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Response of wheat crop to water-logged conditions under different land configurations and nutrient management

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By 2050, the global population is expected to increase from 7.7 billion to 9.7 billion, and wheat will remain crucial for ensuring food security worldwide. It supplies food for more than 4.5 billion individuals in 94 countries and constitutes 40% of the primary diet for the global population. It also has 20% protein and 21% calories. An important concern for wheat cultivation is waterlogging stress, which may escalate in occurrence and intensity due to climate change. The raised bed planting pattern was created to reduce the negative impact of waterlogging stress on wheat productivity. The study was conducted during the rabi seasons of 2017–2018 and 2018–2019 to assess the impact of various nutrient management practices on the growth, yield, and yield characteristics of wheat using flat and raised bed planting methods at the crop research farm in Punjab. The study found that wheat cultivated using a raised bed system with recommended nitrogen, phosphorus, and potassium showed significantly improved plant height (105.28 cm), number of effective tillers per plant (25.08), spike length (11.67 cm), number of grains per spike (72.50), grain yield (6.97 t/ha), and straw yield (9.39 t/ha) compared to traditional planting techniques. Furthermore, these investigations need to be repeated at various locations with various agro-climatic circumstances.

Keywords Flat bed, Growth, Raised bed, Wheat, Water logging, Yield

Wheat is a significant cereal crop cultivated globally and belongs to the *Poaceae* family. Wheat is a fundamental crop for the majority of the world's population among cereal grains. It also has 8–20% protein and provides 17–21% calories globally. Population expansion has led to a rise in the need for food production, especially for cereals. It is projected that worldwide grain output will increase by 60% by 2050[1,2]. The increase in output will face challenges due to global climate change, which is expected to have considerable impacts on food security and agricultural productivity, particularly causing severe negative consequences for wheat production. Dynamic global climatic changes affect the world's food supply, thereby impacting crop output. Water logging stress is a major abiotic element that restricts agricultural yield. Approximately 12% of the global agricultural area is significantly affected by waterlogging stress, resulting in a substantial decrease in crop yield. With the rise in the occurrence of extreme weather events, it is anticipated that there will be a substantial increase in the likelihood of plants experiencing water logging[3]. Wheat is cultivated on 215.5 million hectares globally and 29.6 million hectares locally, yielding 731.4 million metric tonnes and 112.2 million metric tonnes respectively, with an average productivity of 3390 kg/ha and 3371 kg/ha. In India, the predominant technique for cultivating crops is flat planting, despite its drawbacks. Agricultural systems must implement adaptive cropping management to mitigate the adverse impacts of climate change and anticipate its unavoidable outcomes, a prominent subject in the realm of food security[4]. Raised bed planting, which involves planting rows on top of a raised bed and using furrow irrigation, is an alternative to flatbed planting[5].

The optimal period for planting wheat in Punjab is from the second half of October to the first half of December. Germination and the vegetative stage require low temperatures, while the harvest stage demands high temperatures. Rainfall during the rabi season often causes brief flooding when wheat is sown under a flatbed. After harvesting the rice, wheat is usually planted on flat ground in dense rows due to poor drainage of field water or rains, which can lead to waterlogging and damage the crops. Water logging is a key abiotic

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Month	Phenological stage	Total rainfall received (mm)	
		2017–2018	2018–2019
November	Early vegetative stage	5.61	3.64
December	Tillering	16.71	3.39
January	Jointing	13.23	31.55
February	Booting and heading	20.57	67.93
March	Milking	5.75	10.73
April	Hard dough stage	12.84	29.45

Table 1. Total rainfall received during different phenological stages of wheat crop.

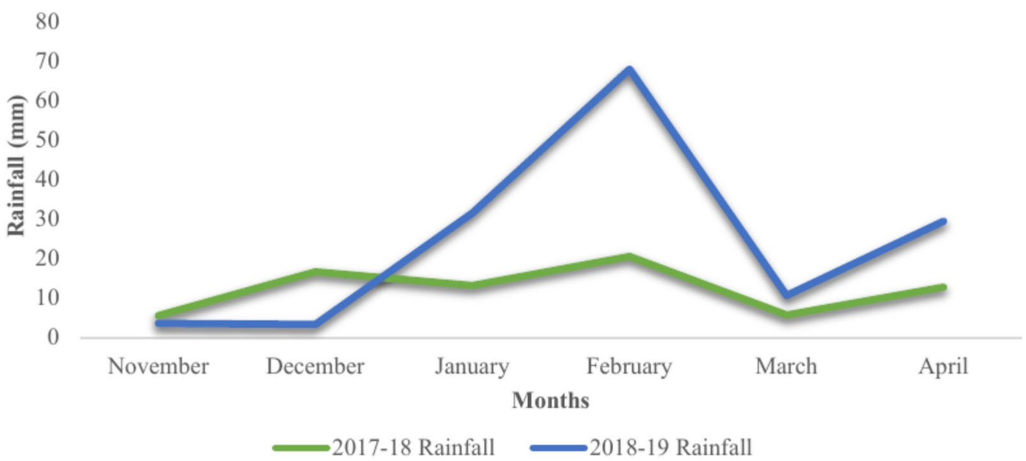

Fig. 1. Total rainfall received during the crop-growing period.

element that significantly impacts agricultural productivity worldwide[6]. However, water is vital for plants, but it can also be detrimental by lowering the oxygen level in the soil, leading to serious consequences of necrosis and stunting[7]. Moreover, plant growth can also be inhibited by decreasing the dry matter accumulation and nitrogen by altering the metabolism and nutrient availability of plants[8–10]. Climate change has caused more frequent flooding disasters due to the rise in heavy and unpredictable rainfall, as reported by IPCC 2021[11] and Pais et al.,[12]. Between 20 and 50% of cultivated wheat fields experience water logging issues, leading to decreased crop yields[10]. Raised beds are an effective planting method that enhances fertilizer and water efficiency, reduces crop lodging, promotes the conservation of rainwater, and minimizes weed infestation thereby providing additional monetary benefits.

