quality and bio-chemical parameters

The fruits were harvested by determining the maturity with starch iodine test [1-10] having starch index of 5 (Zude-Sasse et al., 2000). After the fruits attained maturity ('Jeromine', 24/07/2020, 25/07/2021 and 24/07/2022; 'Redlum Gala', 19/07/2020, 22/07/2021 and 22/07/2022; 'Super Chief', 25/07/2020, 26/07/2021 and 25/07/2022) the samples from each treatment combination were taken for analysis. Twenty healthy fruits were selected at random from the tree's sides and transported in carry bags to the lab for additional examination. With the use of a Mitutoyo digital vernier calliper, the length of 20 randomly chosen fruits was measured between the calyx and styler end, and their diameter was measured between the cheeks of the fruits. The average fruit length and diameter were then expressed in mm. Fruit length/diameter (L/D) ratio was obtained by dividing fruit length by each experimental tree's corresponding fruit diameter. The total soluble solids content (TSS) of fruit samples was determined by Milwaukee MA871 digital refractrometer (0-85°Brix scale). RSC (Red Skin Colour) was quantified visually using a rating scale (0%, 25%, 50%, 75% and 100%) based on the average of over-color covering fruit surface (Castro et al., 2015). The sugars (including total, reducing and non-reducing sugars) were analyzed by the standard procedure (Ranganna, 1995). Anthocyanin content in apple skin was determined following Harborne (1973).

Growth parameters

Ten shoots from the current season's growth were chosen at random from each experimental tree's periphery. At the end of the growth season, in December, the length of these shoots (cm) was measured using a measuring tape, and the mean annual shoot length was calculated. The leaf area (cm^2) was measured with an automatic leaf area meter (Licor Model 3100) and the leaf area index (LAI) using a canopy analyzer (FluorPen Psi).

Statistical analysis

The pooled data of all experimental findings were analyzed using SPSS Statistics 20.0 (SPSS Corporation, Chicago, USA), and expressed as mean ± standard error. Two-way analysis of variance (ANOVA) with Duncan and Dunnett's Post Hoc multiple comparison tests ($p \leq 0.05$) was performed. All the cropping, fruit quality and physicochemical parameters were subjected to principal component analysis (PCA) and correlation between various parameters was computed using (PAST) vers. 4.11 (means and 0.95 confidence intervals).

Results

Extent of thinning

The various thinning methods (chemical and manual) and cultivars had a substantial impact on the extent of thinning (Table 1). T_7 (crop load of 4 fruits cm^{-2} TCSA) had the largest extent of thinning (70.40%), and T_{10} (control) had the lowest extent of thinning (12.32%). Regarding cultivars, 'Redlum Gala' had the highest extent of thinning (45.96%), which was significantly higher than for any other cultivar and 'Jeromine' had the lowest extent of thinning (37.33%). The highest extent of thinning (76.44%) was recorded in T_7C_2 (crop load of 4 fruits cm^{-2} TCSA + 'Redlum Gala'), whereas the lowest extent of thinning (9.36%) was recorded in $T_{10}C_1$ (control + 'Jeromine').

Productivity

With increasing thinning severity, the overall yield and yield efficiency significantly dropped. Additionally, cultivars showed a considerable difference in average yield

Table 1. Effect of different thinning treatments (T_1: 10 mg L^{-1} NAA; T_2: 20 mg L^{-1} NAA; T_3: 100 mg L^{-1} BA; T_4: 200 mg L^{-1} BA; T_5: 100 mg L^{-1} metamitron; T_6: 200 mg L^{-1} metamitron; T_7: crop load of 4 fruits cm^{-2} TCSA; T_8: crop load of 6 fruits cm^{-2} TCSA; T_9: crop load of 8 fruits cm^{-2} TCSA and T_{10}: control - no thinning) and cultivars (C_1: 'Jeromine'; C_2:'Redlum Gala'; C_3:'Super Chief') on extent of thinning, productivity and return bloom in apple under high density plantation.

