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Enhancing water productivity in cabbage cultivation under deficit irrigation strategies in semi-arid climates

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Abstract

Deficit irrigation is gaining attention as an effective water management technique that minimizes water usage while causing only slight reductions in crop yield. However, there is limited research on how water scarcity affects leafy vegetables like cabbage, particularly concerning water use efficiency (WUE) under the semi-arid conditions of Marathwada. To address this gap, the present study was undertaken to assess the impact of different deficit irrigation levels (0.5, 0.75, and 1.0 of full irrigation) on cabbage. Field trials were carried out during the Rabi season of 2024-2025 at the Experimental Farm, Department of Horticulture, College of Horticulture, Vasantao Naik Marathwada Krishi Vidyapeeth, Parbhani, using the cabbage variety 'Superball 50'.

This irrigation strategy shows promise for enhancing water use efficiency without significantly affecting crop yield, particularly if water stress is applied during non-critical stages of plant growth. In water-scarce regions like Marathwada, such methods are vital for sustaining agricultural output while conserving water. For instance, applying irrigation at 50% ET_c (Treatment T27) led to reduced plant size, fresh weight, relative water content, canopy spread in later growth phases, and ultimately lowered head size and total yield. In contrast, irrigating at 75% ET_c (Treatment T14) caused minimal impacts on plant growth and physiological traits, with only a slight decrease in yield. Unlike conventional fixed irrigation schedules of 100%, 75%, or 50% of full irrigation, Regulated Deficit Irrigation (RDI) deliberately introduces water stress during specific, less sensitive stages of crop development to optimize water savings without compromising yield quality, thereby maintaining yield stability while significantly improving water use efficiency (WUE). The field water use efficiency is the highest in (T₁₈)(0.1376 t/ha-mm). The maximum B:C ratio was observed in no stress treatment T1(0.7854), minimum in treatment T27 (0.3737).

Keywords: Cabbage, water stress, yield responses, RDI, Cost of production

Introduction

Water scarcity, in both quantity and quality, is becoming a global concern—not only in traditionally arid and semi-arid regions but even in areas with high rainfall. Agriculture, being the largest consumer of water worldwide, is often viewed as inefficient in water usage, with its water demands perceived to hold less economic value compared to other sectors. Additionally, energy assessments of agricultural activities indicate that irrigation accounts for a major portion of energy consumption compared to other farm operations. This highlights the pressing need to enhance the efficiency of water use in agriculture by improving crop water productivity.

Despite this, leafy vegetables are generally considered less tolerant to water deficits compared to fruit trees. Previous research by Sammis and Wu (1989) demonstrated that cabbage yields increased proportionally with higher irrigation, reaching up to 49.3 t/ha. However, Tiwari *et al.* (2003) found no significant differences in cabbage yields when irrigated at 100%, 80%, and 60% of crop evapotranspiration (ET_c) over a three-year period.

The current study aims to evaluate the effects of deficit irrigation on cabbage growth, water use efficiency (WUE), quality traits such as total soluble solids (TSS), water content, and physiological parameters like plant height and yield. The experiment followed a Randomized Block Design (RBD) with 27 treatments, involving various combinations of water stress applied during three critical growth stages: early vegetative, head formation, and head maturation. Each treatment was replicated twice. Except for treatments T1, T14, and T27, the remaining 24 treatments involved different stress combinations as illustrated in Table 1. The term Regulated

Deficit Irrigation (RDI) is more appropriate here, referring to the strategic reduction of water supply during specific, less sensitive stages of the crop's growth cycle (English *et al.*, 1990) ^[2].

RDI intentionally limits irrigation to control crop water usage as a management tool, requiring precise irrigation systems like micro-irrigation, along with careful monitoring of soil moisture and irrigation timing. The ideal irrigation depth is one that maximizes profitability, either per unit of water or per land area, depending on resource constraints and strategic objectives, whether focused on food production or economic returns. The concept of opportunity cost of water applies at both farm and regional levels, aiding in optimal water allocation decisions (Lorite *et al.*, 2007; Reza *et al.*, 2001; Shangguan *et al.*, 2002). English *et al.* (1996) ^[3] emphasized the importance of considering both direct irrigation costs and overall production expenses, cautioning that incomplete cost assessments might underestimate the potential benefits of deficit irrigation practices.

