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Impact of regulated deficit irrigation on fruit quality and water savings in apple orchards

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Abstract

Water scarcity is the largest constraint on expanding fruit production in arid North Africa. This research assessed Regulated Deficit Irrigation (RDI) on fruit quality, yield, and Water Use Efficiency (WUE) in a seven-year-old Anna apple orchard at Nile Delta Agricultural University, Mansoura, Egypt, during 2022 and 2023. Four drip-irrigation treatments were imposed during fruit development: 100%, 80%, 60%, and 40% crop evapotranspiration (ET_c) in a randomised complete block design with four replications. Reducing irrigation to 80% ET_c caused only a 4.9% yield decline (30.8 vs 32.4 t/ha) while improving total soluble solids by 11.3% and firmness by 8.5%. At 60% ET_c, yield loss reached 16.4% but WUE increased by 39.5%. Severe deficit (40% ET_c) reduced fruit weight to 132.7 g and yield to 21.3 t/ha, penalties too large for commercial acceptance. Mild RDI at 80% ET_c offers the best compromise between water savings and marketable quality for Anna apple in the Egyptian delta.

Keywords: Regulated deficit irrigation, fruit quality, water savings, apple orchards, water use efficiency, drip irrigation, *Malus domestica*, total soluble solids, arid horticulture, Nile Delta

Introduction

Egypt receives less than 80 mm of rainfall annually and depends almost entirely on the Nile for agricultural water, yet per capita availability has fallen below 570 m³, well under the water-poverty threshold of 1,000 m³ [1]. Agriculture consumes roughly 85% of withdrawals, and fruit orchards are among the most water-demanding enterprises [2].

Regulated deficit irrigation reduces water supply below full crop requirements during less sensitive growth stages while maintaining supply during critical periods [3]. The concept was first applied to peach by Chalmers *et al.* [4] and has since been tested on several fruits. Mild water stress during cell expansion can improve sugar concentration without proportionally affecting yield [5].

Apple is a relatively new crop in the Egyptian Delta, introduced through low-chill cultivars like Anna [6]. Growers apply 600-800 mm per season with drip systems but few have adopted water-saving strategies because local RDI data are scarce [7]. Existing literature comes mainly from temperate regions where conditions differ markedly [8]. This research evaluated four irrigation levels (100%, 80%, 60%, 40% ET_c) on Anna apple for effects on physical quality, chemical quality, yield, and WUE at the university experimental orchard (31.04 deg N, 31.38 deg E) over two seasons [9].

Material and Methods

Material

Seven-year-old Anna apple trees on MM.106 rootstock, planted at 4 m x 3 m (833 trees/ha) in sandy loam soil (pH 7.8, EC 1.2 dS/m) at the Nile Delta Agricultural University orchard, Mansoura. Trees were trained as central leaders with standard commercial management. Treatments were imposed from 1 March (fruit set) to 30 June (harvest) in 2022 and 2023. Reference ET₀ was estimated daily using Penman-Monteith; ET_c was calculated using FAO crop coefficients [10]. The 100% treatment received 684 mm seasonally (6,840 m³/ha). Irrigation was applied every two days through 4 L/h drippers, three per tree.

Methods

Four treatments (100%, 80%, 60%, 40% ET_c) were arranged in a RCBD with four replications of four trees each (64 trees total). At harvest, 20 fruits per replicate were

sampled. Fruit weight, diameter, firmness (Chatillon DFE-050 penetrometer, 11.1-mm tip), TSS (digital refractometer), titratable acidity (NaOH titration to pH 8.1), and red colour coverage (visual 0-100% scale by two

assessors) were recorded. Yield per tree was converted to t/ha. WUE = yield / water applied ^[11]. Data from both seasons were pooled; ANOVA in SAS 9.4 with Duncan's test at $p < 0.05$ ^[12].

Results

Table 1: Fruit quality and yield of Anna apple under four irrigation regimes (two-season mean)

Treatment	Wt. (g)	Diameter (mm)	Firmness (N)	TSS (°Brix)	Yield (t/ha)	WUE (kg/m ³)
100% ETc	178.3	72.6	62.1	12.4	32.4	4.74
80% ETc	171.6	70.8	67.4	13.8	30.8	5.63
60% ETc	158.2	66.3	73.8	15.1	27.1	6.61
40% ETc	132.7	59.4	71.2	14.6	21.3	7.79
CD ($p < 0.05$)	8.4	3.1	4.7	0.9	2.3	0.52

Fruit weight and diameter declined progressively with deficit, but losses were small at 80% ETc (3.8% and 2.5%). Firmness peaked at 60% ETc (73.8 N). Red colour coverage was highest at 60% ETc (63.1%) and lowest under full

irrigation (48.3%). TSS rose from 12.4 to 15.1 deg Brix at 60% ETc but dropped at 40% ETc (14.6), likely because severe stress curtailed photosynthate production. Titratable acidity increased linearly with deficit.