Improvement in light interception and air circulation under a raised bed system helps in achieving an optimal phenological rhythm[13]. As a result, there is an increased capacity for grain filling, which enables the optimal distribution of the available nutrients to the spikes. Despite a decrease in spikes per unit area, wheat showed a notable gain in grains per spike and 1000-grain weight when using the bed planting method instead of the flat planting approach[14]. The increased grain yield under the raised bed was due availability of maximum sunlight and energy as well as efficient use of inputs and non-lodging and stronger plant anchorage behavior of the wheat crop on the bed[15]. Studies have shown that bed planting offers several advantages over conventional flat planting, including reduced irrigation water use, lower seeding rates, easier mechanical weeding, and decreased lodging. Despite these benefits, bed planting can maintain or even increase productivity while reducing operational costs[16–19]. The study was conducted to investigate the impact of precipitation on the development and efficiency of wheat, resulting in abiotic stress like water logging, while also evaluating techniques for sowing and the requirements for fertilizers.

Materials and methods

Climatic condition

The field experiment was conducted in 2017 and 2018 at the experimental farm of Lovely Professional University (longitude 75° 42′ E, latitude 31° 15′ N). The mean minimum and maximum temperatures vary significantly over the summer and winter seasons. An increment of maximum temperature (39 °C during 2017–2018 and 40.9 °C during 2018–2019) and decrement in minimum temperature (13 °C during 2017–2018 and 8.4 °C during 2018–2019) was noticed. Wheat crops during 2017–2018 received a total rainfall of 74.71 mm and 146.69 mm during 2018–2019. Maximum rainfall of 20.57 mm in 2017–2018 and 67.93 mm in 2018–2019 was received during the month of February, i.e., during the reproductive stage of the crop (Table 1 and Fig. 1).

Experimental site description

Using an auger, soil samples were randomly taken from the experimental site at a depth of 0 to 15 cm before the start of the experiment. A composite sample was initially taken from the study area and delivered to the lab for soil testing to examine the physical and chemical characteristics. The experimental soil was sandy loam in texture with pH 7.4, cation exchange capacity of 0.33 dS/m, 219.4 kg/ha available nitrogen, 7.74 kg/ha available phosphorus, and 63 kg/ha available potassium. A disc harrow was used twice to create good tilth before planting, and a tractor-drawn cultivator was used for two ploughings. A cultivator pulled by a tractor was utilized to prepare the seedbed for planting. Plots were then created in the field based on the experimental design. In the field, wheat variety HD 2967 was sown at a seeding rate of 100 kg/ha in the first and second week of November of the first (2017–2018) and second year (2018–2019), respectively. Seed and fertilizer drills were used to help sow on raised beds and flatbeds at rates of 70 kg/ha and 100 kg/ha, respectively. Beds 15 cm in height and 60 cm in width were constructed manually using a spade. The beds were raised approximately 2–3 cm above the ground surface. In contrast, the size of plots under flatbeds was 6 × 3 m (18 m^2). In flat sowing, seeds were sown in rows 22.5 cm apart. All the intercultural operations were conducted as and when required, maintaining uniformity and consistency across all treatments.

The experiment was laid out in randomized block design (RBD) with nine treatments that were replicated thrice. The following treatments were utilized: T0: Control, T1: Recommended Dose of P&K + 75% N, T2:100% NPK, T3: Recommended Dose of P&K + 110% N, T4: Recommended Dose of P&K + 130% N, T5: Recommended Dose of P&K + 130% N, T6:100% NPK, T7: Recommended Dose of P&K + 110% N and T8: Recommended Dose of P&K +130% N, where treatments T1 to T4 were carried out under flat sowing while T5 to T8 was carried out under raised bed sowing. The size of individual plots under flat sowing was 18 m^2. Fertilizers were applied as per the treatments. Urea (46% N), DAP (16% N and 48% P_2O_5), and MOP (60% K_2O) were used as sources of fertilizer. Using a seed-cum-fertilizer drill, a full dose of potassium and phosphorus was applied at the time of planting. Nitrogen was applied in three splits. Irrigation and pest control were handled according to local standards. Mechanical methods, such as hand hoeing, were used to control weeds.

Measurements and data analysis

Measurements of plant height were made from the base of the plant to the tips of the spikes, awns were excluded and were expressed in cm. The tagged plant from the net plot was selected and the number of effective tillers per plant was manually counted. Ten randomly selected spikes from each plot were measured to calculate the average length of each spike. To get an average of the number of grains per spike, ten different spikes were counted.

Following the net plot area harvest, wheat bundles were sun-dried for four days, and the biological yield was computed by converting their final weights to tonnes per hectare (ha). The biological yield per net plot area was subtracted from the grain yield to get the straw yield. Grain yield (GY) was calculated for each net plot. The seed index was estimated by manually counting and weighing 100 seeds using an electronic weighing machine. The dry weight data at 30, 60, 90, and 120 DAS was used to calculate the crop growth rate (CGR) and relative growth rate (RGR). To calculate CGR and RGR worked with the following formulas:

Crop growth rate (CGR) g m^{-2} day:

$$\mathrm{CGR} = \frac{\mathrm{w}_2 - \mathrm{w}_1}{\mathrm{T}_2 - \mathrm{T}_1} \times \frac{1}{\mathrm{P}}$$

where W_1 and W_2 are dry weights of plants at times T_1 and T_2 respectively and P is land area.

