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Analysing water productivity response to sowing window, irrigation levels and mulching using CERES-wheat model

PARMINDER SINGH BUTTAR[1], P. K. KINGRA[1]*, R. K. PAL[2], SOM PAL SINGH[1] and SAMANPREET KAUR[3]

[1]*Dept of Climate Change and Agricultural Meteorology, PAU, Ludhiana, India*
[2]*PAU-RRS, Bathinda,* [3]*Dept of Soil and Water Engineering, PAU, Ludhiana, India*
*****Corresponding author: *pkkingra@pau.edu*

ABSTRACT

Field experiments were carried out during *rabi* seasons of 2015-16 and 2016-17 at the Research Farm, Punjab Agricultural University, Ludhiana. Wheat variety PBW 621 was sown on three dates (D_1: 4th week of October, D_2: 2nd week of November and D_3: 4th week of November) with two irrigation levels (I_1: IW/CPE = 0.9, I_2: At CRI, 5-6 weeks after 1st irrigation, 3-4/5-6 weeks after 2nd irrigation, 2/4 weeks after 3rd irrigation as per dates of sowing) and mulch application (M_1: without mulch, M_2: straw mulch @ 5 t ha^{-1}). Earlier sown mulch applied crop with four post-sowing irrigations produced highest (5312.5 kg ha^{-1}) and late sown without mulch application crop with irrigation @IW/CPE = 0.9 produced lowest grain yield (3900.5 kg ha^{-1}). Simulation results depicted -1.1 to 16.8 per cent deviation in crop yield, -1.4 to -21.0 per cent in water use and 12.7 to 45.5 per cent in water productivity. Increase in temperature from 1°C to 3°C decreased wheat yield by 6.3 to 27.0 per cent under D_1 and 3.3 to 17.6 per cent under D_2, however, it increased from 8.1 to 16.2 per cent under D_3, indicating D_3 as most appropriate under future warming scenarios. Increase in CO_2 concentration decreased water use and increased yield and water productivity.

Key words: Water productivity, CERES-wheat, temperature, $CO_{2,}$ irrigation levels, mulch

Wheat is an important cereal crop of India, ranking second after rice in area and production. India is second largest producer of wheat after China with about 12 per cent share in global food production. Area under wheat in Punjab was 35.12 lakh hectares with a production of 178.30 lac tonnes and productivity of 5.08 tha^{-1} during 2017-18 (Anon., 2019). However, large year-to-year fluctuations are observed in its productivity due to significant inter- and intra-seasonal climatic variations in the region (Kingra, 2016, Kingra *et al.*, 2017). The globally averaged combined land and ocean surface temperature data showed that the period from 1880 to 2012 was warmer by 0.85°C (0.65 to 1.06°C) over the previous years (IPCC, 2014). The crop growth processes may be abruptly affected by increase in the frequency of extreme temperature along with the increase in the mean temperature **(**Wu *et al.*, 2006).

The yield and evapotranspiration are affected by the combined effects of higher temperature, elevated CO_2 concentration and change in precipitation (Walker and Schulze, 2008). There is a positive effect of increase in atmospheric CO_2 on photosynthetic rates, which leads to increment in total biomass and yield of C_3 crops (de Costa *et al.*, 2006). There is a significant impact of all these changes on crop yield and water productivity especially in the tropical and sub-tropical regions, which can be managed by microclimatic modifications such as alteration in sowing time, mulch application and irrigation scheduling etc. Crop simulation models can help to find adequate adaptation strategies to avoid or reduce negative climate change effects on crop yield and exploit possible beneficial options (Iqbal *et al.*, 2011).The DSSAT model has been widely used for many different applications (Hoogenboom *et al.*, 2010) and hence used in the present study.

Water shortage is becoming severe in the western Indo-Gangetic Plains (IGP) because of the increasing competition faced by agriculture from the urban and also industrial sectors. As a result, water table is declining at an alarming rate due to which the pumping costs of farmers have increased. (Humphreys *et al.*, 2010). Punjab is facing dual challenge of weather variability and over-exploitation of its ground water resources with significant impact on crop productivity. Keeping this in view, the present study was conducted to simulate crop water requirement, grain yield and water productivity of wheat to variable temperature and CO_2 levels under different dates of sowing, irrigation levels and mulch application.

