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EFFECT OF DEFICIT IRRIGATION AND PLANT BIOREGULATORS ON FRUIT PHYSICAL AND BIOCHEMICAL PROPERTIES OF SWEET ORANGE GROWN IN SHALLOW SOILS

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ABSTRACT

Sweet orange (*Citrus sinensis* L. Osbeck) is an important fruit crop in semi-arid regions, where limited irrigation water can affect fruit development and quality. The present study evaluated the effects of irrigation regimes and bioregulators on fruit quality of sweet orange cv. Nucellar during the Ambia bahar season of 2024 at ICAR–National Institute of Abiotic Stress Management, Baramati, Maharashtra. The experiment was conducted in a split-plot design with 100% and 50% ETc under partial root-zone drying (PRD) as main-plot treatments and eight bioregulator treatments as sub-plots. Fruit quality was assessed for physical and biochemical attributes. Irrigation at 50% ETc under PRD improved biochemical fruit quality, recording higher TSS (12.19 °Brix), DPPH activity (87.09 mg 100 g^{-1}), total sugars (9.51%), reducing sugars (4.46%) and non-reducing sugars (5.06%), with lower acidity (0.74%) than 100% ETc. However, 50% ETc reduced fruit weight (169.19 g), pulp weight (125.47 g) and juice (109.63 ml), compared with 100% ETc (193.03 ,154.05 g and 132.07 ml, respectively), while peel weight increased from 38.98 g to 43.72 g. Among the bioregulator treatments, NPRO20 recorded the highest TSS (12.41 °Brix) and DPPH activity (85.07 mg 100 g^{-1}), whereas NPRO30 resulted in the highest fruit weight (197.40 g), pulp weight (158.93 g), juice (137.22 ml), total sugars (8.81%) and reducing sugars (4.30%). The interaction 50% ETc + NPRO20 recorded the highest DPPH activity (87.61 mg 100 g^{-1}) and reducing sugars (4.97%), while 50% ETc + NSA3 recorded the highest total sugars (10.18%). Overall, 50% ETc under PRD, particularly with NPRO20 or NPRO30 improved several biochemical quality attributes but resulted in a penalty in fruit, pulp weight and juice content.

***Key word*:** Sweet orange; deficit irrigation; partial root-zone drying; proline; salicylic acid.

Introduction

Sweet orange (*Citrus sinensis* L. Osbeck) is an important citrus fruit crop grown widely in tropical and subtropical regions. Its value depends not only on fruit yield but also on fruit quality. Important quality characters include fruit size, juice content, total soluble solids (TSS), titratable acidity, sugars and the balance between sweetness and acidity. Maintaining good fruit quality is becoming difficult in semi-arid regions because of irregular rainfall and limited availability of irrigation water. Therefore, it is important to develop irrigation practices that use water efficiently without reducing fruit quality.

Irrigation has an important role in the growth and development of sweet orange fruits. However, applying more water does not always result in better fruit quality. Both the amount and duration of water supply can affect tree growth, fruit development and the accumulation of important quality components. Properly managed deficit irrigation can reduce water use while maintaining satisfactory yield and fruit quality. In sweet orange, irrigation based on crop evapotranspiration (ETc) has shown potential for saving water while maintaining crop performance, and moderate deficit irrigation can provide a useful balance between water saving and fruit

production (Silveira *et al.*, 2020). The response of citrus trees also depends on the level and timing of water restriction, as well as their ability to adjust to changes in soil moisture (Saitta *et al.*, 2021; Chen *et al.*, 2022). Therefore, irrigation based on crop water requirement can be an effective approach for improving water-use efficiency and maintaining fruit quality.

Bioregulators can also help plants cope with limited water availability. Salicylic acid (SA) plays an important role in plant growth, stress response and antioxidant defence. Its application may help plants maintain normal physiological activity and improve fruit biochemical characteristics under stressful conditions (Serna-Escolano *et al.*, 2021). Proline is another important compound involved in plant response to water stress. It helps plants maintain water balance and protect cells when water availability is low. In addition, nano-formulations of bioregulators may improve the delivery and uptake of active compounds by plants. However, their effectiveness may vary depending on the crop, formulation, application method and growing conditions.