Relative growth rate (RGR) g^{-1} g^{-1} day:

$$RGR = \frac{\mathrm{Log}_e W_2 - Log_e - W_1}{T_2 - T_1}$$

where W_1 and W_2 are the dry weights of plants at times T_1 and T_2 respectively and P is land area.

Statistical analysis

Statistical analysis was carried out using R studio. Analysis of variance (ANOVA) was used to calculate the means and significant differences between the various treatments. A significance level of *p* 0.05 was employed to compare the treatment means. The graphs were prepared on Origin.

Results

A view of the effect of waterlogging stress due to heavy rainfall on wheat crops at the vegetative stage and the reproductive stage in (a &c) raised bed and (b &d) flat bed is shown in Fig. 2.

Plant height (cm)

In most regions of the world, supplying too much water poses a serious risk to the establishment and growth of wheat. The impact of the flat and raised bed with different levels of nutrient application on the plant height of the wheat crop is presented in Fig. 3 and Table 2. Among the flat and raised beds, the treatments carried out under raised beds gave significant improvement in plant height. The recommended fertilizer application (T6) had the highest plant height compared to the control treatment (T0) under flatbed planting with the most significant

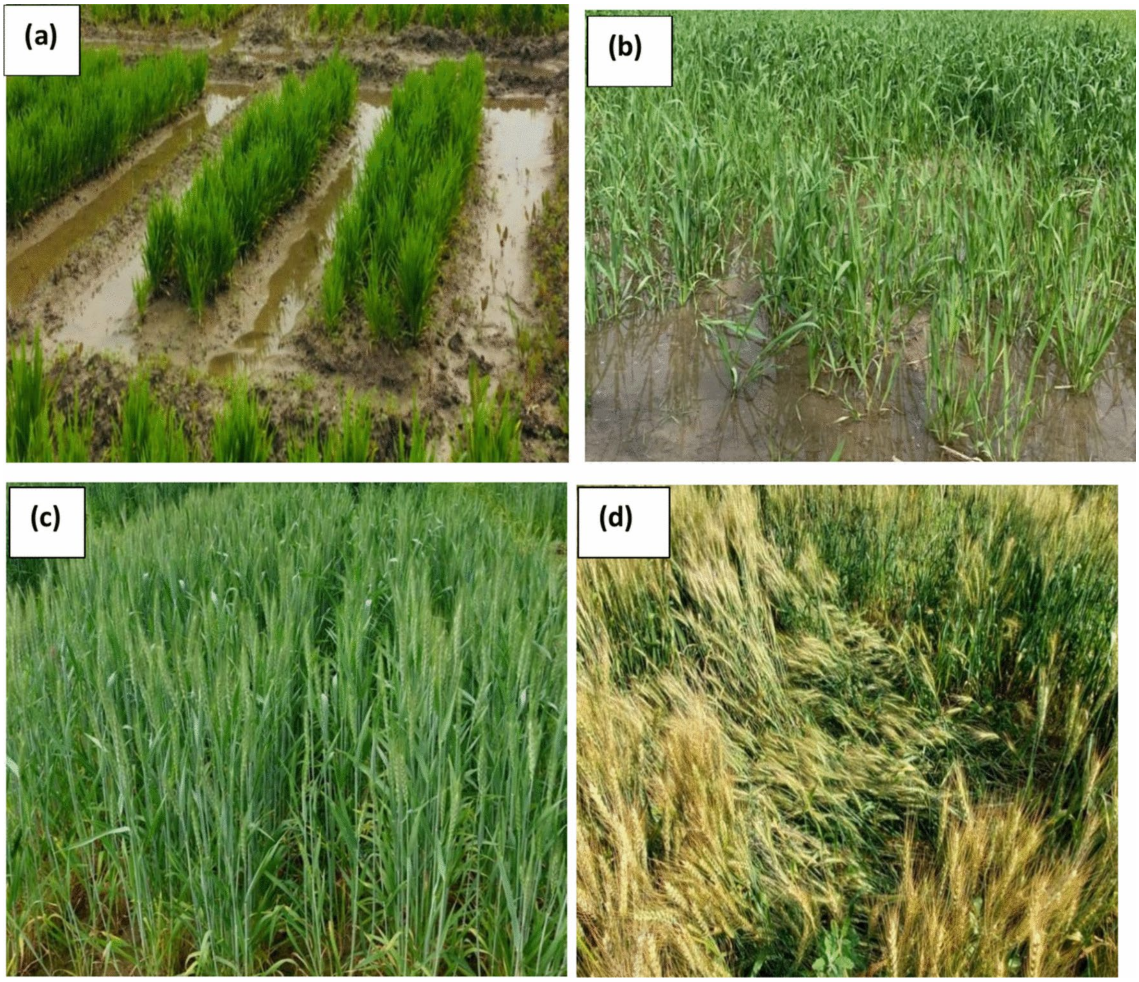

Fig. 2. Effect of waterlogging stress due to heavy rainfall on wheat crop at the vegetative stage and the reproductive stage in (**a** and **c**) raised bed and (**b** and **d**) flatbed. Note: (**a** and **b**) denote the vegetative stage; (**c** and **d**) denote the reproductive stage.

increase of 18.53%. No significant difference was observed with T1, T2, T3, T4, T5, T7, and T8, however, it was found to be statistically at par with the highest treatment. It was also observed that treatments T2, T3, T4, T5, T6, T7, T8 exhibit non-significant effect with each other.

Crop growth rate

Among different doses of nutrient application along with the method of sowing the CGR ranged from 1.08 to 1.30 from 0 to 30 days after sowing. CGR was found to be significant from 30 to 60 days after sowing where maximum was observed for T9 (9.12 g m^{-2} day^{-1}) which was found to be at par with T6 and T5. T7 (23.15 g m^{-2}) was found to be significantly higher from 60 to 90 days after sowing and was at par with T6 (19.16 g m^{-2}). Whereas from 90 to 120 days after sowing the maximum crop growth rate was observed for T6 (9.72 g m^{-2}). The lowest value for crop growth rate was found for treatment T0 (Fig. 4).