Treatments[1]	C_1[2]	C_2	C_3	Mean
		Extent of thinning (%)		
T_1	58.98 ± 3.11^{IJ}	70.26 ± 1.70^{BC}	66.68 ± 2.00^{DEF}	65.31 ± 2.04^{c}
T_2	62.49 ± 1.47^{GHI}	72.36 ± 1.22^{B}	67.93 ± 1.04^{CDE}	67.59 ± 1.56^{b}
T_3	26.46 ± 1.09^{P}	34.30 ± 0.64^{M}	30.13 ± 0.44^{NO}	30.30 ± 1.20^{f}
T_4	27.51 ± 1.05^{OP}	35.29 ± 1.21^{M}	32.18 ± 1.18^{MN}	31.66 ± 1.27^{f}
T_5	14.59 ± 0.70^{TU}	21.90 ± 1.05^{QR}	18.72 ± 0.74^{RS}	18.41 ± 1.14^{h}
T_6	16.70 ± 0.35^{ST}	24.63 ± 1.09^{PQ}	20.42 ± 0.51^{R}	20.58 ± 1.20^{g}
T_7	65.18 ± 1.48^{EFG}	76.44 ± 0.99^{A}	69.59 ± 1.02^{BCD}	70.40 ± 1.74^{a}
T_8	56.55 ± 1.30^{J}	63.84 ± 0.82^{FGH}	60.70 ± 1.39^{HI}	60.36 ± 1.21^{d}
T_9	35.50 ± 1.30^{M}	45.45 ± 1.64^{K}	40.56 ± 1.20^{L}	40.50 ± 1.60^{e}
T_{10}	9.36 ± 0.59^{V}	15.08 ± 0.89^{TU}	12.52 ± 0.80^{UV}	12.32 ± 0.91^{i}
Mean	37.33 ± 3.82^{C}	45.96 ± 4.07^{A}	41.94 ± 3.95^{B}	
		Productivity (Mt ha^{-1})		
T_1	50.74 ± 2.89^{B}	31.93 ± 0.41^{K}	33.04 ± 0.60^{K}	38.57 ± 3.17^{e}
T_2	37.67 ± 0.95^{J}	31.41 ± 2.03^{K}	33.65 ± 0.81^{K}	34.24 ± 1.15^{f}
T_3	50.08 ± 0.47^{BC}	41.30 ± 0.42^{FGHI}	44.39 ± 0.44^{E}	45.25 ± 1.30^{b}
T_4	50.60 ± 0.31^{B}	41.20 ± 0.38^{FGHI}	43.74 ± 0.31^{EF}	45.18 ± 1.41^{b}
T_5	50.51 ± 0.53^{B}	39.73 ± 0.87^{GHIJ}	42.71 ± 0.76^{EF}	44.32 ± 1.65^{bc}
T_6	47.82 ± 0.38^{CD}	39.85 ± 0.39^{GHIJ}	42.20 ± 0.39^{EFG}	43.29 ± 1.20^{bcd}
T_7	31.81 ± 0.74^{K}	26.80 ± 1.21^{L}	27.17 ± 1.00^{L}	28.59 ± 0.95^{g}
T_8	42.93 ± 0.95^{EF}	38.90 ± 0.48^{IJ}	41.95 ± 0.79^{EFGH}	41.26 ± 0.72^{d}
T_9	54.32 ± 1.42^{A}	49.92 ± 0.90^{BCD}	50.58 ± 0.70^{B}	51.61 ± 0.86^{a}
T_{10}	47.38 ± 0.14^{D}	39.16 ± 0.81^{IJ}	39.50 ± 0.73^{HIJ}	42.01 ± 1.38^{cd}
Mean	46.39 ± 1.26^{A}	38.02 ± 1.17^{B}	39.89 ± 1.21^{B}	
		Return bloom (No. of flowers cm^{-2} TCSA)		
T_1	27.64 ± 0.83^{JKL}	40.39 ± 2.07^{CDE}	33.47 ± 0.72^{GH}	33.83 ± 1.96^{c}
T_2	31.42 ± 0.78^{HIJ}	45.72 ± 2.68^{B}	38.45 ± 1.60^{DEF}	38.53 ± 2.26^{b}
T_3	22.41 ± 1.48^{M}	32.20 ± 1.35^{GHI}	27.85 ± 0.21^{IJK}	27.49 ± 1.53^{ef}
T_4	23.92 ± 1.17^{KLM}	36.44 ± 1.51^{EFG}	29.95 ± 1.77^{HIJ}	30.10 ± 1.96^{de}
T_5	21.33 ± 1.26^{M}	29.83 ± 1.69^{HIJ}	23.39 ± 1.13^{LM}	24.85 ± 1.45^{f}
T_6	22.39 ± 1.48^{M}	32.28 ± 0.92^{GH}	25.20 ± 0.58^{KLM}	26.62 ± 1.56^{f}
T_7	36.52 ± 1.50^{EFG}	53.25 ± 3.63^{A}	41.42 ± 1.45^{BCD}	43.73 ± 2.76^{a}
T_8	29.88 ± 1.79^{HIJ}	43.87 ± 2.66^{BC}	35.82 ± 1.77^{FG}	36.52 ± 2.29^{b}
T_9	25.42 ± 0.53^{KLM}	38.33 ± 1.60^{DEF}	31.25 ± 1.54^{HIJ}	31.67 ± 1.98^{cd}
T_{10}	10.17 ± 0.03^{O}	15.50 ± 0.36^{N}	11.75 ± 0.29^{NO}	12.47 ± 0.80^{g}
Mean	25.11 ± 1.29^{C}	36.78 ± 1.90^{A}	29.86 ± 1.54^{B}	
Significance				
T	***	***	***	
C	***	***	***	
T × C	NS	***	NS	

Data represent the mean of 5 replicates ± standard error (SE). Lowercase superscripts letters in the column of the mean, uppercase superscripts letters on the line of mean and italics uppercase superscripts letters in the column and line of mean specifies statistically significant difference between the means ($p \leq 0.05$, Duncan Multiple Range Test). *: $p \leq 0.05$; **: $p \leq 0.01$;***: $p \leq 0.001$; NS = non-significant.

Table 2. Effect of different thinning treatments (T_1: 10 mg L^{-1} NAA; T_2: 20 mg L^{-1} NAA; T_3: 100 mg L^{-1} BA; T_4: 200 mg L^{-1} BA; T_5: 100 mg L^{-1} metamitron; T_6: 200 mg L^{-1} metamitron; T_7: crop load of 4 fruits cm^{-2} TCSA; T_8: crop load of 6 fruits cm^{-2} TCSA; T_9: crop load of 8 fruits cm^{-2} TCSA and T_{10}: control - no thinning) and cultivars (C_1: 'Jeromine'; C_2:'Redlum Gala'; C_3:'Super Chief') on fruit length, diameter and L/D ratio in apple under high density plantation.