Although irrigation management and bioregulators have each shown potential for improving plant performance under water stress, their combined effect on the fruit quality of Nucellar sweet orange under field conditions is still not well understood. In particular, limited information is available on the interaction of irrigation levels with salicylic acid, proline and their nano-formulations. Understanding these interactions may help in developing a practical approach to save water without sacrificing fruit quality. Therefore, the present study was conducted to evaluate the effects of different irrigation regimes and bioregulator applications, alone and in combination, on the physical and biochemical quality of sweet orange (*Citrus sinensis* L. Osbeck) cv. Nucellar and to identify a suitable irrigation × bioregulator combination for improving fruit quality under limited water availability.

Materials and Methods

The field experiment was conducted during the Ambia bahar season of 2024 at the ICAR–National Institute of Abiotic Stress Management (NIASM), Baramati, (Fig. 1) Maharashtra, India (18°09’ 30.62” N, 74°30’ 03.08” E; 570 m above mean sea level). The experimental site falls under the Deccan Plateau region (AER-6; AZ-95), which receives an average annual rainfall of about 560 mm. The monthly meteorological conditions recorded at the experimental site during the study period are presented in Table 1. The orchard consisted of 10-year-old sweet orange (*Citrus sinensis* L. Osbeck) cv. Nucellar trees grafted on Rangpur lime and planted at a spacing of 5.0 × 4.5 m. Ambia bahar flowering was induced during January–February by withholding irrigation during November–December. The experiment was laid out in a split-plot design, with two irrigation regimes assigned to the main plots: 100% crop evapotranspiration (ETc) (I_1) and 50% ETc under partial root-zone drying (PRD) (I_2). Eight bioregulator treatments were imposed in the sub-plots, comprising nano-encapsulated proline at 20 and 30 mM (NPRO20 and NPRO30), nano salicylic acid at 2 and 3 mM (NSA2 and NSA3), proline at 30 mM (PRO30), salicylic acid at 4 mM (SA4), untreated control (UC), and water spray (WS) and three replications. The foliar treatments were applied at four important crop stages, namely shoot development, flowering, fruit growth, and colour break. Under PRD, irrigation was alternated between the two drip laterals at seven-day intervals.

The experimental soil was alkaline (pH 8.0–8.2), well drained, and relatively low in fertility, with available N, P and K contents of 90, 1.5 and 100 kg ha^{-1}, respectively. The irrigation water had a pH of 8.14 and an electrical conductivity of 0.33 dS m^{-1}. Each tree was irrigated through four emitters, each delivering 8 L h^{-1}. Irrigation requirements were estimated following the FAO-56 approach (Allen *et al.*, 1998), where reference evapotranspiration *(ET€)* was calculated as $ET€ = Epan \times Kp$, with a pan coefficient *(Kp)* of 0.80, and crop evapotranspiration *(ETc)* was calculated as $ETc = ET€ \times Kc$. Crop coefficients of 0.60, 0.75 and 0.70 were used for the initial, mid-season and late-season stages, respectively. A wetted-area factor of 0.50 and drip irrigation efficiency of 0.90 were considered for scheduling irrigation.

Fruit quality parameters were evaluated at harvest in November 2024. Fruits were harvested at physiological maturity, as indicated by the development of characteristic fruit colour and attainment of the appropriate maturity stage. Fruit, pulp, juice and peel weights were recorded from five mature fruits selected from each treatment by weighing the fruits individually, followed by separating and weighing the pulp and peel, and the values were expressed in grams (g). Juice was extracted from pulp and expressed in millilitres (ml). Total soluble solids (TSS) were measured using a digital refractometer (Erma Tokyo-A032) and expressed as °Brix. Titratable acidity was estimated by titrating a 5 g homogenized fruit pulp sample, diluted to 50 ml with distilled water, against 0.1 N NaOH using phenolphthalein as an indicator and expressed as percentage. Total sugars were estimated by the phenol-sulphuric acid method, with absorbance recorded at 490 nm. Reducing sugars were determined

by the Nelson–Somogyi method (Nelson, 1944; Somogyi, 1952), using glucose as the standard and absorbance measured at 620 nm. Non-reducing sugars were calculated as the difference between total and reducing sugars and expressed as percentage. Antioxidant activity was determined by the DPPH radical-scavenging assay using 20 mg fresh fruit extract in 80% methanol, with absorbance measured at 517 nm after 30 min incubation in the dark and expressed in mg 100 g^{-1}. The data were analysed by R and KAU GRAPE software, and treatment means were compared using CD at the 5% significance level.