MATERIALS AND METHODS

The present investigation was carried out at the Research Farm of Punjab Agricultural University, Ludhiana situated at latitude of 30°54›N, longitude of 75°54›E and altitude of 247m above the sea level. Wheat variety PBW 621 was sown on three dates (D_1: 4th week of October, D_2: 2nd week of November and D_3: 4th week of November) with two irrigation levels (I_1: IW/CPE = 0.9, I_2: Irrigation at CRI stage, 5-6 weeks after 1st irrigation, 3-4/5-6 weeks after 2nd irrigation, 2/4 weeks after 3rd irrigation as per date of sowing) and mulch application (M_1: without mulch, M_2: straw mulch @ 5 t ha^{-1}). The experiment was laid out in a split plot design with dates of sowing in the main plots and irrigation and mulch application in combination as sub-plots. The soil of the experimental site was sandy loam. The soil properties used in the CERES-wheat model have been depicted in Table 1.

Crop yield under different treatments was recorded at the time of harvesting. Crop water use was recorded by periodic water depletion method and water productivity was computed from evapotranspiration and crop yield as mentioned below:

$$WP = Y/ET$$

Where,

WP= Water productivity (kg ha^{-1} mm of water); Y = marketable yield (kg ha^{-1}) ; ET = Evapotranspiration (mm)

Crop yield, crop water requirements and water productivity were simulated using CERES-wheat model. The genetic coefficients used for wheat variety PBW-621 have been given in Table 2. Observed and simulated yield, water use and water productivity were then analysed statistically by computing standard deviation, correlation and root mean squared error. Sensitivity analysis was carried out to evaluate water productivity of wheat under variable temperatures (+1^{o}C, +2^{o}C and +3^{o}C) and CO_2 levels (+200 ppm, +400 ppm and +600 ppm) for different treatments.

RESULTS AND DISCUSSION

Wheat yield

The results revealed that early sown mulch applied crop with four post-sowing irrigations ($D_1I_2M_2$) produced highest grain yield (5313 kg ha^{-1}) followed by (5096 kg ha^{-1}) mid November sown mulch applied crop ($D_2I_2M_2$), whereas the lowest yield (3901 kg ha^{-1}) was observed in the late sown without mulch application crop with irrigation @IW/CPE = 0.9 ($D_3I_1M_1$) (Table 3). The simulation analysis also depicted highest yield (5257 kg ha^{-1}) under earlier sown mulch applied crop with four recommended post-sowing irrigations ($D_1I_2M_2$) followed by (5186 kg ha^{-1}) under mid November sown mulch applied crop ($D_2I_2M_2$). Although less crop yield was observed under late sown conditions, but simulation analysis depicted the scope of improvement in wheat yield (5091 kg ha^{-1}) with irrigation management and mulch application ($D_3I_2M_2$). Simulation results depicted deviation in crop yield in the range of -1.1 to 16.8 per cent in different treatments.

Crop water use

Among different treatments, crop water depletion was observed to be highest (408 mm) under earlier sown without mulch applied crop with four recommended post-sowing irrigations ($D_1I_2M_1$) (Table 3) as compared with rest of the treatments. In general, water depletion decreased with delay in sowing, which might be due to reduction in crop duration under late sown conditions. However, irrigation management and mulch application seemed to be quite effective in checking water depletion under all the dates of sowing. Simulation analysis also depicted highest crop water use (362 mm) under earlier sown without mulch crop with four recommended post-sowing irrigations ($D_1I_2M_1$) and lowest (290 mm) under late November sown mulch applied crop with four post-sowing irrigations ($D_3I_2M_2$). Simulation analysis under-estimated crop water use in all the treatments, the deviation ranging from -1.4 to -21.0 per cent.