Treatments[1]	C_1[2]	C_2	C_3	Mean
		Fruit length (mm)		
T_1	64.21±0.16^{C}	58.47±0.09^{I}	59.71±0.10^{H}	60.80±0.87$^{\mathrm{c}}$
T_2	65.50±0.03^{B}	60.83±0.23^{FG}	60.45±0.03^{FGH}	62.26±0.82$^{\mathrm{ab}}$
T_3	58.38±0.33^{I}	54.57±0.31^{L}	57.25±0.21^{J}	56.73±0.58$^{\mathrm{e}}$
T_4	61.49±0.28^{EF}	57.14±0.24^{J}	57.86±0.06^{IJ}	58.83±0.68$^{\mathrm{d}}$
T_5	55.18±0.13^{KL}	55.19±0.13^{KL}	55.33±0.29^{KL}	55.23±0.10$^{\mathrm{f}}$
T_6	59.88±0.13^{GH}	55.40±0.09^{KL}	55.85±0.43^{K}	57.04±0.72$^{\mathrm{e}}$
T_7	67.63±1.23^{A}	61.48±0.62^{EF}	61.01±0.23^{F}	63.37±1.14$^{\mathrm{a}}$
T_8	66.17±0.56^{B}	62.39±0.76^{DE}	60.48±0.32^{FGH}	63.01±0.88$^{\mathrm{a}}$
T_9	63.40±0.44^{CD}	60.66±0.17^{FGH}	61.18±0.16^{F}	61.74±0.44$^{\mathrm{bc}}$
T_{10}	50.85±0.17^{M}	49.16±0.03^{N}	50.88±0.50^{M}	50.30±0.29$^{\mathrm{g}}$
Mean	61.27±0.94$^{\mathrm{A}}$	57.53±0.72$^{\mathrm{B}}$	58.00±0.58$^{\mathrm{B}}$	
		Fruit diameter (mm)		
T_1	69.82±0.20^{E}	67.17±0.35^{GH}	65.21±0.27^{IJ}	67.40±0.68$^{\mathrm{d}}$
T_2	72.72±0.10^{B}	69.16±0.35^{EF}	68.97±0.21^{F}	70.28±0.62$^{\mathrm{b}}$
T_3	66.73±0.18^{H}	64.78±0.45^{J}	61.41±0.09^{N}	64.30±0.79$^{\mathrm{f}}$
T_4	68.78±0.05^{F}	65.72±0.50^{I}	62.90±0.14^{L}	65.80±0.86$^{\mathrm{e}}$
T_5	67.80±0.06^{G}	63.66±0.50^{K}	60.64±0.24^{O}	64.03±1.05$^{\mathrm{f}}$
T_6	69.36±0.27^{EF}	65.83±0.61^{I}	61.45±0.21^{N}	65.54±1.16$^{\mathrm{e}}$
T_7	75.22±0.19^{A}	71.89±0.28^{C}	70.78±0.16^{D}	72.63±0.68$^{\mathrm{a}}$
T_8	72.91±0.09^{B}	71.16±0.54^{D}	64.98±0.09^{J}	69.68±1.21$^{\mathrm{b}}$
T_9	71.87±0.09^{C}	69.31±0.12^{EF}	64.55±0.12^{J}	68.58±1.07$^{\mathrm{c}}$
T_{10}	62.19±0.17^{M}	59.86±0.12^{P}	57.89±0.14^{Q}	59.98±0.63$^{\mathrm{g}}$
Mean	69.74±0.66$^{\mathrm{A}}$	66.85±0.69$^{\mathrm{B}}$	63.88±0.79$^{\mathrm{C}}$	
		L/D ratio		
T_1	0.92±0.01^{BC}	0.87±0.01^{HIJK}	0.92±0.01^{BCD}	0.90±0.01$^{\mathrm{a}}$
T_2	0.90±0.00^{DEF}	0.88±0.0^{GHI}	0.88±0.01^{GHIJ}	0.89±0.00$^{\mathrm{abc}}$
T_3	0.88±0.01^{GHIJ}	0.84±0.01^{LM}	0.93±0.01^{AB}	0.88±0.01$^{\mathrm{abc}}$
T_4	0.89±0.01^{EFG}	0.87±0.01^{HIJK}	0.92±0.01^{BCD}	0.89±0.01$^{\mathrm{ab}}$
T_5	0.81±0.01^{N}	0.87±0.01^{HIJK}	0.91±0.01^{CD}	0.87±0.01$^{\mathrm{c}}$
T_6	0.86±0.01^{JKL}	0.84±0.01^{M}	0.91±0.01^{CDE}	0.87±0.01$^{\mathrm{bc}}$
T_7	0.90±0.02^{DEF}	0.86±0.01^{KLM}	0.86±0.01^{IJK}	0.87±0.01$^{\mathrm{bc}}$
T_8	0.91±0.01^{CDE}	0.88±0.02^{GHIJ}	0.93±0.01^{AB}	0.91±0.01$^{\mathrm{a}}$
T_9	0.88±0.01^{GHI}	0.88±0.01^{GHIJ}	0.95±0.01^{A}	0.90±0.02$^{\mathrm{a}}$
T_{10}	0.82±0.01^{N}	0.82±0.00^{N}	0.88±0.01^{FGH}	0.84±0.01$^{\mathrm{d}}$
Mean	0.88±0.01$^{\mathrm{B}}$	0.86±0.00$^{\mathrm{C}}$	0.91±0.01$^{\mathrm{A}}$	
Significance				
T	***	***	***	
C	***	***	***	
T × C	***	***	***	

Data represent the mean of 5 replicates ± standard error (SE). Lowercase superscripts letters in the column of the mean, uppercase superscripts letters on the line of mean and italics uppercase superscripts letters in the column and line of mean specifies statistically significant difference between the means (p≤0.05, Duncan Multiple Range Test). *: p≤0.05; **: p≤0.01;***: p≤0.001; NS = non-significant.

(see Table S1 [suppl]). Simultaneously, the productivity was variable influenced by different thinning treatments and cultivars (Table 1). The maximum productivity (51.61 MT ha^{-1}) was recorded in treatment T_9, and T_7 had the lowest productivity (28.59 MT ha^{-1}). 'Jeromine' had the highest productivity (46.39 MT ha^{-1}), while 'Redlum Gala' had the lowest productivity (38.02 MT ha^{-1}). Regarding treatment combinations, the maximum productivity (54.32 MT ha^{-1}) was observed in T_9C_1 which was significantly followed by T_1C_1, T_3C_1, T_4C_1, T_5C_1 and T_9C_3, whereas the minimum yield (26.80 MT ha^{-1}) was observed in T_7C_2.

Return bloom

Return bloom was triggered by the thinning treatments in the following year. The return bloom increased with increasing thinning intensity (Table 1). T_7 had the highest return bloom (43.73), while un-thinned apple trees (T_{10}) had the lowest return bloom (12.47). Regarding cultivars, 'Redlum Gala' had the highest return bloom (36.78), while 'Jeromine' had the lowest (25.11). The highest return bloom (53.25) was recorded in T_7C_2, whereas the lowest return bloom (10.17) was found in $T_{10}C_1$.