Results and Discussions

Irrigation regime and bioregulator treatments markedly affected the biochemical quality of sweet orange fruits (Table 3 and Table 4). Irrigation regime significantly influenced fruit weight, pulp weight, juice (ml) and peel weight of sweet orange, whereas the irrigation × bioregulator interaction was non-significant for all four parameters (Table 2). Fruits under 100% ETc recorded significantly higher fruit weight (193.03 g), pulp weight (154.05 g) and juice (132.07 ml) than those under 50% ETc (169.19 g ,125.47 g and 109.63 ml, respectively), representing reductions of 12.35 ,18.55 and 15.93%, respectively, under deficit irrigation. In contrast, peel weight was significantly higher under 50% ETc (43.72 g) than under 100% ETc (38.98 g), indicating a 12.16% increase under water deficit. Among the bioregulators, NPRO30 recorded the highest mean fruit weight (197.40 g), at par with NPRO20 (189.90 g), NSA3 (188.49 g), PRO30 (189.01 g), NSA2 (183.75 g) and SA4 (182.17 g), while UC (156.94 g) and WS (161.23 g) recorded significantly lower fruit weights. A similar trend was observed for pulp weight and juice(ml) with NPRO30 recording the highest mean pulp weight (158.93 g) and juice (137.22 ml) and WS was lowest in (116.27 g) pulp wt and juice (91.96 ml). In contrast, WS recorded the highest mean peel weight (44.96 g), followed by UC (44.49 g), while NPRO30 recorded the lowest (38.47 g). The reduction in fruit size under 50% ETc was also evident