Relative growth rate

The relative growth rate (RGR) was not significantly impacted by variations in fertilizer management and sowing procedures (Fig. 4). Significantly, the RGR exhibited an increase during 30–60 DAS in comparison to the later stages, suggesting a decline in RGR as the crop aged.

Yield attributes

Data on yield-attributing characteristics, such as spike length, number of grains per spike and weight of 100 seeds (seed index) were significantly affected by a variety of land and nutrient management strategies (Table 2).

Maximum spike length to the tune of 11.67 cm was obtained with the recommended dose of NPK (T6) under a raised bed system and was found to be at par with T5, T7, and T8 respectively (Fig. 5). Also, a planting method along with different doses of fertilizers has a significant impact on the number of grains per spike (Fig. 5). In the T6 treatment, the highest number of grains per spike (72.50) was obtained and was found to be statistically at par with T7. Treatments T1, T3, T5, and T8 were found to be statistically at par with each other. The seed index

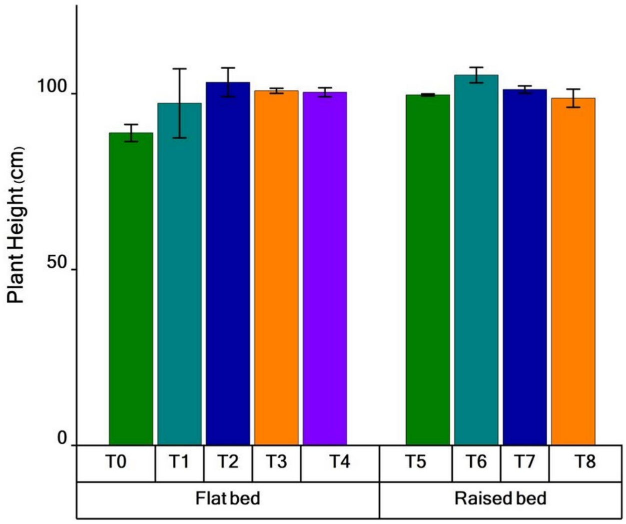

Fig. 3. Plant height under different doses of nutrient application on plant height of wheat (*Note:* T0:Control, T1: Recommended Dose of P&K + 75% N, T2:100% NPK, T3: Recommended Dose of P&K + 110% N, T4: Recommended Dose of P&K + 130% N, T5: Recommended Dose of P&K + 130% N, T6:100% NPK, T7: Recommended Dose of P&K + 110% N and T8: Recommended Dose of P&K + 130% N: T0-T4: Carried under flat sowing, T5-T8: carried under raised bed, Data represents the mean ± standard deviation of three replications).

Treatments		Plant height (cm)	Effective tillers/plant	Spike length (cm)	Number of grains/spikes	Seed index	Grain yield (t/ha)	Straw yield (t/ha)
Conventional methods (flat sowing)	Control (T0)	88.82^{c}	15.17^{d}	8.81^{d}	49.35f.	2.26f.	2.93^{fe}	4.99^{e}
	Rec, PK + 75% N (T1)	97.25^{b}	19.01^{bcd}	10.33^{c}	62.50^{d}	3.62^{de}	5.00 ^{cd}	6.94 ^{cd}
	Rec. NPK (T2)	103.24^{ab}	21.86^{ab}	11.34^{ab}	67.17^{bc}	5.76^{ab}	5.51^{bc}	7.44^{bcd}
	Rec.PK + 110%N (T3)	100.81^{ab}	19.83^{bc}	10.59^{bc}	64.67 ^{cd}	4.07^{cde}	5.29^{bcd}	7.88^{b}
	Rec.PK + 130%N (T4)	100.39^{ab}	16.49 ^{cd}	10.69^{bc}	55.50^{e}	3.27^{e}	4.44^{d}	6.61^{c}
Raised beds	Rec.PK + 75%N (T5)	99.64^{ab}	20.55^{bc}	11.33^{ab}	64.30 ^{cd}	4.50 ^{cd}	5.99^{ab}	8.42^{ab}
	Rec. NPK (T6)	105.28^{a}	25.08^{a}	11.67^{a}	72.50^{a}	6.70^{a}	6.97^{a}	9.39^{a}
	Rec.PK + 110%N (T7)	101.16^{ab}	21.54^{ab}	11.56^{a}	70.00^{ab}	5.01^{bc}	5.77^{bc}	8.04^{b}
	Rec.PK + 130%N (T8)	98.69^{ab}	20.84^{b}	11.16^{ab}	64.33 ^{cd}	4.71^{c}	5.81^{bc}	8.47^{ab}
	LSD (5%)	7.06	4.14	0.82	4.12	0.95	0.98	1.19

Table 2. Effect of different treatments on growth, yield, and yield attributes of wheat (pooled data). Different letters indicate significant differences to $p \leq 0.05$.

ranged from 2.26 to 6.70 g and the highest was achieved with treatment T6 (Fig. 5). However, treatments T6 and T2 were found to be statistically at par with each other and the least seed index was obtained under control (T0).

Effective tillers/plant

Effective tillers are the ones bearing fertile spikes and the number of effective tillers/plants is a crucial yield characteristic that primarily explains the variance in wheat grain yield. Data on effective tillers/plants is represented in Fig. 5 and Table 2. Among the different treatments, a maximum number of effective tillers/plant (25.07) was recorded under T6 treatment compared to all other treatments except T7 and T2 respectively. Control exhibited the lowest value (15.17) for effective tiller per plant indicating lesser response as compared to other treatments.