Fruit quality

The fruit length and diameter (Table 2) and RSC (Table 3) increased significantly with the reduction in the crop load per tree. T_7 had the largest fruit length (63.37 mm), fruit diameter (72.63 mm), and RSC (96.84%), whereas T_8 had the highest L/D ratio (0.91). Simultaneously, both T_1 and T_9 had also a L/D ratio of 0.90. However, the minimum fruit length (50.30 mm), fruit diameter (59.98 mm), L/D ratio (0.84), and RSC (88.33%) was recorded in T_{10} (control). With respect to cultivars, 'Jeromine' had the largest fruit length (61.27 mm), diameter (69.74 mm) and RSC (95.20%), whereas the highest L/D ratio (0.91) was found in 'Super Chief'. 'Redlum Gala' had the lowest fruit length (57.53 mm) and L/D ratio (0.86), and 'Super Chief' had the lowest fruit diameter (63.88 mm), and RSC (89.25%). The maximum fruit length (67.63 mm), diameter (75.22 mm) and RSC (99.00%) was recorded in T_7C_1, significantly followed by T_2C_1. However, the minimum fruit length (49.16 mm) and fruit diameter (59.86 mm) were found in $T_{10}C_2$ and RSC (85.00%) in $T_{10}C_2$. The maximum fruit L/D ratio (0.95) was recorded in T_9C_3, significantly followed by T_1C_1, T_1C_3, T_3C_3, T_4C_3, T_8C_3 and T_9C_2. However, the minimum fruit L/D ratio (0.81) was observed in T_5C_1, significantly followed by $T_{10}C_1$ and $T_{10}C_2$.

Fruit bio-chemical parameters

Fruit total soluble solids, total sugars (Table 3) and anthocyanin content (Table 4) increased with the rate of thinning intensity. T_7 had the highest fruit TSS (14.51%), total sugars (13.87%), and anthocyanin content (0.62%). However, the lowest TSS (9.73%), total sugars (9.12%), and anthocyanin content (0.50) was recorded in T_{10}. Regarding cultivars, 'Redlum Gala' had the highest fruit TSS (13.04%), and total sugars (11.83%), and 'Jeromine' had the highest anthocyanin content (0.62). 'Super Chief' had the lowest TSS (11.55%) and total sugars (10.71%); contrarily, 'Redlum Gala' had the lowest anthocyanin content (0.45). The maximum fruit TSS (15.37%) was recorded in T_7C_2 and the minimum (9.26%) in $T_{10}C_3$. The highest anthocyanin content (0.70) was recorded in T_7C_1 and the lowest (0.39) in $T_{10}C_2$.

Growth

The maximum annual shoot growth (63.76 cm), and maximum LAI (2.21) were recorded in T_7, while the minimum annual shoot growth (33.92 cm), and LAI (1.21) in T_{10} (Table 4). 'Redlum Gala' had the maximum annual shoot growth (48.98 cm), while LAI (2.15) was highest in 'Jeromine'. 'Super Chief' had the lowest annual shoot growth (38.44 cm), whereas 'Redlum Gala' had the lowest LAI (1.62). The highest annual shoot growth (66.46 cm) was recorded in T_7C_2, whereas the lowest annual shoot growth (30.11 cm) was recorded in $T_{10}C_3$. The maximum LAI (2.45) was recorded in T_7C_1, whereas the minimum (1.03) in $T_{10}C_2$.

Principal component analysis and correlations results of different thinning treatments and cultivars

The PCA model was applied to all parameter data to identify any group patterns and to determine the most important variables that explain the relationships between the ten thinning treatments and three cultivars used (Figure 1). The two major components explained 95.46% of total variance (91.16% for PC 1 and 4.30% for PC 2). When different thinning treatments and cultivars were tested, it was found that the extent of thinning (percent) was directly related to return bloom. Fruit length was strongly associated to fruit diameter and L/D ratio. T_7 accounted for the highest extent of thinning, return bloom, fruit length and diameter, TSS and sugars content; T_8 exhibited the maximum L/D ratio and T_9 the highest productivity. In addition, 'Jeromine' accounted for highest productivity, fruit length, fruit diameter and RSC, 'Redlum Gala' the highest extent of thinning and return bloom and 'Super Chief' the highest L/D ratio.

The correlations between various cropping, fruit quality, physico-chemical, and growth parameters of different thinning treatments and cultivars were examined (Table 5). It was found that thinning treatments exhibited a significant