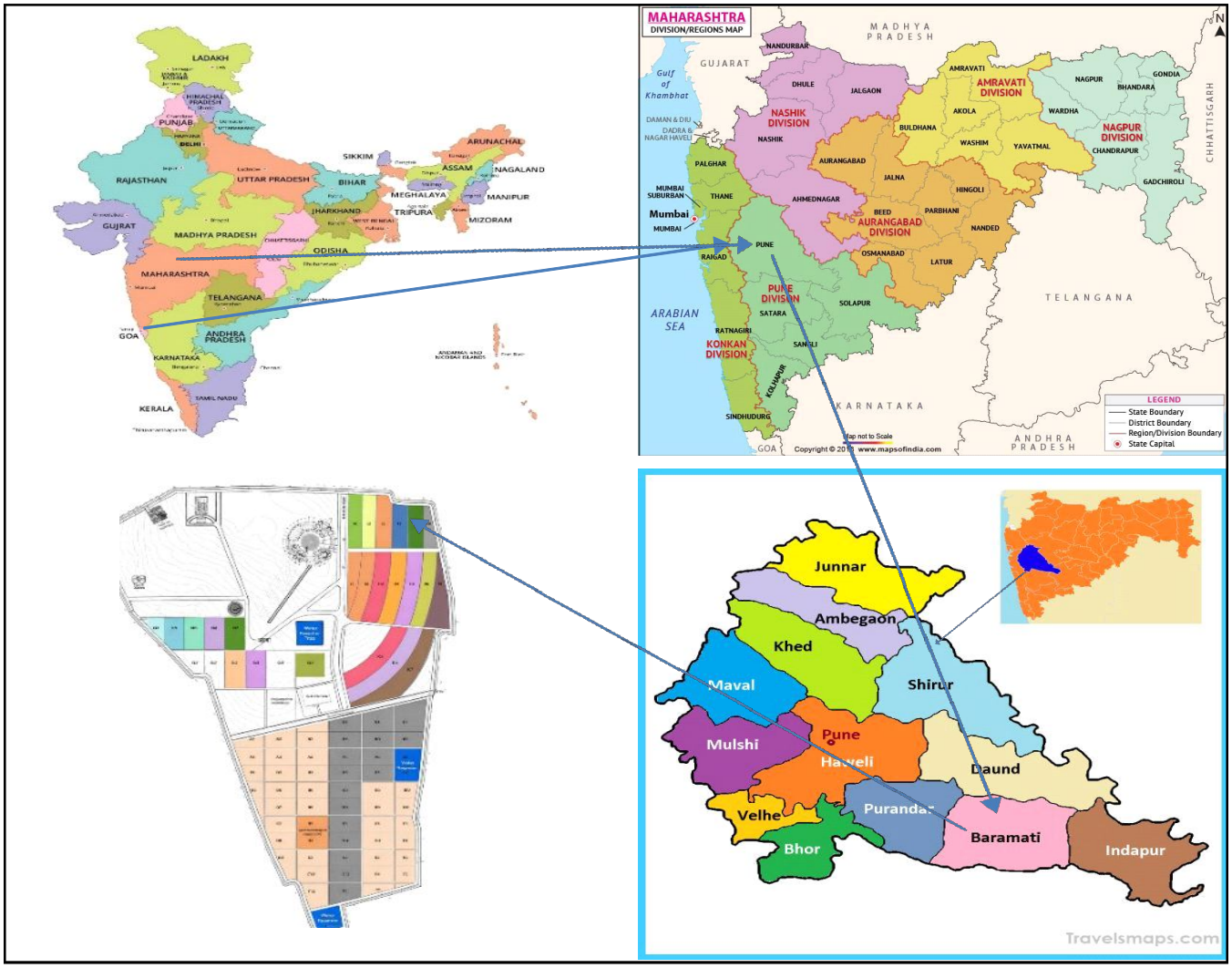

Fig. 1: Study area map of the experimental site in ICAR- NIASM.

Table 1: Meteorological data of the experimental site period from January 2024 to December 2024 at ICAR-NIASM, Maharashtra.

Month	Temperature (°C)			Relative Humidity (%)			Wind (km/hr)	Rain (mm)	Evaporation (mm)
	Max	Min	Mean	Max	Min	Mean			
January	29.9	13.8	21.8	85	38.1	61.5	4.5	0.1	4.1
February	33.4	15	24.2	75.7	24.6	50.1	4	0.1	6
March	36.1	17.5	26.8	62.8	19.8	41.3	5.7	0.1	8.2
April	38.6	21.9	30.2	58.6	23	40.8	5.8	0.7	9
May	38.1	22.3	30.2	72	31.1	51.5	8.5	1.5	9.1
June	32.7	22	27.4	88.1	58	73	8.4	8.3	5.6
July	29.6	21.7	25.6	92.3	71	81.6	9.5	3.1	3.4
August	30.4	21.1	25.8	91.8	64.8	78.3	7.5	4.8	3.8
September	30.7	20.4	25.6	91.2	60.3	75.8	8.5	2.9	4.5
October	32	20.1	26.1	93	52	72.5	5.4	2.7	4.1
November	30.1	14.9	22.5	83.8	36.6	60.2	3.5	0	4.1
December	29.8	15.6	22.7	87.1	42	64.5	3.9	0	3.4

from the representative fruits shown in Fig. 2 and Fig. 3. The greater fruit and pulp weight under full irrigation may be attributed to improved plant water status, greater cell expansion and enhanced assimilate translocation during fruit development, whereas water deficit can restrict cell division and expansion and consequently reduce fruit size. The higher peel weight under 50% ETc may indicate relatively greater allocation or concentration of dry matter in the peel under water-limited conditions. The beneficial effect of adequate irrigation on citrus fruit size is consistent with previous reports showing that water deficit can reduce fruit growth and fresh weight, while appropriate irrigation promotes cell expansion and fruit enlargement. Pérez-Pérez *et al*., (2009) reported that deficit irrigation in 'Lane Late' sweet orange influenced fruit growth and reduced fruit size under water-limited conditions. Similarly, García-Tejero *et al*., (2010) reported that regulated deficit irrigation affected fruit size and quality characteristics of citrus. The superior performance of NPRO30 for fruit and pulp weight in the present study suggests that this treatment may have promoted better fruit growth and assimilate accumulation under the experimental conditions. However, because the irrigation × bioregulator interaction was non-significant, the data do not support a statistically significant synergistic effect between irrigation regime and bioregulator treatment for these traits. Overall, 100% ETc was more favourable for maintaining higher fruit, pulp weight and juice (ml), whereas 50% ETc resulted in greater peel weight, and among the bioregulators, NPRO30 showed the most consistent advantage for fruit size and edible pulp development.