Materials and Methods

Study Area

The field experiment to study the effect of deficit irrigation of different quantities in cabbage (*Brassica oleracea* L.) cv.

Superball50 was conducted during rabiseason of 2024-2025 at the Experimental Farm of Department of Horticulture, College of Horticulture, Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani. Geographically Parbhani district has the expansion of 18.45 and 20.01 North latitudes and of 76.13 and 77.26. East longitudes in the Deccan plateau. District covers an area of about 6511 square km. District has an average elevation of 457.50 meters above mean sea level. Climatically the region falls under the semi-arid and sub-tropical zone. The average maximum and minimum temperature were 33.34 °C and 12.52 °C and average maximum and minimum relative humidity were 77.04% and 25.84% respectively during crop growth period. The average wind speed was 3.31 km/hr. Average sun shine hours during crop growth period was 7.71 hours. The total rainfall during crop growth period was 0mm (no rainfall). Experiment was carried out in Randomized Block Design (RBD) with twenty-seven treatments and two replications based on different combinations of the quantity of water stress days (no stress- 0.00S, 25% stress- 0.25S and 50% stress- 0.50S) during different crop growth stages. Vegetative Stage (VS) - up to 30 days, head stage (HS) - 31 to 75 days and maturity stage (MS) - 76 up to harvest. The 27 treatments were

Table 1: Treatments Combination

T1[VS-0.00s; HS-0.00s; MS-0.00s]
T2[VS-0.00s; HS -0.00s; MS -0.25s]
T3[VS-0.00s; HS -0.00s; MS -0.50s]
T4[VS-0.00s; HS -0.25s; MS -0.00s]
T5[VS-0.00s; HS -0.25s; MS -0.25s]
T6[VS-0.00s; HS -0.25s; MS -0.50s]
T7[VS-0.00s; HS -0.50s; MS -0.00s]
T8[VS-0.00s; HS -0.50s; MS -0.25s]
T9[VS-0.00s; HS -0.50s; MS -0.50s]
T10[VS-0.25s; HS -0.00s; MS -0.00s]
T11[VS-0.25s; HS -0.00s; MS -0.25s]
T12[VS-0.25s; HS -0.00s; MS -0.50s]
T13[VS-0.25s; HS -0.25s; MS -0.00s]
T14[VS-0.25s; HS -0.25s; MS -0.25s]
T15[VS-0.25s; HS -0.25s; MS -0.50s]
T16[VS-0.25s; HS -0.50s; MS -0.00s]
T17[VS-0.25s; HS -0.50s; MS -0.25s]
T18[VS-0.25s; HS -0.50s; MS -0.50s]
T19[VS-0.50s; HS -0.00s; MS -0.00s]
T20[VS-0.50s; HS -0.00s; MS -0.25s]
T21[VS-0.50s; HS -0.00s; MS -0.50s]
T22[VS-0.50s; HS -0.25s; MS -0.00s]
T23[VS-0.50s; HS -0.25s; MS -0.25s]
T24[VS-0.50s; HS -0.25s; MS -0.50s]
T25[VS-0.50s; HS -0.50s; MS -0.00s]
T26[VS-0.50s; HS -0.50s; MS -0.25s]
T27[VS-0.50s; HS -0.50s; MS -0.50s]

The irrigation rates were 100, 75, and 50% ET_c for T1, T14, T27, and rest treatments shows varying stress combination as shown. The adjustment of the deficit irrigation rate depends on ET_c. The ET_c values were estimated using weather data from a local weather station and the Penman-Monteith method, and the application of stage-specific crop coefficients (Allen *et al.* 1998). Total irrigation was 345,259 and 172mm for 100, 75 and 50% respectively. Total fertilizers applied as fertigation were 140 N-57 P-23 K kg/ha

Field water use efficiency

$$\text{Field water use efficiency} = \frac{Y}{WR}$$

Where,

Y = crop yield, kg/ha

WR = total amount of water applied in the field, mm

Deficit irrigation (DI) often leads to improved water use efficiency (WUE) for several reasons. Firstly, application efficiency (E_{appl}) improves when water is applied below full crop evapotranspiration (ET), as the limited water stays within the root zone, reducing losses from runoff and deep percolation. Consumption efficiency (E_c), which is the ratio of evapotranspired water to the water present in the root zone, can also increase because plants are compelled to extract water more effectively from the soil. Additionally, yield efficiency (E_{yld})—the proportion of biomass allocated to the harvestable part—may rise, as full irrigation often promotes excessive vegetative growth in crops like cotton and grapevines, which can be reduced through DI.