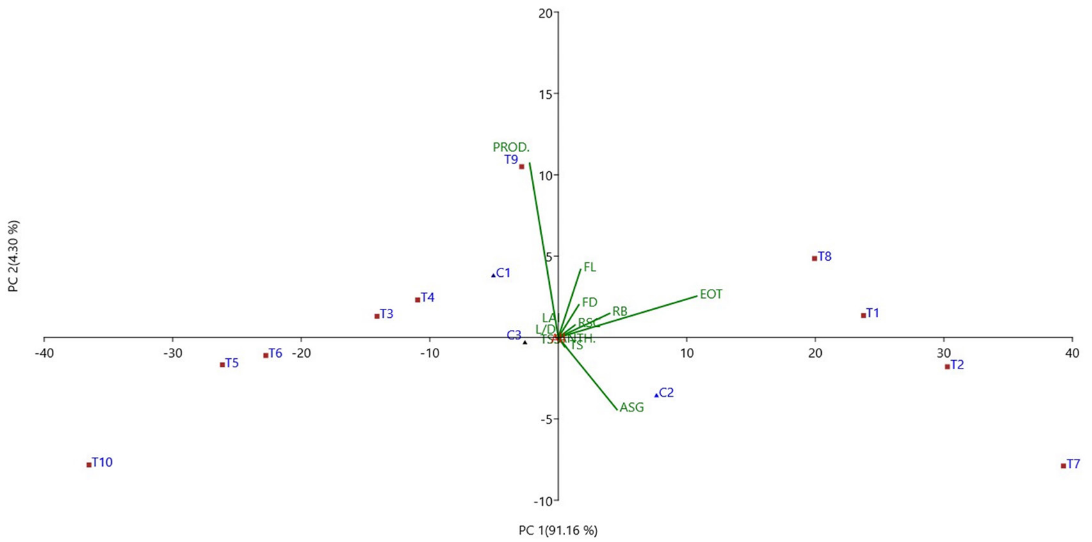

Figure 1. Biplot diagram of the PCA analysis (PCA 1 vs PCA 2). T: thinning treatments. T1: 10 mg L^{-1} NAA. T2: 20 mg L^{-1} NAA. T3: 100 mg L^{-1} BA. T4: 200 mg L^{-1} BA. T5: 100 mg L^{-1} metamitron. T6: 200 mg L^{-1} metamitron. T7: crop load of 4 fruits cm^{-2} TCSA. T8: crop load of 6 fruits cm^{-2} TCSA. T9: crop load of 8 fruits cm^{-2} TCSA and T10: control - no thinning. C: cultivars. C1: 'Jeromine'. C2:'Redlum Gala'. C3:'Super Chief'. EOT: extent of thinning. PROD: productivity, Mt ha-1. RB: return bloom. FL: fruit length. FD: fruit diameter. LD: L/D ratio. RSC: red skin colour. TSS: total soluble solids. TS: total sugars. ANTH: anthocyanin content. ASG: annual shoot growth. LAI: leaf area index.

negative correlation with extent of thinning, return bloom, TSS, total sugars and LAI (r = -0.32; r = -0.27; r = -0.31; r = -0.31; r = -0.32, respectively). The cultivars exhibited significant negative correlation with productivity, fruit length, fruit diameter, RSC, annual shoot growth and LAI (r = -0.36; r = -0.30; r = -0.56; r = -0.58; r = -0.24 and r = -0.31, respectively), and significant positive correlation with L/D ratio (r= 0.38). It was also observed a significant positive correlation between extent of thinning and return bloom, fruit length, fruit diameter, L/D ratio, RSC, TSS, total sugars, anthocyanin content, annual shoot growth and LAI; whereas extent of thinning had a significant negative correlation with productivity (r = -0.65). Return bloom had a significant positive correlation with extent of thinning, fruit length and diameter, RSC, TSS, total sugars, annual shoot growth and LAI and significant negative correlation with productivity. The negative correlation was observed between fruit length and productivity; however, fruit length had a significant positive correlation with fruit diameter, L/D ratio, RSC, TSS, total sugars, anthocyanin content and LAI.

Discussion

Extent of thinning

Our findings demonstrated that as hand thinning intensity grew, so did the amount of thinning, increasing thinning intensity and decreasing retention of total number of fruits per tree (see Table S1 [suppl] data). The findings are in line with past research which showed that intensifying hand thinning increased the extent of thinning percentage in fruit crops (Sharma et al., 2001; Thakur and Chandel, 2004; Kumar et al., 2017). According to Anthony et al. (2019) in apple cv. 'WA38', less fruits were produced per tree with an increase in thinning extent relative to a lower crop load cm^{-2} TCSA. Cultivars may respond to thinning to a greater or lesser degree, hence the variance in thinning with respect to cultivars may be caused by the cultivar response (Costa et al., 2018b; Botton & Costa, 2020). In terms of chemical thinning, 20 mg L^{-1} NAA, applied 10 days after petal fall, caused the greatest extent of thinning, followed by 10 mg L^{-1} NAA. In comparison to other chemical thinning agents, NAA caused a greater degree of thinning because it decreases diffusible auxin efflux, particularly from weaker fruitlets, and decreases the availability of carbohydrates to developing fruits by impeding photosynthesis, which encourages abscission in young fruitlets (Bangerth, 2000; Schroder & Bangerth, 2006; Zhu et al., 2011). These findings support those of Fruk et al. (2017), who observed increased thinning percentages with 20 mg L^{-1} NAA, when treated at fruit diameter of 6-8 mm followed by application of 10 mg L^{-1} NAA in apple cv. 'Braeburn. Metamitron, the novel chemical thinner, failed to exhibit any appreciable thinning effect because it was only applied once and at a low concentration. However, Metamitron, when used at a higher concentration with two applications, is effective as a thinner in apples (Costa et al., 2018a; Rocchi & Costa, 2018).

Table 3. Effect of different thinning treatments (T_1: 10 mg L^{-1} NAA; T_2: 20 mg L^{-1} NAA; T_3: 100 mg L^{-1} BA; T_4: 200 mg L^{-1} BA; T_5: 100 mg L^{-1} metamitron; T_6: 200 mg L^{-1} metamitron; T_7: crop load of 4 fruits cm^{-2} TCSA; T_8: crop load of 6 fruits cm^{-2} TCSA; T_9: crop load of 8 fruits cm^{-2} TCSA and T_{10}: control - no thinning) and cultivars (C_1: 'Jeromine'; C_2:'Redlum Gala'; C_3:'Super Chief') on RSC, TSS and total sugars content in apple under high density plantation.