Water productivity

Late October and mid November sown mulch

Table 1: Soil properties used for CERES-wheat model

@ SCOM	SALB	SLU1	SLDR	SLRO	SLNF	SLPF	SMHB	SMPX	SMKE	
-99	0.13	6	0.4	73	1	1	IB001	IB001	IB001	
@ SLB	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLHW
15	0.13	0.236	0.343	1	1	1.74	0.41	29	10	6.9
30	0.115	0.251	0.321	0.638	1	1.8	0.33	29	6	7.1
45	0.109	0.231	0.347	0.472	1	1.73	0.22	30	4	6.6
60	0.101	0.226	0.385	0.35	1	1.63	0.21	28	7	6.9
75	0.111	0.203	0.366	0.259	1	1.68	0.2	28	6	7
90	0.102	0.201	0.389	0.192	1	1.62	0.14	27	7	7
105	0.099	0.222	0.354	0.142	1	1.71	0.19	28	6	7.1
120	0.104	0.196	0.343	0.105	1	1.74	0.17	26	6	7.1

SCOM: Colour, moist, munsell hue	SLB: Depth, base of layer, cm
SALB: Albedo, fraction	SLLL: Lower limit cm^3 cm^{-3}
SLU1: Evaporation limit, mm	SDUL: Upper limit, drained, cm^3 cm^{-3}
SLDR: Drainage rate, fraction day^{-1}	SSAT: Upper limit, saturated, cm^3 cm^{-3}
SLRO: Runoff curve no. (Soil conservation service)	SRGF: Root growth factor, soil only, 0.0 to 1.0
SLNF: Mineralisation factor, 0 to 1 scale	SSKS: Saturated hydraulic conductivity, macropore, cm h^{-1}
SLPF: Photosynthesis factor, 0 to 1 scale	SBDM: Bulk density, g cm^{-3}
SMHB: pH in buffer determination method, code	SLOC: Organic carbon, %
SMPX: Phosphorus determination code	SLCL: Clay (<0.002mm), %
SMKE: Potassium determination method, code	SLSI: Silt (0.05 to 0.002mm), %
-99: Not available	SLHW: pH in water

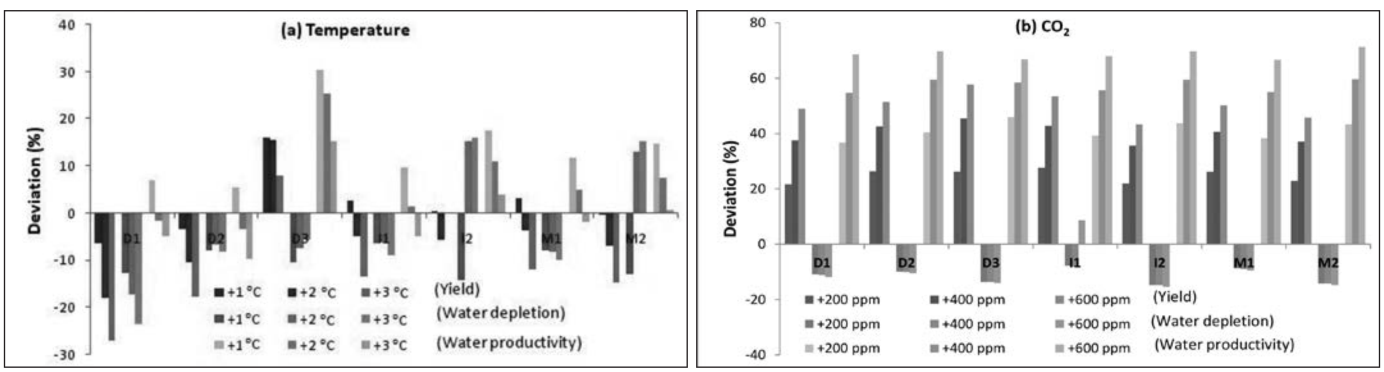

Fig. 1: Effect of increase in air temperature and CO_2 concentration on yield, water depletion and water productivity of wheat under different dates of sowing, irrigation levels and mulch application

applied crop with four post-sowing irrigations ($D_2I_2M_2$ and $D_1I_2M_2$) reported highest water productivity (13.5 and 13.4 kg ha^{-1} mm^{-1}, respectively) followed by earlier sown mulch applied crop (13.0 kg ha^{-1} mm^{-1}) with irrigation application @IW/CPE = 0.9 ($D_1I_1M_2$). Among all the dates of sowing and irrigation levels, mulch application improved crop water productivity. Simulation analysis also depicted highest water productivity (17.6 and 16.7 kg ha^{-1} mm^{-1}) under late and mid November sown mulch applied crop with four post-sowing irrigations ($D_3I_2M_2$ and $D_2I_2M_2$, respectively). Over-estimation of simulated water productivity was observed, the deviation being in the range of 12.8 – 45.0 per cent under different treatments. However, the deviation ranged from 14.5 – 16.2 per cent for late October sown crop, 12.7 – 23.7 per cent for mid November and 25.5 – 45.5 per cent for end November sown crop, depicting ample scope of improvements in wheat productivity with microclimatic modifications especially under late sown conditions (Table 3).