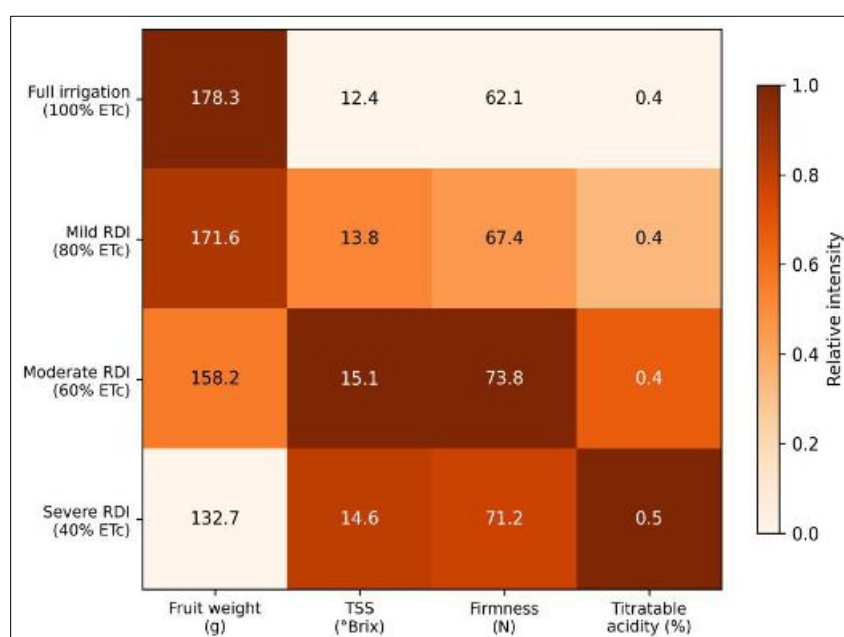


Fig 1: Heatmap of fruit quality parameters across RDI treatments in Anna apple

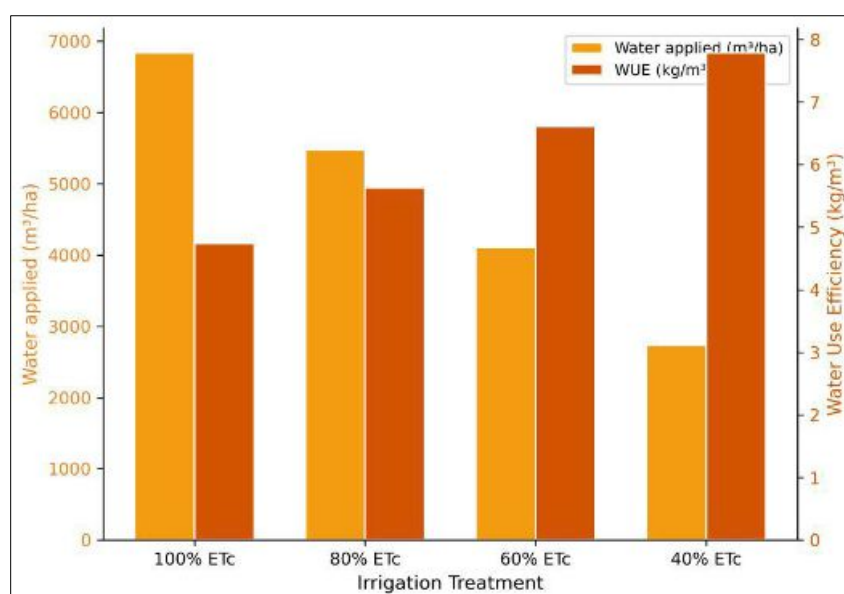


Fig 2: Water applied (m³/ha) and water use efficiency (kg/m³) under four irrigation treatments

The heatmap (Figure 1) reveals a trade-off: moving from full to severe deficit, fruit weight declines while firmness and TSS rise. The 80% ETc row offers the most balanced pattern. The bar chart (Figure 2) shows WUE increased almost linearly, with the steepest practical gain between 100% and 80% ETc where 20% less water produced only 5% less fruit.

Discussion

The 11.3% TSS increase at 80% ETc without meaningful yield loss echoes Mpelasoka *et al.* [14] in Braeburn apple. The mechanism involves a concentration effect as cell water declines, together with enhanced sucrose synthase activity triggered by abscisic acid [5]. Improved red colour is consistent with stress-mediated anthocyanin biosynthesis [15].

The sharp decline at 40% ETc underlines the need to keep the deficit within tolerable limits. At this level, stomatal conductance likely fell below the threshold for carbon fixation, reducing sugar translocation. Similar breakpoints have been reported for olive at 30-40% ETc [3] and grape at 45% ETc [16].

WUE improved by 18.8% between 100% and 80% ETc. In a country facing absolute water scarcity, even modest per-hectare savings matter when aggregated across Egypt's estimated 38,000 hectares of apple orchards [2]. And because mild-RDI fruit had firmer flesh and higher sugar, it's better suited to export cold-chain requirements [13]. A limitation is that RDI was applied uniformly across the entire fruit-development period; staged RDI might further optimise the quality-yield balance [17].

Conclusion

This two-season research showed that RDI at 80% ETc delivered the best balance between water conservation and fruit quality in Anna apple. The mild deficit reduced water use by 20%, improved TSS by 11.3%, raised firmness by 8.5%, and enhanced red colour from 48.3% to 56.7%, while limiting yield loss to 4.9%. At 60% ETc, quality gains were larger but the 16.4% yield reduction may be too steep commercially. Severe deficit at 40% ETc caused unacceptable losses.

For Egyptian orchardists under tight water allocations, RDI at 80% ETc represents a practical, low-cost adjustment that conserves a scarce resource and may improve access to premium export markets. Future work should explore stage-specific RDI protocols and test different rootstock-scion combinations.

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