Treatments[1]	**C_1**[2]	**C_2**	**C_3**	**Mean**
		RSC (%)		
T_1	96.00 ± 1.61^{ABCD}	93.00 ± 2.64^{CDEFGHI}	90.00 ± 2.27^{HIJKL}	93.00 ± 1.31^{bc}
T_2	97.00 ± 0.58^{ABC}	95.00 ± 0.58^{ABCDEF}	93.50 ± 1.32^{CDEFGH}	95.17 ± 0.68^{ab}
T_3	93.00 ± 1.15^{CDEFGHI}	89.00 ± 0.58^{IJKLM}	87.00 ± 1.44^{LM}	89.67 ± 1.04^{de}
T_4	95.50 ± 1.04^{ABCDE}	90.50 ± 1.50^{GHIJKL}	88.50 ± 1.50^{JKLM}	91.50 ± 1.24^{cd}
T_5	92.00 ± 1.50^{DEFGHIJ}	88.00 ± 1.53^{JKLM}	85.50 ± 1.80^{M}	88.50 ± 1.24^{e}
T_6	94.50 ± 1.04^{BCDEFG}	90.50 ± 2.26^{GHIJKL}	87.50 ± 1.04^{KLM}	90.83 ± 1.28^{cd}
T_7	99.00 ± 1.58^{A}	97.00 ± 0.58^{ABC}	94.50 ± 1.44^{BCDEFG}	96.84 ± 0.81^{a}
T_8	98.00 ± 0.50^{AB}	94.00 ± 1.15^{BCDEFGH}	92.00 ± 1.15^{DEFGHIJ}	94.67 ± 1.01^{ab}
T_9	96.00 ± 1.15^{ABCD}	91.50 ± 1.76^{EFGHIJK}	89.00 ± 0.58^{IJKLM}	92.17 ± 1.20^{c}
T_{10}	91.00 ± 2.02^{FGHIJKL}	89.00 ± 2.00^{IJKLM}	85.00 ± 2.02^{M}	88.33 ± 1.34^{e}
Mean	95.20 ± 0.56^{A}	91.75 ± 0.67^{B}	89.25 ± 0.68^{C}	
		TSS (%)		
T_1	11.88 ± 0.16^{HI}	12.63 ± 0.03^{FG}	12.06 ± 0.13^{H}	12.19 ± 0.13^{c}
T_2	13.05 ± 0.05^{DE}	13.97 ± 0.09^{BC}	12.67 ± 0.16^{FG}	13.23 ± 0.20^{b}
T_3	11.68 ± 0.02^{IJK}	12.54 ± 0.06^{G}	10.95 ± 0.02^{LM}	11.72 ± 0.23^{d}
T_4	11.84 ± 0.12^{HI}	12.82 ± 0.02^{EF}	11.56 ± 0.01^{JK}	12.07 ± 0.19^{c}
T_5	10.81 ± 0.06^{MN}	13.22 ± 0.02^{D}	11.05 ± 0.03^{LM}	11.69 ± 0.38^{d}
T_6	11.53 ± 0.02^{K}	13.83 ± 0.01^{C}	11.14 ± 0.09^{L}	12.17 ± 0.42^{c}
T_7	14.19 ± 0.17^{B}	15.37 ± 0.09^{A}	13.97 ± 0.07^{BC}	14.51 ± 0.22^{a}
T_8	11.80 ± 0.09^{IJ}	12.88 ± 0.11^{EF}	11.63 ± 0.16^{IJK}	12.10 ± 0.20^{c}
T_9	10.81 ± 0.08^{MN}	12.54 ± 0.06^{G}	11.19 ± 0.06^{L}	11.51 ± 0.26^{d}
T_{10}	9.38 ± 0.12^{O}	10.56 ± 0.02^{N}	9.26 ± 0.20^{O}	9.73 ± 0.22^{e}
Mean	11.70 ± 0.23^{B}	13.04 ± 0.22^{A}	11.55 ± 0.22^{B}	
		Total sugars (%)		
T_1	11.41 ± 0.03^{IJ}	12.13 ± 0.02^{G}	11.21 ± 0.01^{KL}	11.58 ± 0.14^{c}
T_2	12.66 ± 0.01^{E}	13.78 ± 0.01^{C}	12.20 ± 0.01^{F}	12.88 ± 0.23^{b}
T_3	10.32 ± 0.01^{P}	11.16 ± 0.01^{LM}	10.17 ± 0.02^{Q}	10.55 ± 0.15^{e}
T_4	11.13 ± 0.01^{M}	11.64 ± 0.01^{H}	10.77 ± 0.02^{O}	11.18 ± 0.13^{d}
T_5	9.56 ± 0.01^{S}	11.22 ± 0.01^{KL}	9.26 ± 0.01^{T}	10.01 ± 0.30^{g}
T_6	9.59 ± 0.01^{S}	11.45 ± 0.01^{I}	9.78 ± 0.03^{R}	10.27 ± 0.30^{f}
T_7	13.88 ± 0.04^{B}	14.24 ± 0.01^{A}	13.49 ± 0.05^{D}	13.87 ± 0.11^{a}
T_8	11.39 ± 0.01^{J}	12.14 ± 0.01^{FG}	11.25 ± 0.01^{K}	11.59 ± 0.14^{c}
T_9	10.18 ± 0.06^{Q}	10.94 ± 0.01^{N}	10.21 ± 0.01^{Q}	10.44 ± 0.13^{ef}
T_{10}	8.98 ± 0.01^{U}	9.62 ± 0.01^{S}	8.77 ± 0.02^{V}	9.12 ± 0.13^{h}
Mean	10.91 ± 0.27^{B}	11.83 ± 0.24^{A}	10.71 ± 0.25^{C}	
Significance				
T	***	***	***	
C	***	***	***	
T × C	NS	***	***	

Data represent the mean of 5 replicates ± standard error (SE). Lowercase superscripts letters in the column of the mean, uppercase superscripts letters on the line of mean and italics uppercase superscripts letters in the column and line of mean specifies statistically significant difference between the means ($p\leq0.05$, Duncan Multiple Range Test). *: $p\leq0.05$; **: $p\leq0.01$;***: $p\leq0.001$; NS = non-significant.

Table 4. Effect of different thinning treatments (T_1: 10 mg L^{-1} NAA; T_2: 20 mg L^{-1} NAA; T_3: 100 mg L^{-1} BA; T_4: 200 mg L^{-1} BA; T_5: 100 mg L^{-1} metamitron; T_6: 200 mg L^{-1} metamitron; T_7: crop load of 4 fruits cm^{-2} TCSA; T_8: crop load of 6 fruits cm^{-2} TCSA; T_9: crop load of 8 fruits cm^{-2} TCSA and T_{10}: control - no thinning) and cultivars (C_1: 'Jeromine'; C_2:'Redlum Gala'; C_3:'Super Chief') on anthocyanin content, annual shoot growth and LAI in apple under high density plantation.