Relation between observed and simulated parameters

A good correlation was found in observed and simulated yield. Average wheat yield of 4552.4$\pm$390.3 and 4718.3$\pm$445.8 kg ha^{-1} was observed during 2015-16 and 2016-17 seasons, respectively, whereas simulated yield for the corresponding years was 4721.9$\pm$237.8 and 5185.0$\pm$246.7 kg ha^{-1}, respectively with correlation coefficient of 0.84 and 0.81 and RMSE of 277.9 and 540.0

Table 2: Genetic coefficients of wheat

Genetic coefficient	Definition	Value
P1V	Days,optimum vernalizing temperature,required for vernalization	20
P1D	Photoperiod response (% reduction in rate/10 h drop in pp)	65
P5	Grain filling (excluding lag) phase duration (^oC.d)	780
G1	Kernel number per unit canopy weight at anthesis (#/g)	20
G2	Standard kernel size under optimum conditions (mg)	42
G3	Standard,non-stressed mature tiller wt (incl grain) (g dwt)	2.4
PHINT	Interval between successive leaf tip appearances (^oC.d)	90

Table 3: Actual and predicted yield, evapotranspiration and water productivity of wheat under different dates of sowing, irrigation levels and mulch application

Treatments	Yield			Evapotranspiration			Water productivity		
	Actual (kg ha^{-1})	Simulated (kg ha^{-1})	Deviation (%)	Actual (mm)	Simulated (mm)	Deviation (%)	Actual (kg ha^{-1} mm^{-1})	Simulated (kg ha^{-1} mm^{-1})	Deviation (%)
$D_1I_1M_1$	4669	4923	5.4	379	348	-8.2	12.4	14.2	14.5
$D_1I_1M_2$	4782	4999	4.5	367	332	-9.5	13.0	15.1	16.2
$D_1I_2M_1$	5040	5186	2.9	408	362	-11.3	12.4	14.3	15.3
$D_1I_2M_2$	5313	5257	-1.1	398	340	-14.6	13.4	15.5	15.7
$D_2I_1M_1$	4354	4837	11.1	370	365	-1.4	11.8	13.3	12.7
$D_2I_1M_2$	4549	4895	7.6	359	324	-9.7	12.7	15.2	19.7
$D_2I_2M_1$	4917	5143	4.6	388	340	-12.4	12.7	15.1	18.9
$D_2I_2M_2$	5096	5186	1.8	379	311	-17.9	13.5	16.7	23.7
$D_3I_1M_1$	3901	4556	16.8	354	331	-6.5	11.0	13.8	25.5
$D_3I_1M_2$	4276	4668	9.2	344	289	-16.0	12.5	16.1	28.8
$D_3I_2M_1$	4292	4703	9.6	367	315	-14.2	11.7	15.0	28.2
$D_3I_2M_2$	4439	5091	14.7	367	290	-21.0	12.1	17.6	45.5