In semi-arid regions, where rainfall is sparse, summers are hot and dry, and evaporative demand is high, RDI (Regulated Deficit Irrigation) has been successfully employed to manage vegetative and reproductive growth in fruit trees, leading to positive agronomic and economic outcomes (Romero *et al.*, 2004) [4]. However, the profitability of DI strategies is heavily influenced by local factors, such as water availability and its cost, making universal economic conclusions difficult (Camp, 1998).

Regarding yield components, cabbage heads were harvested at full maturity on March 20, 2025. Throughout the crop cycle, growth parameters like plant height, leaf count, and canopy spread were recorded periodically. At harvest, measurements of curd diameter, curd volume, and Total Soluble Solids (TSS) were taken, along with the determination of specific gravity of the curd. In terms of production costs, when varying irrigation depths influence both yield and the duration of the crop cycle, the cost functions become nonlinear (Capra *et al.*, 2007 and 2008). Water savings achieved through reduced irrigation depths can be redirected to irrigate additional land, thereby boosting farm income. This added benefit is known as the opportunity cost of water. For example, 50 mm of water could be applied to 1 hectare, or 25 mm to 2 hectares, potentially increasing total profitability.

In water-scarce scenarios, economic returns can be maximized by reducing water depths and expanding the irrigated area, until the product of marginal profit per hectare and the total irrigated area equals the overall farm profit. For each treatment, production costs were calculated, which included expenses for labor, seeds, fertilizers, water charges, interest on capital, system

depreciation, and maintenance of the irrigation infrastructure.

Gross monetary returns per hectare were computed by considering the yield from each treatment and the market price of cabbage. Net income was then determined by subtracting production costs from gross returns. The benefit-cost (B:C) ratio was calculated by dividing gross returns by production costs for every treatment.

Research in DI has increasingly emphasized integrating agronomic and economic assessments to optimize its application (English, 1990) [2]. While most studies acknowledge a certain level of yield reduction under DI, they highlight its potential economic gains. For instance, English and Raja (1996) [3] analyzed DI's economic viability across crops like wheat in the USA, cotton in California, and maize in Zimbabwe. Their findings suggested that irrigation deficits ranging from 15% to 59% could be economically beneficial depending on context.

For data analysis, the experiment was designed using a Randomized Block Design (RBD) with 27 treatments and 2 replications. An Analysis of Variance (ANOVA) was performed using the 'F' test, considering a significance level of 5% ($p=0.05$).

Results and Discussion

Estimation of Crop Water Requirement of Cabbage

$$ET_c = K_c \times ET_o \text{ (mm/day),}$$

It is observed from the K_c values estimated using field method varies from 0.70 to 1.11.

It is observed from Table 2, that the total depth of water applied was maximum in treatment T1 (no stress treatment) and minimum in treatment T27 (maximum stress treatment). The total depth of water applied for treatment T1 which is 0% water stress throughout the crop growth period was 345mm and the total depth of water applied for treatment T14 which is 25% water stress throughout the crop growth period was 259 mm and for treatment T27 which was 50% water stress throughout the crop growth period shown the total depth of water applied were 172 mm. Plant size was temporarily reduced by 50% E_{Tc} irrigation as compared to 100% E_{Tc} irrigation. Deficit irrigation at 75% E_{Tc} had no significant effect on plant size as compared to 100% E_{Tc} irrigation. Reduced plant width 60 DAP might result from leaf senescence and wilt under temporary heat stress

Table 2: Total depth of irrigation water applied at plot (mm)

Sr. No	Number of irrigation	Total amount of water applied at plot (mm)	Reduction in water needed compared to no stress treatment (%)
T1	10	345.87	0
T2	10	335.46	3.01
T3	10	325.06	6.02
T4	10	294.5	14.85
T5	10	284.09	17.86
T6	10	273.68	20.87
T7	10	221.1	36.07
T8	10	210.69	39.08
T9	10	200.29	42.09
T10	10	321.18	7.14
T11	10	310.77	10.15
T12	10	300.37	13.16
T13	10	269.81	21.99
T14	10	259.4	25
T15	10	248.99	28.01