Grain yield

Numerous crops around the world have shown yield advantages in studies comparing bed to flat planting[2,20]. From the data (Fig. 6) it was revealed that there was a profound increment in grain yield under the raised bed sowing method. In the raised bed, the grain yield varied with the change in nutrient doses. Application of the recommended dose of NPK under a raised bed system increased the yield by 137. 8% as compared to the control. Sowing under a raised bed over a flatbed still showed a considerable improvement in grain yield. Raised bed planting had a positive response with a relative yield advantage of 26.5% under the same nutrient application. Furthermore, effective tiller development was positively encouraged by the improved soil moisture conditions,

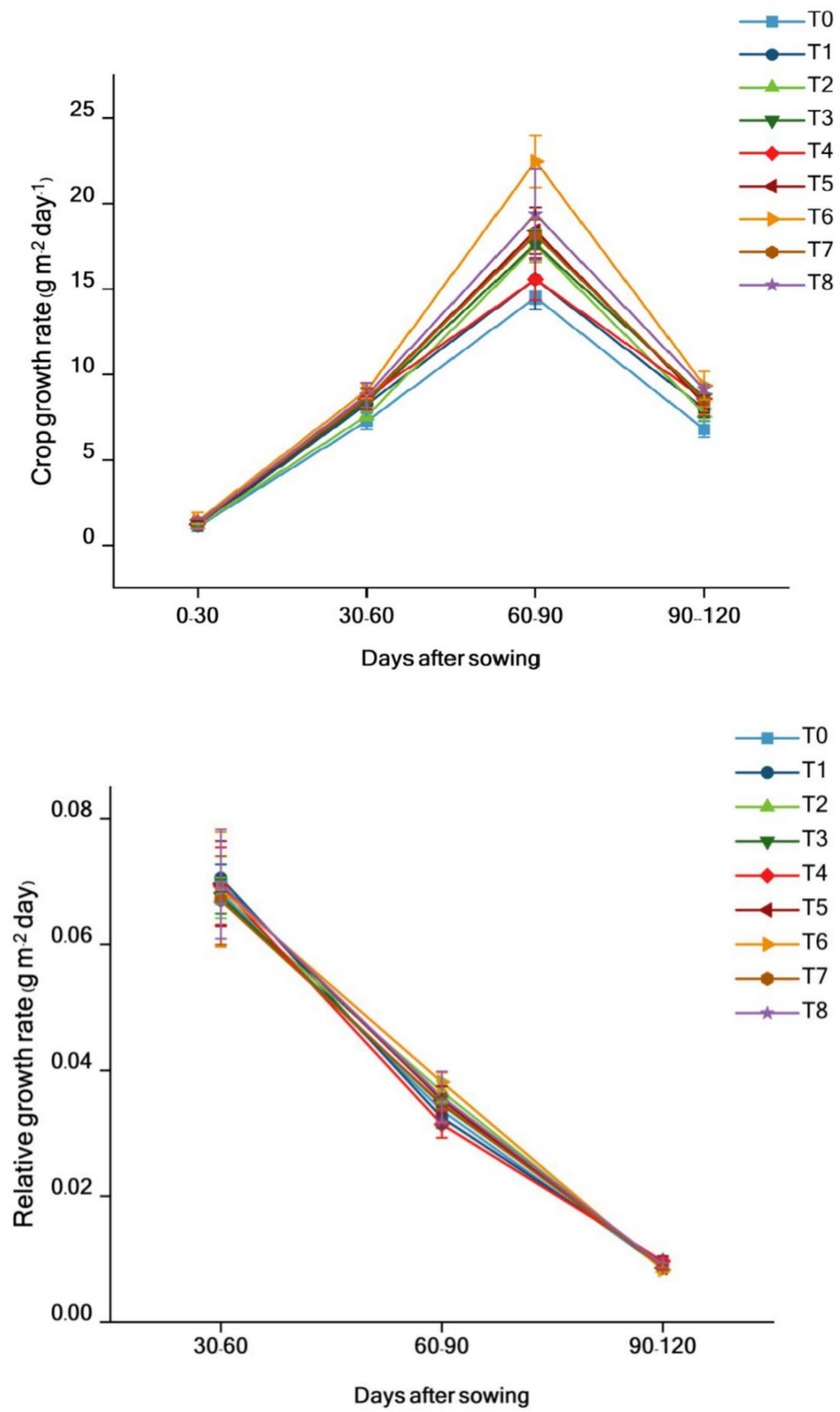

Fig. 4. Crop growth rate and relative growth rate under different doses of nutrient application on plant height of wheat (*Note:* T0:Control, T1: Recommended Dose of P&K + 75% N, T2:100% NPK, T3: Recommended Dose of P&K + 110% N, T4: Recommended Dose of P&K + 130% N, T5: Recommended Dose of P&K + 130% N, T6:100% NPK, T7: Recommended Dose of P&K + 110% N and T8: Recommended Dose of P&K + 130% N: T0-T4: Carried under flat sowing, T5-T8: carried under raised bed, Data represents the mean ± standard deviation of three replications).