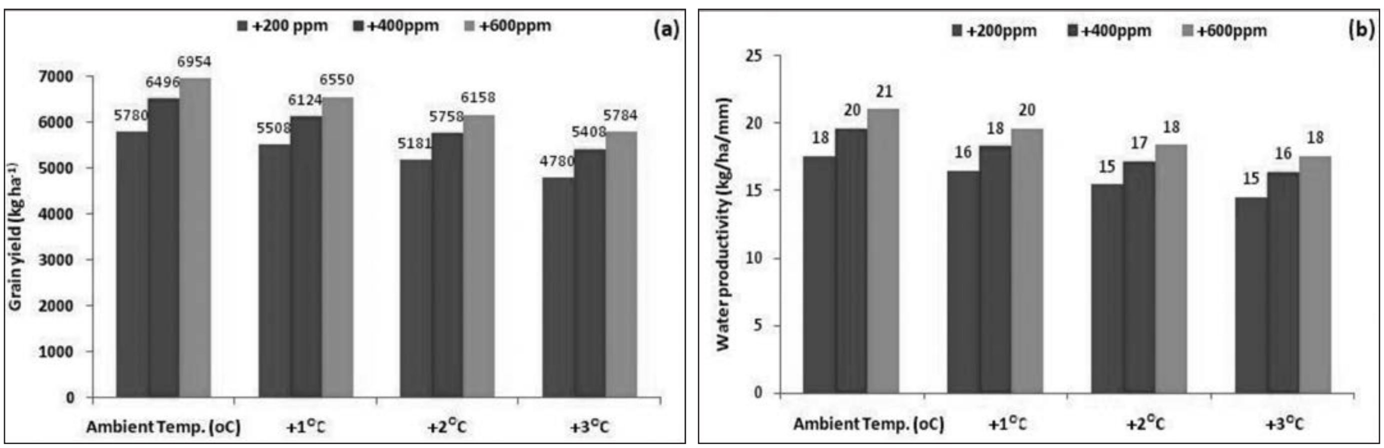

Fig. 2: Interaction effect of temperature and CO_2 on (a) yield and (b) water productivity of wheat

kg ha^{-1}, respectively (Table 4). However, pooled analysis depicted average observed and simulated productivity of 4635.4$\pm$418.5 and 4953$\pm$334.8 kg ha^{-1} with correlation coefficient of 0.71 and RMSE of 429.4 kg ha^{-1}. Similarly, average observed and simulated crop water use was found to be 367.5$\pm$21.2 and 327.0$\pm$22.1 mm, respectively during 2015-16 and 379.2$\pm$16.3 and 330.7$\pm$29.0 mm during 2016-17 with correlation coefficient of 0.59 and 0.47 and RMSE of 44.6 and 54.4 mm during both the years. However, pooled analysis indicated observed ET of 373.3$\pm$19.4 mm and simulated ET of 328.9$\pm$25.3 m with correlation coefficient of 0.51 and RMSE of 49.7 mm. Average water productivity of wheat was observed to be 12.4 kg ha^{-1} mm^{-1}during both the years as well as in polled analysis, whereas simulated water productivity was 14.5$\pm$1.1 kg ha^{-1} mm^{-1} during 2015-16, 15.8$\pm$1.5 kg ha^{-1} mm^{-1} during 2016-17 and 15.1$\pm$1.4 kg ha^{-1} mm^{-1} in the pooled analysis with correlation coefficients of 0.52,

Table 4: Statistical analysis of observed and predicted yield, evapotranspiration and water productivity of wheat

Period / Parameter	Actual	Simulated	Correlation coefficient	RMSE
Yield (kg ha^{-1})				
2015-16	4552.4$\pm$390.3	4721.9$\pm$237.8	0.84**	277.9
2016-17	4718.3$\pm$445.8	5185.0$\pm$246.7	0.81**	540.0
Pooled	4635.4$\pm$418.5	4953.5$\pm$334.8	0.71**	429.4
Evapotranspiration (mm)				
2015-16	367.5$\pm$21.1	327.0$\pm$22.1	0.59*	44.6
2016-17	379.2$\pm$16.3	330.7$\pm$29.0	0.47	54.4
Pooled	373.3$\pm$19.4	328.9$\pm$25.3	0.51	49.7
Water productivity (kg ha^{-1} mm^{-1})				
2015-16	12.4$\pm$0.6	14.5$\pm$1.1	0.52	2.3
2016-17	12.4$\pm$0.9	15.8$\pm$1.5	0.34	3.6
Pooled	12.4$\pm$0.8	15.1$\pm$1.4	0.37	3.0

Significant at 5 (*) and 1 (**) percent Probability level

0.34 and 0.37 and RMSE of 2.3, 3.6 and 3.0 kg ha^{-1} mm^{-1} during the corresponding periods.