T16	10	196.41	43.21
T17	10	186	46.22
T18	10	175.6	49.23
T19	10	296.49	14.28
T20	10	286.08	17.29
T21	10	275.68	20.29
T22	10	245.12	29.13
T23	10	234.71	32.14
T24	10	224.31	35.15
T25	10	193.75	43.98
T26	10	183.34	46.99
T27	10	172.93	50

Field water use efficiency (FWUE)

It is observed from Table that, the maximum field water use efficiency is obtained in treatment T18 (0.1376 t/ha-mm) and minimum in treatment T14 (0.0851 t/ha-mm). It is observed that amongst different water stress treatments, the treatment T2 (0.1019 t/ha-mm) and T3 (0.0999 t/ha) with less water requirement i.e. applying 25% and 50% less water at maturity stages gave relative more water use efficiency, compared to other treatments. Over all FWUE was statically non-significant for different treatments; indicating under water scarce situation, the water stress to cabbage can be regulated but reducing yield. The water use efficiency (WUE) therefore varied significantly

($P \geq 0.05$) among different treatment and the increase and decrease in WUE under different treatments showed positive relationship with increase in cabbage weight. This indicates that the higher the yield obtained as a result of higher volume of water applied the lower the water use efficiency and vice versa. The low FWUE obtained could be attributed to high soil evaporation in relation to crop evapotranspiration. Therefore to increase the water use efficiency and still obtain the optimum yield, the crop should be irrigated in the evening since soil evaporation is minimal in the evening. Mulching of the soil could also be incorporated as cultural practice to minimize soil moisture evaporation

Table 3: Field water use efficiency (t/ha-mm)

Treatments	Total yield (t/ha)	Total depth of water applied(mm)	FWUE (t/ha-mm)
T1	38.96	345.87	0.1126
T2	34.18	335.46	0.1019
T3	32.49	325.06	0.0999
T4	37.71	294.5	0.128
T5	30.36	284.09	0.1069
T6	25.2	273.68	0.0921
T7	26.26	221.1	0.1188
T8	24.92	210.69	0.1183
T9	21.59	200.29	0.1078
T10	27.96	321.18	0.087
T11	30.47	310.77	0.0981
T12	27	300.37	0.0899
T13	25.85	269.81	0.0958
T14	22.07	259.4	0.0851
T15	22.93	248.99	0.0921
T16	24.85	196.41	0.1265
T17	24.43	186	0.1314
T18	24.16	175.6	0.1376
T19	26	296.49	0.0877
T20	29.45	286.08	0.1029
T21	26.8	275.68	0.0972
T22	24.36	245.12	0.0994
T23	22.39	234.71	0.0954
T24	19.18	224.31	0.0855
T25	19.95	193.75	0.103
T26	18.43	183.34	0.1005
T27	16.64	172.93	0.0962
S.E			16.0459
C.D at 5%			5.51981

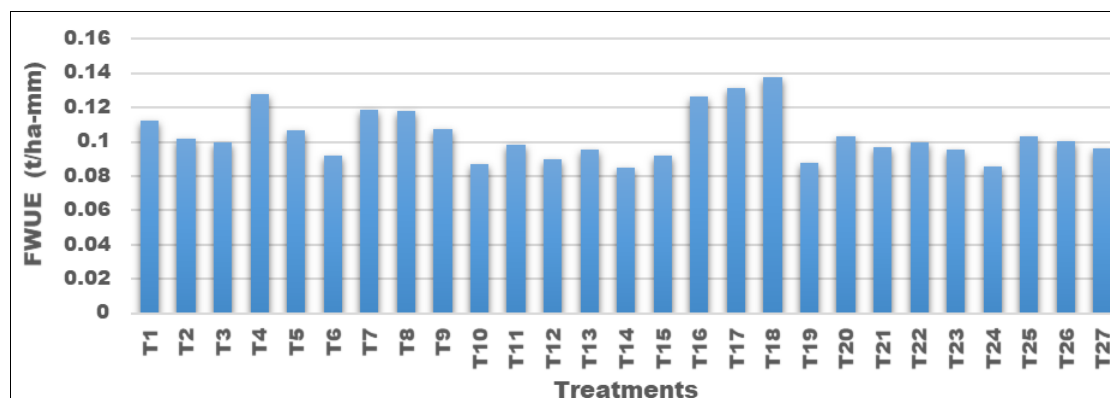


Fig 1: Field water use efficiency (t/ha-mm)