The reduction in fruit size under PRD may be related to limited water availability during fruit development, which can restrict fruit hydration and cell expansion, particularly in the edible pulp. Hutton and Loveys (2011) also observed a slight reduction in fruit size under PRD

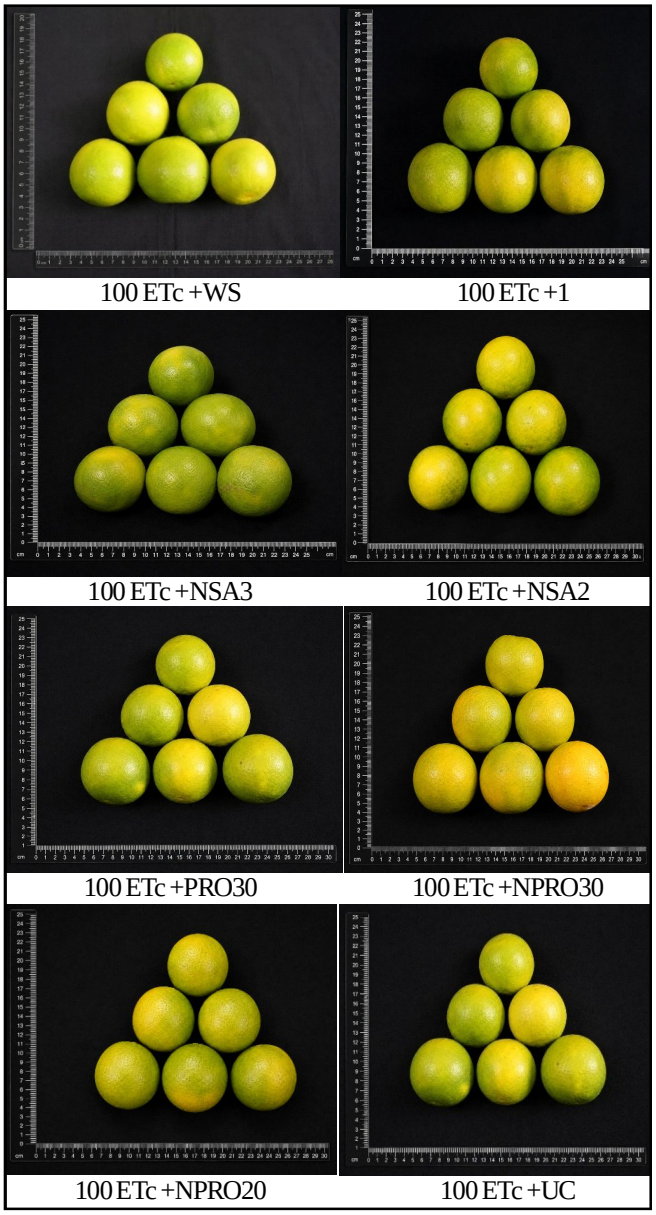

Fig. 2: Effect of irrigation regime (100 % ETc) and bioregulators on fruit.

Table 2. Effect of irrigation regimes and bioregulators on physical fruit quality parameters of sweet orange

	Fruit weight(g)			Pulp weight (g)			Peel weight (g)			Juice (ml)		
	100 ETc	50 ETc	BM	100 ETc	50 ETc	BM	100 ETc	50 ETc	BM	100 ETc	50 ETc	BM
NPRO20	203.39	176.4	189.90^{a}	167.82	131.74	149.78^{ab}	35.57	44.66	40.12^{cd}	143.16	114.63	128.89^{ab}
NPRO30	208.67	186.13	197.40^{a}	172.9	144.96	158.93^{a}	35.77	41.17	38.47^{d}	147.06	127.37	137.22^{a}
NSA2	193.23	174.28	183.75^{a}	155.23	131.9	143.56^{ab}	38	42.38	40.19^{cd}	133.61	114.82	124.22^{ab}
NSA3	201.73	175.25	188.49^{a}	166.28	133.24	149.76^{ab}	35.45	42.01	38.73^{d}	147.91	123	135.46^{a}
PRO30	202.07	175.95	189.01^{a}	163.75	131.72	147.74^{ab}	38.31	44.23	41.27^{bcd}	140.73	112.56	126.65^{ab}
SA4	191.34	173	182.17^{a}	149.71	129.49	139.60^{b}	41.63	43.51	42.57^{abc}	127.49	113.61	120.55^{b}
UC	171.89	141.99	156.94^{b}	129.06	95.83	112.45^{c}	42.82	46.16	44.49^{ab}	104.69	79.23	91.96^{c}
WS	171.92	150.54	161.23^{b}	127.67	104.87	116.27^{c}	44.26	45.67	44.96^{a}	111.9	91.84	101.87^{c}
IRM	193.03^{a}	169.19^{b}	—	154.05^{a}	125.47^{b}	—	38.98^{b}	43.72^{a}	—	132.07^{a}	109.63^{b}	
	S.E (m)±	C.D at 5%		S.E (m)±	C.D at 5%		S.E (m)±	C.D at 5%		S.E (m)±	C.D at 5%	
Main Plot	2.44	14.89		2.97	18.09		0.56	3.43		1.14	6.98	
Sub Plot	6.78	19.65		6.73	19.5		1.13	3.29		3.37	9.78	
Interaction	9.59	N.S		9.52	N.S		1.6	N.S		4.77	N.S	