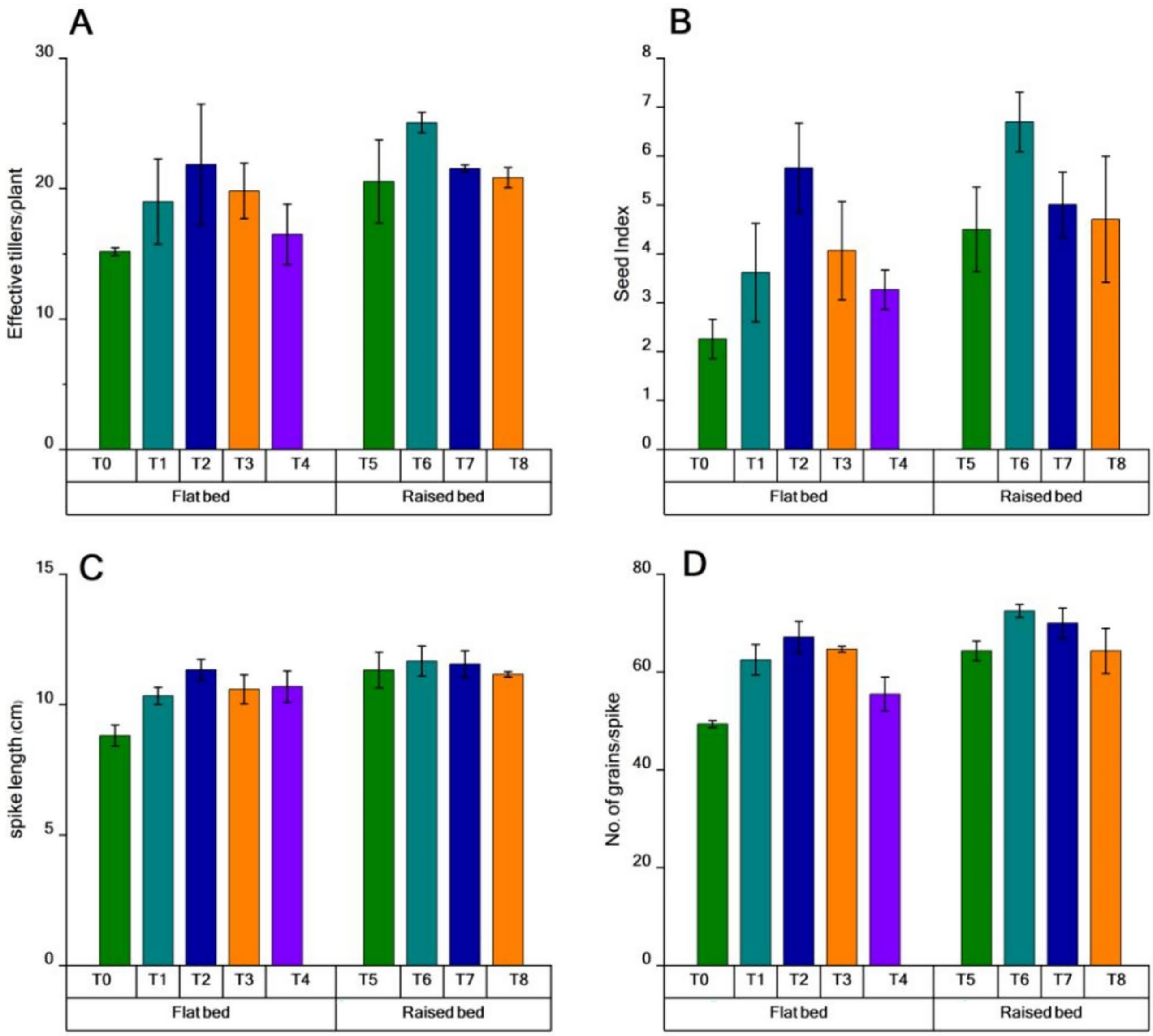

Fig. 5. Impact of flat and raised bed along with different doses of nutrient application (**A**) effective tillers/plant (**B**) seed index (**C**) spike length (cm) (**D**) no. of grains/spike (*Note:* T0:Control, T1: Recommended Dose of P&K + 75% N, T2:100% NPK, T3: Recommended Dose of P&K + 110% N, T4: Recommended Dose of P&K + 130% N, T5: Recommended Dose of P&K + 130% N, T6:100% NPK, T7: Recommended Dose of P&K + 110% N and T8: Recommended Dose of P&K + 130% N: T0-T4: Carried under flat sowing, T5-T8: carried under raised bed, Data represents the mean ± standard deviation of three replications).

which may have contributed to the higher grain number on the final spikes[2]. Water logging stress on plant growth was lessened and the soil water status was enhanced under a raised bed planting system. The examination of yield components revealed that an increase in the number of grains per spike was the cause of the higher wheat grain yield under raised bed planting. It was also observed that treatments T2, T3, T5, T7, and T8 gave statistically similar results with each other. Treatment T0 (control) exhibited the lowest grain yield of 2.93 t/ha indicating the least effect compared to other treatments.

Straw yield

The investigation revealed that different treatments had a significant effect on straw yield, which varied from 4.99 to 9.39 t/ha respectively. It was found that straw yield improved significantly under nutrient management on raised beds as compared to conventional flat sowing (Fig. 6). Maximum straw yield was obtained with treatments T6 and was found to be at par with T5 and T8. The percent increment of straw yield as compared to control was 88%. It was observed a 29% increase in biological yield was observed in the raised bed planting method[21].