Effect of increased temperature

Increase in temperature from 1^{o}C to 3^{o}C decreased wheat yield by -6.3 to -27.0 per cent under D_1 and -3.3 to -17.6 per cent under D_2, however, increase in yield from 8.1 to 16.2 per cent was observed under D_3, which indicates that sowing of wheat during 4th week of November is most appropriate sowing window under future warming scenarios (Fig. 1a). Similarly, increase in temperature resulted in reduced grain yield under irrigation and mulch treatments. Simulation results also depicted decrease in water uptake by the crop with increase in temperature under all the dates of sowing, which might be due to enhanced maturity under warming scenarios. I_2 irrigation regime and mulch application resulted in reduced water depletion, thus improving crop water productivity. The simulation analysis also revealed that under I_1 and M_1 treatments crop water productivity decreased beyond 2^{o}C increase in temperature, however, with irrigation management (I_2) and mulch application (M_2), the crop water productivity could be managed even upto 3^{o}C increase in temperature.

A critical appraisal of simulation analyses clearly depicted the effect of sowing time, irrigation and mulching in sustaining wheat productivity under warming scenarios. The analysis indicated that with increase in temperature by 3^{o}C, the wheat yield could be improved from 3614 kg ha^{-1} to 4568 kg ha^{-1} by shifting sowing time from 4th week of October to 4th week of November as crop water requirement decreases and water productivity increases. As in the 4th November sown crop, water depletion decreased by 5-10 per cent and water productivity improved by 15-30 per cent with increase in temperature by 1 to 3^{o}C (Fig.1a).

Effect of increased CO_2 concentration

Increase in CO_2 concentration from 200 to 600 ppm increased grain yield under all the treatments, in the range of 21.7 to 49.0%, 26.4 to 51.5 per cent and 26.3 to 57.7 per cent under D_1, D_2 and D_3, respectively. Among the irrigation levels, increase in yield was 27.7 to 53.4 per cent and 22.0 to 43.4 per cent under I_1 and I_2, respectively and under mulch treatment, it was improved to the tune of 26.2 to 50.3 per cent without mulch application and 22.9 to 45.8 per cent under mulch (Fig. 1b). Simulation results also depicted decrease in water depletion and increase in water productivity with increase in CO_2 concentration in all the treatments. Among the dates of sowing, the crop sown in fourth week of November depicted highest decrease in water depletion ranging from 13.7 to 14.0 per cent. Similarly, irrigation management and mulch application significantly reduced water depletion and improved water productivity. I_2 irrigation level decreased water depletion by 14.8 to 15.4 per cent and improved water productivity by 43.7 to 69.8 per cent. Similarly, mulch application reduced water depletion by 14.2 to 14.8 per cent and improved water productivity by 43.4 to 71.3 per cent with increased CO_2 concentration from 200 to 600 ppm. Among all the treatments, mulch application depicted maximum water productivity (22.1 kg ha^{-1} mm^{-1}) with increased CO_2 concentration upto 600 ppm.

Interaction effect of increased temperature and CO_2

Analysis of interactive effect of temperature and CO_2 had revealed that reduction in yield and water productivity due to increase in temperature could be negated by the positive effect of increase in CO_2 concentration. Almost comparable grain yield was observed at ambient temperature with increase in CO_2 by 200 ppm (5780 kg ha^{-1}), with 2^{o}C increase in temperature and CO_2 concentration increment by 400 ppm (5758 kg ha^{-1}) and 3^{o}C increase in temperature with increase in CO_2 by 600 ppm (5784 kg ha^{-1}) (Fig. 2a&b). Similar effect was observed for water productivity at ambient temperature with 200 ppm increase in CO_2 concentration, 1^{o}C increase in temperature with CO_2 increment by 400 ppm and 2-3^{o}C increase in temperature with CO_2 concentration increment of 600 ppm (18 kg ha^{-1} mm^{-1} each). These results indicate that increase in CO_2 concentration by 600 ppm can counter balance the negative effect of global warming scenarios by 2-3^{o}C on wheat grain yield and water productivity.

CONCLUSION

The study concluded that adoption of appropriate sowing time, irrigation management and mulch application have a significant effect on sustaining crop yield and water productivity even under late sown conditions in wheat. Simulation analysis indicated sowing of wheat during fourth week of November to be most appropriate in view of future global warming scenarios. Sensitivity analysis indicated that increase in CO_2 concentration by 600 ppm can counterbalance the negative effect of global warming scenarios by 2-3^{o}C on wheat grain yield and water productivity in the region.

Conflict of Interest Statement : The author(s) declare(s) that there is no conflict of interest.

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