Footnote: BM = Bioregulator means; IRM = Irrigation regime means; S.E. (m) ± = standard error of mean; C.D. = critical difference at 5% level of significance; N.S. = non-significant. Means followed by the same superscript letter are not significantly different according to Duncan's multiple range test (DMRT) at the 5% level of significance.

in mature Navel orange, along with improved water-use efficiency. In the present study, the extent of fruit-size reduction may have been influenced by the light, gravelly loamy-sand soil at the experimental site, which has a relatively low capacity to retain available water. Under restricted irrigation, soil moisture in such conditions can decline more rapidly, especially during periods of high evaporative demand. This is particularly relevant to PRD, where only part of the root zone is wetted at a given time. Therefore, the seven-day alternation of irrigation laterals requires careful management to avoid excessive drying of the active root zone.The response observed in the present study does not imply that PRD is unsuitable for light soils. Consoli *et al*., (2017) reported improved water-use efficiency under 50% ETc PRD in orange, demonstrating the potential of PRD as a water-saving approach even under reduced irrigation. In the present experiment, the lower fruit size under PRD was accompanied by improved water productivity, showing that water savings were achieved at the expense of some fruit growth. Thus, PRD may be useful in semi-arid and water-limited regions when irrigation frequency and alternation of the wetted root zone are carefully managed. However, where maximum fruit size and absolute yield

Table 3: Effect of irrigation regimes and bioregulators on TSS, acidity and antioxidant activity of sweet orange fruit.

	TSS (°Brix)			Acidity (%)			DPPH (mg 100 g^{-1})		
	100 ETc	50 ETc	BM	100 ETc	50 ETc	BM	100 ETc	50 ETc	BM
NPRO20	11.4	13.42	12.41^{a}	0.87^{b}	0.68^{a}	0.78^{ab}	82.54^{ab}	87.61^{a}	85.07^{a}
NPRO30	11.13	12.46	11.79^{b}	0.88^{b}	0.57^{a}	0.73^{a}	83.15^{ab}	86.43^{a}	84.79^{a}
NSA2	10.92	11.84	11.73^{b}	0.66^{a}	0.92^{b}	0.79^{ab}	82.22^{ab}	86.68^{a}	84.45^{a}
NSA3	10.87	12.59	11.38^{bc}	1.03^{c}	0.61^{a}	0.82^{ab}	81.00^{abc}	87.49^{a}	84.24^{a}
PRO30	10.72	11.89	11.32^{bc}	0.99^{c}	0.75^{ab}	0.87^{ab}	73.95^{bc}	87.40^{a}	80.68^{ab}
SA4	10.43	12.21	11.30^{bc}	0.74^{a}	0.87^{b}	0.81^{ab}	72.20^{c}	87.30^{a}	79.75^{ab}
UC	10.07	11.61	10.84^{cd}	1.08^{c}	0.76^{ab}	0.92^{b}	63.17^{d}	86.87^{a}	75.02^{b}
WS	9.11	11.53	10.31^{d}	1.07^{c}	0.75^{ab}	0.91^{b}	78.44^{abc}	86.93^{a}	82.68^{a}
IRM	10.58^{b}	12.19^{a}	—	0.91^{b}	0.74^{a}	—	77.08^{b}	87.09^{a}	—
	S.E (m)±	C.D at 5%		S.E (m)±	C.D at 5%		S.E (m)±	C.D at 5%	
Main Plot	0.12	0.7		0.01	0.06		0.3	1.85	
Sub Plot	0.29	0.84		0.04	0.12		2.13	6.17	
Interaction	0.29	N.S		0.06	0.17		3.01	8.73	

Note: DPPH = 2,2-diphenyl-1-picrylhydrazyl; BM = Bioregulator means; IRM = Irrigation regime means; S.E. (m) ± = standard error of mean; C.D. = critical difference at 5% level of significance; N.S. = non-significant. Means followed by the same superscript letter are not significantly different according to Duncan's multiple range test (DMRT) at the 5% level of significance.

Table 4: Effect of irrigation regimes and bioregulators on sugar composition of sweet orange fruit.