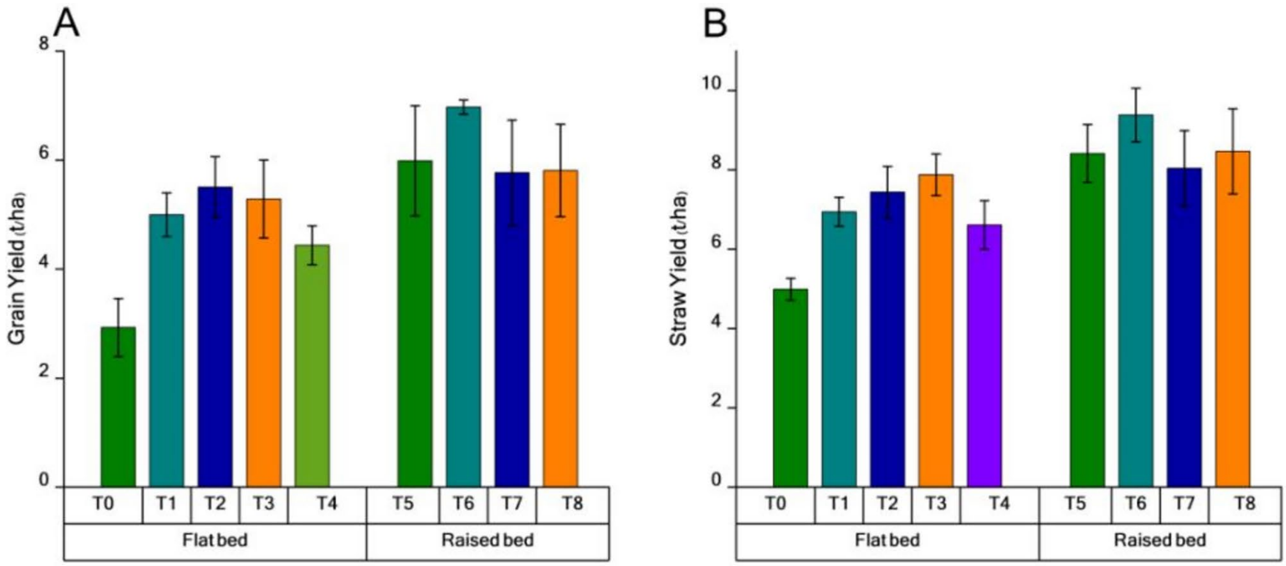

Fig. 6. Impact of flat and raised bed along with different doses of nutrient application on (**A**) grain yield (t/ha) and (**B**) straw yield of wheat. (*Note:* T0:Control, T1: Recommended Dose of P&K + 75% N, T2:100% NPK, T3: Recommended Dose of P&K + 110% N, T4: Recommended Dose of P&K + 130% N, T5: Recommended Dose of P&K + 130% N, T6:100% NPK, T7: Recommended Dose of P&K + 110% N and T8: Recommended Dose of P&K + 130% N: T0-T4: Carried under flat sowing, T5-T8: carried under raised bed, Data represents the mean ± standard deviation of three replications).

Relationship between grain yield and different growth and yield contributing factors

The pooled analysis for both years on wheat grain yield showed a significant positive correlation with shoot dry matter, plant height as well as with number of effective tillers per plant. The regression coefficient (R^2) for dry matter per plant, plant height and effective tiller count per plant was 0.84, 0.74, and 0.89 which fit the observations in a linear trend line (Fig. 7). This signifies the importance of these factors in improving the grain yield Similar kind of association was found by Mondal et al. 2020 for effective tillers per plant.

Discussion

A waterlogged environment can lead to a deficiency of oxygen which can limit the root growth and ultimately lead to the death of the root. Critical physiological activities reliant on energy, including the uptake of water and nutrients and their subsequent translocation to the aerial parts of the plant, are adversely affected. This impairment compromises the overall growth of the plant[22–24] and eventually the yield[24–26]. However, the water logging stress significantly inhibited the growth of the plant under flatbed planting but under raised bed planting method can effectively reduce the damage of stress caused by the waterlogged conditions to the plants. In this study, waterlogged conditions have significantly reduced the plant height in wheat grown under flatbed planting, indicating that the raised beds provide better ventilation for plants exposed to the sun and well-designed preparation systems were used during the sowing process[27]. Further, the stress caused by water logging conditions was decreased in raised bed planting as there was an increase in infiltration and water drainage. This was in line with earlier research's findings that bed-furrow systems can enhance crop growth by simultaneously improving the soil water status[28]. The diminished crop growth rate (CGR) figures were documented in the initial phases of vegetative growth yet surged to their peak during the subsequent vegetative growth stages, a trend that was similarly noted by previous researchers[29–31]. The notable rise in CGR could be ascribed to the synergistic impact of NPK fertilizers on plant nutrition, possibly resulting from enhanced nutrient availability and efficient transformation of macronutrients at the location of photosynthetic activity into pigments[32]. The relative growth rate typically decreases during the latter stages and becomes negative as maturity is reached, primarily as a result of the significant loss of CO_2 through respiration. This process occurs continuously in all metabolically active tissues, with the amount of CO_2 lost exceeding that which is assimilated through photosynthesis. Photosynthesis, on the other hand, occurs exclusively in cells containing chlorophyll and is activated when exposed to light[33]. The findings are consistent with the outcomes reported in the studies conducted by Azarpour et al. (2014)[34], Paul et al. (2016)[35], and Salem et al. (2011)[36].

Previously, a 7.8% increase in effective tillers was observed under the raised bed approach compared to the flatbed way of sowing with equal fertilizer administration[37]. The reduced effect of water logging was observed in raised bed planting due to improved soil and water conditions which ultimately led to better seed establishment, root growth, accelerated stem, and tiller development[38]. A higher number of yield attributes has been reported in the raised bed planting method because the higher amount of uptake of nutrients in raised bed planting may be due to less leaching loss of nutrients and the availability of sufficient moisture for mineralization of applied nutrients[17,37–39]. Furthermore, effective tiller development was positively encouraged by the improved soil