Effects of cabbage influenced by different deficit irrigation

The growth parameters viz. plant height, number of leaves, plant spread, specific gravity, moisture content and total soluble solid (TSS) were measured during the study to find the effect of deficit irrigation on plant growth parameters. The plant height, plant leaves, plant spread, specific gravity, moisture content were found maximum in treatment T1 (25.5cm, 22, 64cm, 0.8(gm/cm³), 92.69% respectively). Total Soluble Solid (TSS) was found maximum in T27 (6.34). The growth parameters viz.

plant height, number of leaves, plant spread, specific gravity, moisture content and total soluble solid (TSS) linearly increased with advancement of crop age and reached rich maximum after 60 DAT (at harvest) during crop growth period of cabbage in all treatments. The results indicated that water stress has significant effect on growth dynamics of plant. Mean Weight of Cabbage Heads In Kilograms. mean head weight was maximum for treatment T1 (1.331 kg) and minimum in treatment T27 (0.748 kg)

Table 4: Post harvest quality of cabbage influenced by different deficit irrigation

Treatment	Plant height, (cm)	Total yield	Mean Head weight, (kg)	Specific gravity(gm/cm ³)	Total soluble solid (%)	Moisture content (%)
T1	25.50	38.962	1.33	0.80	4.72	92.69
T2	23.50	34.177	1.30	0.79	4.85	92.24
T3	23.00	32.487	1.31	0.79	5.43	91.93
T4	21.50	37.707	1.33	0.80	4.77	92.89
T5	22.80	30.362	1.29	0.78	5.58	92.27
T6	23.50	25.197	1.29	0.79	5.53	92.65
T7	23.00	26.257	1.29	0.78	5.32	91.60
T8	23.30	24.917	1.24	0.79	5.40	91.98
T9	23.00	21.592	1.22	0.78	5.87	91.41
T10	23.50	27.957	1.27	0.79	6.03	91.40
T11	23.30	30.472	1.22	0.79	5.67	91.36
T12	23.80	27.002	1.21	0.78	5.55	91.66
T13	23.00	25.847	1.22	0.78	5.79	91.86
T14	23.50	22.067	1.18	0.79	6.18	91.91
T15	21.80	22.927	1.18	0.78	5.64	91.74
T16	22.00	24.847	1.17	0.78	5.96	91.04
T17	23.00	24.432	1.16	0.78	6.30	91.16
T18	23.00	24.162	1.15	0.77	6.06	91.35
T19	21.30	26.002	1.18	0.79	5.74	91.71
T20	18.50	29.452	1.17	0.79	5.75	92.28
T21	19.50	26.802	1.11	0.77	6.11	90.62
T22	21.50	24.357	1.05	0.78	5.58	91.75
T23	19.80	22.387	0.99	0.77	6.11	90.49
T24	21.00	19.182	0.93	0.77	5.44	90.74
T25	22.00	19.952	0.87	0.78	6.28	91.03
T26	21.40	18.427	0.81	0.77	6.07	89.78
T27	21.20	16.637	0.75	0.77	6.35	89.81

Cost of production

Data regarding cost of production are reported in Table 5. It is observed that maximum cost of production was in treatment T1 and minimum cost in treatment T27. It indicates that water stress has influence on cost of production due to less requirement of water. The cost of production was decreased as water stress increased. maximum gross monetary returns was obtained from no stress treatment T1(8,616 Rs/ha), from

treatment T4(8,254 Rs/ha) and minimum from maximum stress treatment T27 (4,032 Rs/ha). maximum net income was gained from treatment T1 (6,737 Rs/ha) and minimum net income was gained from treatment T27 (2,157 Rs/ha, from table and figure that the maximum B:C ratio was observed in no stress treatment T1(0.7854), minimum in treatment T27 (0.3737). The B:C ratio was 0.7548 in treatment T4, where it most similar to T1 value.