	Total sugars (%)			Reducing sugars (%)			Non-reducing sugars (%)		
	100 ETc	**50 ETc**	**BM**	**100 ETc**	**50 ETc**	**BM**	**100 ETc**	**50 ETc**	**BM**
NPRO20	6.93^{gh}	9.75^{bc}	8.34^{c}	3.50^{efg}	4.97^{a}	4.24^{a}	3.43^{h}	4.78^{d}	4.11^{e}
NPRO30	7.77^{f}	9.84^{b}	8.81^{a}	3.86^{de}	4.73^{ab}	4.30^{a}	3.91^{f}	5.11^{b}	4.51^{c}
NSA2	7.87^{f}	9.22^{d}	8.55^{b}	3.68^{ef}	4.13^{cd}	3.91^{bc}	4.19^{e}	5.09^{b}	4.64^{bc}
NSA3	7.10^{g}	10.18^{a}	8.64^{b}	3.42^{fgh}	4.83^{ab}	4.13^{ab}	3.68^{g}	5.01^{bc}	4.35^{d}
PRO30	7.09^{g}	9.56^{c}	8.33^{c}	3.22^{gh}	4.67^{ab}	3.95^{bc}	3.87^{fg}	5.14^{b}	4.51^{c}
SA4	6.78^{h}	9.30^{d}	8.04^{d}	3.11^{hi}	4.45^{bc}	3.78^{c}	3.67^{g}	4.83^{cd}	4.25^{de}
UC	7.11^{g}	9.01^{e}	8.06^{d}	2.79^{ij}	4.11^{cd}	3.45^{d}	4.32^{e}	5.08^{b}	4.70^{b}
WS	6.94^{gh}	9.24^{d}	8.09^{d}	2.65^{j}	3.78^{def}	3.22^{d}	4.29^{e}	5.46^{a}	4.88^{a}
IRM	7.20^{b}	9.51^{a}	—	3.28^{b}	4.46^{a}	—	3.92^{b}	5.06^{a}	—
	S.E (m)±	**C.D at 5%**		**S.E (m)±**	**C.D at 5%**		**S.E (m)±**	**C.D at 5%**	
Main Plot	0.08	0.47		0.01	0.04		0.09	0.47	
Sub Plot	0.05	0.15		0.09	0.25		0.05	0.15	
Interaction	0.07	0.21		0.12	0.35		0.07	0.21	

Note: BM = Bioregulator means; IRM = Irrigation regime means; S.E. (m) ± = standard error of mean; C.D. = critical difference at 5% level of significance. Means followed by the same superscript letter are not significantly different according to Duncan's multiple range test (DMRT) at the 5% level of significance.

are the main production objectives, the reduction in fruit size associated with deficit irrigation should be considered when selecting the irrigation strategy.

Fruits under 50% ETc recorded higher TSS (12.19 °Brix), DPPH activity (87.09 mg 100 g^{-1}), total sugars (9.51%), reducing sugars (4.46%) and non-reducing sugars (5.06%) than those under 100% ETc (10.58 °Brix, 77.08 mg 100 g^{-1}, 7.20%, 3.28% and 3.92%, respectively), whereas acidity declined from 0.91 to 0.74%. Thus, 50% ETc increased TSS, DPPH activity and total, reducing and non-reducing sugars by 15.2, 13.0, 32.1, 35.9 and 29.1%, respectively (Table 3 and Table 4), while lowering acidity by 18.7%. This response agrees partly with Pérez-Pérez *et al*., (2009), who reported improved TSS under deficit irrigation in 'Lane Late' sweet orange, although their treatment increased rather than decreased titratable acidity; such differences may reflect variation in cultivar, stress intensity and timing. Moderate deficit irrigation has also been reported to maintain fruit quality while improving irrigation efficiency in sweet orange, supporting the suitability of regulated water limitation during fruit maturation (Aguado *et al*., 2012). Bioregulators, NPRO20 produced the highest TSS (12.41 °Brix) and DPPH activity (85.07 mg 100 g^{-1}), whereas NPRO30 recorded the highest total sugars (8.81%) and reducing sugars (4.30%), WS had the highest non-reducing sugars (4.88%), while UC showed the highest acidity (0.92%) and lowest DPPH activity (75.02 mg 100 g^{-1}). The interaction means further showed that 50% ETc + NPRO20 produced the highest DPPH activity (87.61 mg 100 g^{-1}) and reducing sugars (4.97%), 50% ETc + NSA3 the highest total sugars (10.18%), and 50% ETc + WS