Treatments[1]	C_1[2]	C_2	C_3	Mean
		Anthocyanin content (OD)		
T_1	0.64±0.01^{CD}	0.47±0.02^{MN}	0.61±0.01^{EFG}	0.57±0.03^{c}
T_2	0.67±0.01^{B}	0.50±0.01^{L}	0.63±0.02^{DE}	0.60±0.02^{b}
T_3	0.61±0.01^{EFG}	0.44±0.01^{OP}	0.58±0.01^{IJ}	0.54±0.03^{ef}
T_4	0.61±0.01^{EF}	0.45±0.01^{NO}	0.59±0.01^{HIJ}	0.55±0.02^{e}
T_5	0.59±0.01^{HIJ}	0.43±0.01^{P}	0.58±0.01^{IJ}	0.53±0.02^{f}
T_6	0.62±0.01^{DEF}	0.46±0.01^{MNO}	0.60±0.01^{FGHI}	0.56±0.02^{d}
T_7	0.70±0.01^{A}	0.51±0.01^{L}	0.65±0.01^{BC}	0.62±0.03^{a}
T_8	0.65±0.01^{BC}	0.48±0.01^{M}	0.62±0.01^{DEF}	0.58±0.03^{c}
T_9	0.60±0.01^{FGH}	0.44±0.01^{OP}	0.59±0.01^{GHIJ}	0.54±0.03^{ef}
T_{10}	0.57±0.01^{J}	0.39±0.01^{Q}	0.54±0.01^{K}	0.50±0.03^{g}
Mean	0.62±0.01^{A}	0.45±0.01^{C}	0.60±0.01^{B}	
		Annual shoot growth (cm)		
T_1	49.24±1.29^{E}	56.84±2.10^{CD}	43.65±1.30^{GHIJ}	49.91±2.07^{c}
T_2	57.65±1.06^{CD}	60.46±1.43^{BC}	44.58±2.14^{EFGH}	54.23±2.57^{b}
T_3	37.96±1.60^{KLMNO}	43.07±1.62^{GHIJ}	34.12±1.37^{OPQ}	38.38±1.51^{ef}
T_4	40.17±1.60^{HIJKL}	44.25±1.56^{FGHI}	34.97±1.80^{MNOP}	39.80±1.59^{de}
T_5	35.92±1.72^{LMNO}	39.72±1.50^{IJKLM}	30.70±0.40^{PQ}	35.45±1.42^{fg}
T_6	36.42±1.14^{KLMNO}	40.06±1.70^{HIJKL}	30.95±1.13^{PQ}	35.81±1.48^{fg}
T_7	64.97±1.04^{AB}	66.46±0.98^{A}	59.84±1.69^{CD}	63.76±1.19^{a}
T_8	48.87±0.89^{EF}	55.25±4.59^{D}	39.05±1.33^{JKLMN}	47.72±2.74^{c}
T_9	40.96±1.67^{HIJK}	46.84±2.91^{EFG}	36.46±1.20^{KLMNO}	41.42±1.82^{d}
T_{10}	34.83±1.71^{NOPQ}	36.82±0.69^{KLMNO}	30.11±1.06^{Q}	33.92±1.17^{g}
Mean	44.70±3.35^{B}	48.98±3.40^{A}	38.44±3.00^{C}	
		LAI		
T_1	2.26±0.05^{BCD}	1.71±0.01^{KLM}	1.94±0.02^{H}	1.97±0.08^{c}
T_2	2.30±0.02^{BC}	1.73±0.01^{KL}	2.08±0.13^{G}	2.04±0.09^{b}
T_3	2.15±0.01^{EFG}	1.61±0.06^{MN}	1.86±0.02^{HIJ}	1.87±0.08^{de}
T_4	2.23±0.02^{CDE}	1.66±0.05^{LMN}	1.93±0.02^{HI}	1.94±0.08^{d}
T_5	2.12±0.09^{FG}	1.58±0.03^{N}	1.83±0.03^{IJ}	1.84±0.08^{e}
T_6	2.18±0.02^{DEFG}	1.64±0.02^{LMN}	1.91±0.05^{HI}	1.91±0.08^{cd}
T_7	2.46±0.03^{A}	1.96±0.02^{H}	2.22±0.06^{CDEF}	2.21±0.07^{a}
T_8	2.33±0.06^{B}	1.77±0.05^{JK}	2.12±0.03^{FG}	2.07±0.08^{b}
T_9	2.13±0.04^{EFG}	1.57±0.03^{N}	1.83±0.02^{IJ}	1.84±0.09^{e}
T_{10}	1.37±0.02^{O}	1.03±0.01^{Q}	1.23±0.02^{P}	1.21±0.05^{f}
Mean	2.15±0.05^{A}	1.63±0.04^{C}	1.90±0.05^{B}	
Significance				
T	***	***	***	
C	***	***	***	
T × C	NS	NS	NS	

Data represent the mean of 5 replicates ± standard error (SE). Lowercase superscripts letters in the column of the mean, uppercase superscripts letters on the line of mean and italics uppercase superscripts letters in the column and line of mean specifies statistically significant difference between the means (p≤0.05, Duncan Multiple Range Test). *: p≤0.05; **: p≤0.01;***: p≤0.001; NS = non-significant.

Table 5. Correlation between thinning, cultivars different cropping, fruit quality, bio-chemical and growth parameters.