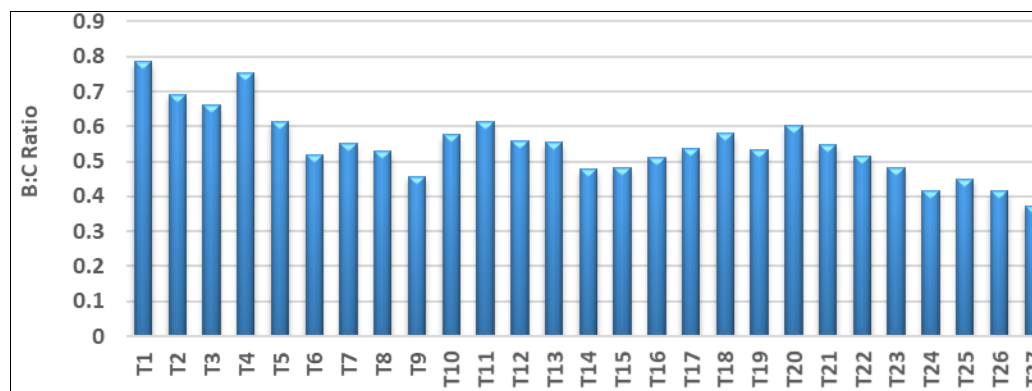


Fig 2: B:C ratio in different deficit irrigation treatments for cabbage crop

Table 5: B:C ratio in different deficit irrigation treatments for cabbage crop

Treatments	Cost of production (Rs)	Gross monetary return (Rs)	Net income (Rs)	B:C Ratio
T1	10,970	8,616	6,737	0.7854
T2	10,937	7,576	5,698	0.6927
T3	10,907	7,200	5,323	0.6601
T4	10,936	8,254	6,376	0.7548
T5	10,913	6,698	4,820	0.6138
T6	10,906	5,666	3,789	0.5195
T7	10,907	6,014	4,137	0.5514
T8	10,903	5,762	3,885	0.5285
T9	10,871	4,964	3,087	0.4566
T10	10,919	6,294	6,737	0.5764
T11	10,888	6,684	5,698	0.6139
T12	10,874	6,072	5,323	0.5584
T13	10,884	6,030	6,376	0.554
T14	10,897	5,208	3,331	0.4779
T15	10,866	5,222	3,345	0.4806
T16	10,867	5,572	3,695	0.5127
T17	10,839	5,830	3,954	0.5379
T18	10,839	6,294	4,416	0.5807
T19	10,877	5,802	3,925	0.5334
T20	10,876	6,548	4,671	0.6021
T21	10,831	5,944	4,068	0.5488
T22	10,859	5,604	3,728	0.5161
T23	10,829	5,228	3,352	0.4828
T24	10,809	4,484	2,609	0.4148
T25	10,836	4,878	3,002	0.4502
T26	10,804	4,480	2,605	0.4147
T27	10,788	4,032	2,157	0.3737

Conclusion

The present study, conducted under a Randomized Block Design with 27 treatments, highlights the effectiveness of Regulated Deficit Irrigation (RDI) as a sustainable water management strategy in cabbage cultivation. By imposing water stress during specific critical growth and non-critical growth stages excluding treatments T1, T14, and T27 which served as full-irrigation, and control benchmarks the trial demonstrated that RDI can significantly enhance water use efficiency (WUE) without causing severe yield penalties. Notably, severe deficit during all stages (T27, 50% ETc) led to visible reductions in plant growth, head development, and yield attributes. Experimental results clearly indicate that RDI offers a more resource-efficient and sustainable alternative, especially in water-scarce regions. By targeting non-critical phenological phases for water reduction, RDI minimizes yield penalties that are otherwise evident in uniform deficit irrigation treatments (50% or 75% throughout the season). Further more, it avoids the excessive and often

wasteful application of water seen in full irrigation (100%). Different water depths modify both yield and crop cycle length, the cost function may be nonlinear. When saved water, obtained by reducing water depths, can be used to irrigate additional land, farmers can increase their income. To maintain yield stability and conserve water in water-scarce regions like Marathwada, making RDI a promising approach for climate-resilient vegetable production.

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