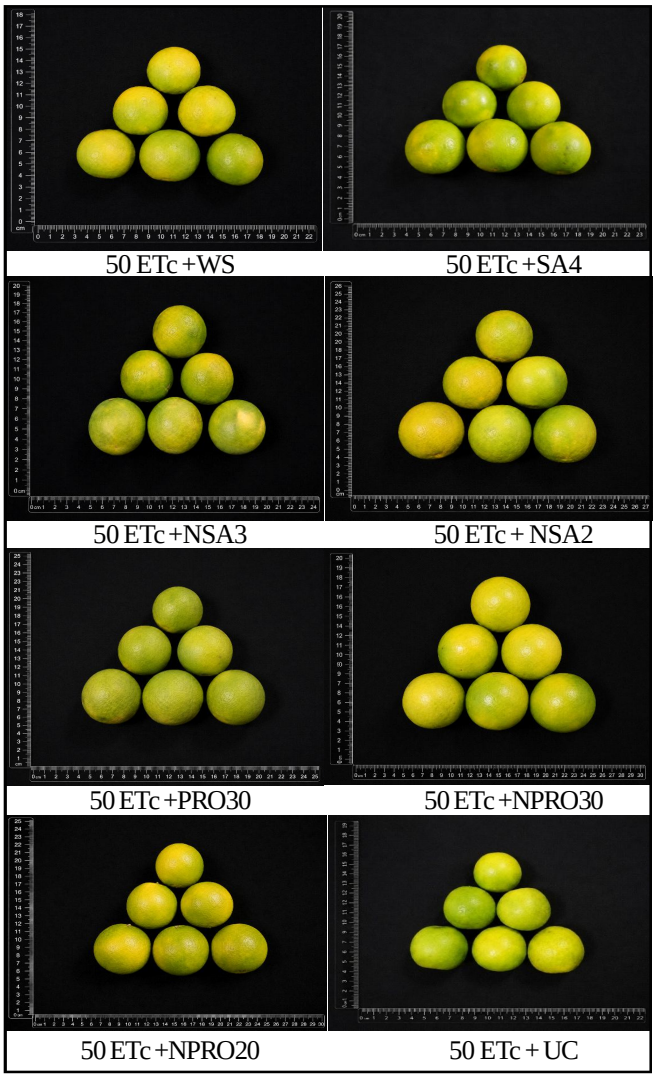

Fig. 3: Effect of irrigation regime (50 % ETc) and bioregulators on fruits.

the highest non-reducing sugars (5.46%). Conversely, 100% ETc + WS recorded the lowest TSS (9.11 °Brix) and reducing sugars (2.65%), while 100% ETc + UC had the lowest DPPH activity (63.17 mg 100 g^{-1}); the lowest total and non-reducing sugars occurred with 100% ETc + NPRO20 (6.93 and 3.43%), respectively. Acidity was highest under 100% ETc + UC (1.08%) and lowest under 50% ETc + NPRO30 (0.57%). The better performance of proline treatments under deficit irrigation may be associated with the role of proline in osmotic adjustment and protection against oxidative stress, including regulation of reactive oxygen species (Hayat *et al*., 2012). Overall, 50% ETc, particularly with NPRO20 and NPRO30, showed potential for improving biochemical fruit quality while reducing irrigation water use.

Conclusion

The study revealed that 100% ETc produced higher fruit weight (193.03 g), pulp weight (154.05 g) and juice (132.07 ml). However, 50% ETc under PRD improved the biochemical quality of sweet orange fruits, with higher TSS (12.19 °Brix), DPPH activity (87.09 mg 100 g^{-1}), total sugars (9.51%), reducing sugars (4.46%) and non-reducing sugars (5.06%), along with lower acidity (0.74%) than 100% ETc. Among bioregulators, NPRO20 recorded the highest TSS and DPPH activity, whereas NPRO30 recorded the highest fruit weight, pulp weight, juice, total sugars and reducing sugars. The interaction 50% ETc + NPRO20 resulted in the highest DPPH activity (87.61 mg 100 g^{-1}) and reducing sugars (4.97%), while 50% ETc + NSA3 produced the highest total sugars (10.18%). Thus, 50% ETc with nano-encapsulated proline, particularly NPRO20 and NPRO30, offers potential for improving fruit quality while reducing irrigation water use.

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