	T	C	EOT	PROD.	RB	FL	FD	LD	RSC	TSS	TS	ANTH.	ASG	LAI
T	1													
C	0.00	1												
EOT	-0.32**	0.09	1											
PROD.	0.19	-0.36**	-0.60**	1										
RB	-0.27*	0.20	0.82**	-0.58**	1									
FL	-0.20	-0.30**	0.71**	-0.09	0.54**	1								
FD	-0.12	-0.56**	0.65**	-0.16	0.54**	0.86**	1							
LD	-0.20	0.38**	0.30**	0.08	0.17	0.50**	-0.01	1						
RSC	-0.08	-0.58**	0.54**	-0.13	0.35**	0.70**	0.83**	-0.04	1					
TSS	-0.31**	-0.04	0.68**	-0.63**	0.85**	0.51**	0.62**	-0.04	0.45**	1				
TS	-0.31**	-0.06	0.86**	-0.69**	0.85**	0.63**	0.70**	0.06	0.57**	0.92**	1			
ANTH.	-0.13	-0.14	0.22**	0.09	-0.11	0.56**	0.38**	0.46**	0.36**	-0.10	0.08	1		
ASG	-0.19	-0.24*	0.82**	0.60**	0.73**	0.62**	0.76**	-0.07	0.65**	0.79**	0.91**	0.07	1	
LAI	-0.32**	-0.31**	0.42**	0.05	0.26*	0.80**	0.69**	0.39**	0.55**	0.31**	0.38**	0.81**	0.33**	1

** Correlation significant at p≤ 0.01 level (2- tailed). * Correlation significant at p≤ 0.05 level (2-tailed). T: thinning treatments. C: cultivars. EOT: extent of thinning. PROD: productivity, Mt ha-1. RB: return bloom. FL: fruit length. FD: fruit diameter. LD: L/D ratio. RSC: red skin colour. TSS: total soluble solids. TS: total sugars. ANTH: anthocyanin content. ASG: annual shoot growth. LAI: leaf area index.

Productivity

The different thinning methods had a substantial impact on productivity and varied with respect to cultivars. The lower extent of thinning in 'Jeromine' in comparison to other cultivars accounted for the retention of a greater number of fruits (see Tables S1 and S2 [suppl]), which may have led to differences in yield, yield efficiency and ultimately productivity. These findings are consistent with those of Anthony et al. (2019), who also noted a significant impact of crop load on production, with yields ranging from 28 to 83 Mt ha^{-1}, with the highest yield of 82.8 Mt mg L^{-1} in a crop load of 8 fruits cm^{-2} TCSA in apple cv. 'WA38' under high density plantation. Radivojevic et al. (2014) similarly concluded that 'Braeburn' and 'Gala' may both have up to 13 fruits cm^{-2} of TCSA to produce a high output (50 Mt ha^{-1}). Salvador et al. (2006) also set the maximum acceptable crop load for the 'Golden Delicious' apple cultivar at 8 fruits cm^{-2} TCSA, further exceeding crop load was considered not suitable for quality production of fruits.

Return bloom

The enhanced return bloom due to severity of thinning may be due to the removal of source of gibberellic acid (GA) present in the seeds of young fruitlets. The GA, which is exported from seeds in developing fruits (at 3-4 weeks after bloom) is known to inhibit flower bud initiation and exert an inhibitory impact on return bloom (Koutinas et al., 2010). These findings are in line with those of Embree et al. (2007), who found that during 'Honeycrisp' apple cultivar "off" years, trees with crop loads of 3 and 6 fruits cm^{-2} TCSA displayed considerably more bloom per cluster than those with 9 fruits cm^{-2} TCSA and the unthinned (control) trees. The findings corroborate those of Anthony et al. (2019), who similarly noted a higher return bloom with a lighter crop load that was ideal at around 6 fruits cm^{-2} TCSA in apple 'WA38'.

Fruit quality

T_7 produced fruits of higher grade, while T_{10} fruits of lower quality. The reduced number of fruits as a result of the greater extent of thinning led to an increase in leaf area per fruit (Table S2 [suppl]), in turn increased the assimilate availability to the remaining apple fruitlets. This is one explanation for the observed effect. At the same time, bigger fruit size under lower crop loads might be caused by less resource rivalry during cell division, a time of high carbon requirement and a stage that determines superior fruit size. The results are consistent with those of Jemric et al. (2003), who also noted that fruits from hand-thinned trees of the 'Golden Delicious Clone B' exhibited higher firmness, soluble solids content (SSC), and colour than fruits from chemically-thinned trees. Castro et al. (2015) likewise concluded that crop loads in the range of 3-7 fruits cm^{-2} TCSA for 'Eva' and 5-7 fruits cm^{-2} TCSA for 'Caricia' are ideal for achieving acceptable yields of high-quality fruits in apple plantations with high densities. These results are consistent with those of Anthony et al. (2019), who also observed that an increase in crop load had an influence on fruit quality since it lowered the weight and hardness of apple fruit.

Fruit bio-chemical parameters

The creation of more dry matter and improvement of the fruit's physico-chemical qualities are ultimately caused by the availability of more photo assimilates per fruit and higher levels of thinning. These findings are in line with those of Jemric et al. (2003), who found that manual thinning of the apple 'Golden Delicious Clone B' resulted in higher SSC and lower titratable acidity than chemical thinning. Differences in acid metabolism between extensively thinned and less thinned apple trees account for negative connection between titratable acidity and heavy level of thinning (Salvador et al., 2006). In a similar vein, Serra et al. (2016) found that the lowest crop loads of 4.7 fruits cm^{-2} TCSA had higher percentages of flushed colour, firmness, SSC and dry matter.

Growth

The extent of the thinning percentage has a favourable effect on growth indicators including yearly shoot growth and LAI in apple under high density plantations. The leaf to fruit ratio improves with increased fruit reduction and thinning, and some of the additional metabolite supply that results is diverted into apple vegetative development (Forshey & Elfving, 1989). Similar to this, Palmer et al. (1997) found considerable leaf area reduction in apple 'Braeburn' on M.26 apple rootstock due to increased crop load. When crop burden is reduced, the vegetation often responds by increasing leaf area, vegetative dry matter, and annual shoot growth (Wünsche et al., 2005).

Conclusions

Crop load management in apple under high density plantation is a novel idea in India, the current study is a preliminary one. The paper's explanation of how to optimize crop load will help to guarantee the production of apples grown in high-density plantations that are of higher quality, have better marketability, and yield higher returns. The cultivar 'Jeromine' produced more fruit with better quality when naphthalene acetic acid was applied at 10 and 20 mg L^{-1}, while 'Redlum Gala' had the highest return bloom, closely followed by 'Super Chief' and 'Jeromine'. However an ideal crop load range is around 4-6 fruits cm^{-2} trunk cross section area, among various chemical and manual thinning treatments with respect to production, fruit quality and consistent return bloom in high density orchards in India.

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