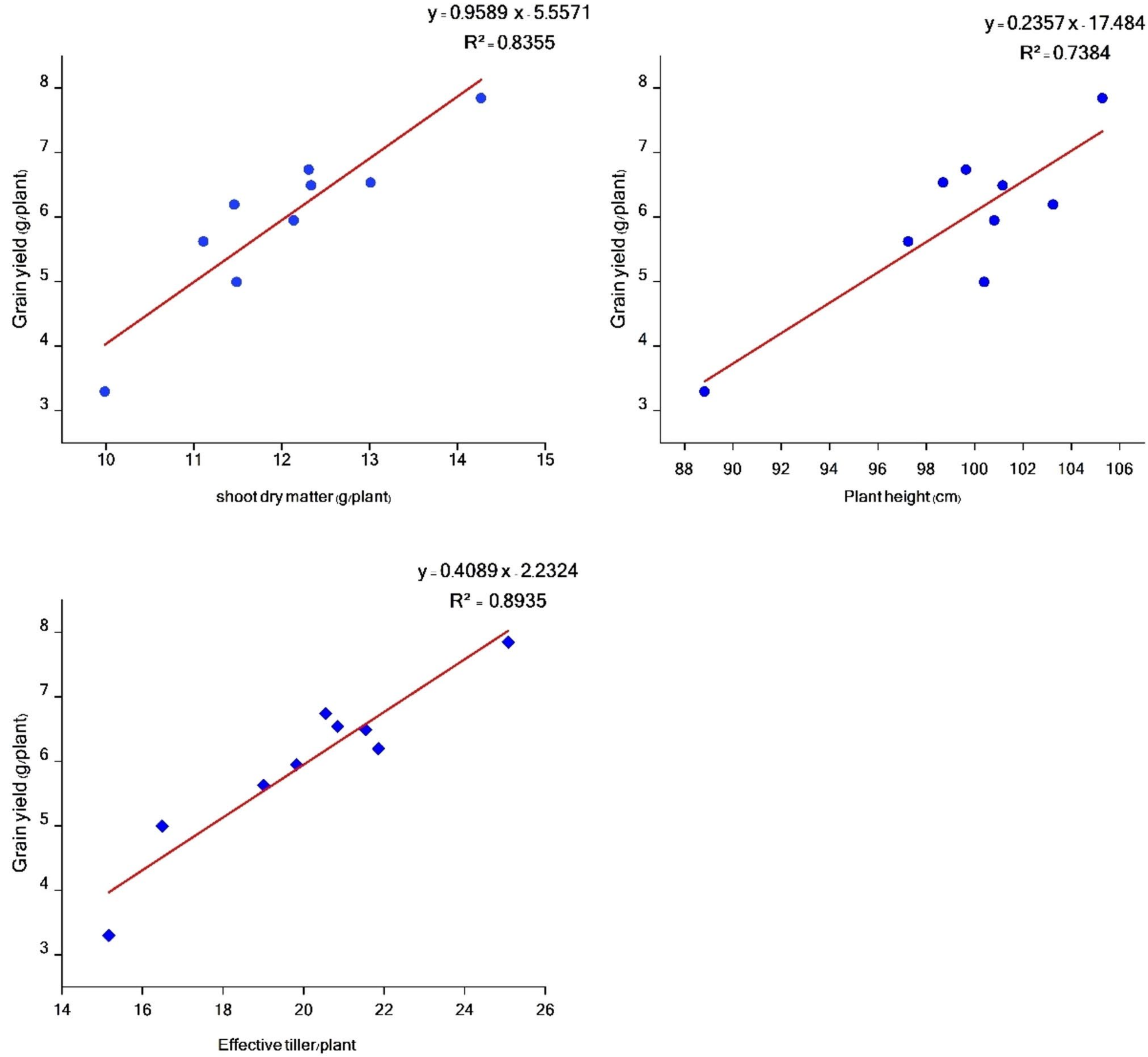

Fig. 7. Relationship between grain yield and shoot dry matter, plant height, and effective tiller count per plant as influenced by different sowing methods and nitrogen management.

moisture conditions, which may have contributed to the higher grain number on the final spikes[2]. Water logging stress on plant growth was lessened and the soil water status was enhanced under a raised bed planting system. Raised bed planting enhanced the moisture content of the soil and lessened the impact of waterlogging stress on plant development, which ultimately raised yield attributes and raised wheat productivity. Because raised bed planting exhibits superior root attachment on beds and resistance to water stress, the results also showed that this strategy was less vulnerable to the negative effects of climate change. Also, it was stated that wheat grown on raised beds leads to an increased Nitrogen Use Efficiency (NUE) and decreased disease pressure which leads to improved grain quality and increased grain yield by more than 10%[21]. The improvement in wheat yield under raised beds can be attributed to the enhanced vertical distribution of photosynthetic active radiation within the wheat canopies[40]. Additionally, the plants in the outer rows tend to tiller well and effectively fill in any gaps, ensuring that all available light is captured and also reducing the harmful effects of anoxia. Similar findings were inferred by Mazeed et al. [41] and Aboelsoud et al.[42] where they suggested that wheat crops raised under raised bed systems showed improvement in yield[41]. In addition, he also concluded that during the construction of a bed about one-third of the applied nitrogen is collected in beds given that fertilizers are broadcast initially and then beds are made by taking soil from furrows on the beds. Moreover, planting beds minimized the amount of soil exposed to flooding, which prevented surface soil crusting on top of the wheat-planting bed[37]. Furthermore, the application of the recommended dose of fertilizer under raised bed planting methods has resulted in a significant increase in the growth and yield of the wheat plant.

Conclusions

It is determined that cultivating wheat crops on raised beds enhanced plant height, yield, and yield characteristics of wheat when following recommended nutrient treatment. Raised bed planting can enhance plant stand in waterlogged circumstances. Raised bed planting demonstrated superior root anchoring capacity on beds, resistance to water stress, and potential resilience to the adverse impacts of climate change, as indicated by our findings. Utilizing raised bed planting postponed the late-season aging process and boosted the grain count per spike, leading to a notable rise in wheat production. The results indicate that in anticipated water-logging conditions, utilizing raised bed planting could effectively mitigate waterlogging stress and enhance crop output. The ramifications may also affect agricultural adaptability in future climate circumstances. The study found that applying the recommended dose of NPK under raised bed conditions (T6) enhanced the growth and yield of wheat crops under abiotic stress.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Declarations

Competing interests
The authors declare no competing interests.

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