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Research Article

Site-Specific Fertilizer Recommendation for Barley (*Hordeum vulgare L.*) Using the QUEFTS Model in Wolaita Zone in Southern Ethiopia

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Although Ethiopia is a center of barley domestication and diversity, and barley has an important place in African dry land agriculture due to its resilience to wide-ranging stresses; the average yield continues to be low, mainly due to low soil fertility. Site-specific fertilizer recommendation for barley in Wolaita, Ethiopia, has a pivotal role not only in optimizing barley productivity but also in maintaining ecological balance. Thus, this study was conducted to assess the relationship between grain yield and site-specific nutrient requirements for a target yield using a Quantitative Evaluation of the Fertility of Tropical Soil (QUEFTS) model. The data input was derived from field experiments predominantly in the major barley production areas of Wolaita, Ethiopia. Calibration of the QUEFTS model was estimated by describing the two boundary lines of the maximum accumulation and dilution of N, P, and K contents targeting the barley grain yield. The study revealed that balanced nutrient requirements estimated by the QUEFTS model had a good correlation between the simulated and observed grain yields ($r2 = 0.82^*$, 0.88^*, and 0.83^*) for different sites, namely, Doga Mashido, Kokate, and Gurimo Koyisha, respectively, while evaluation of the QUEFTS model by U-Theil values showed a good agreement between the simulated and observed yields. Therefore, the study concluded that the QUEFTS model can be used for determining nutrient requirements of crops, thereby contributing to the development of site-specific fertilizer recommendations.

1. Introduction

Ethiopia is implementing an agriculture-based strategy to meet the challenges of food insecurity, poverty, and overall national economic development [1]. As one of the main components of agriculture, cereal crops in Ethiopia are by far the largest group in terms of their share in area cultivated, output, and consumption. Barley is one of the most important cereal crops, which rank fourth after wheat, maize, and rice in the world and third in Ethiopia both in terms of area and production [2]. However, in Ethiopia, barley yields have been consistently below the East African and world average yields [3], which could be the result of a decline in the natural supply of one or more crop nutrients, excessive or imbalanced mineral-fertilizer application, and soil acidity. Studies have shown that there is imbalance between fertilizer application and nutrient requirements for crops, resulting in both reduced crop yields and inefficient fertilizer use. To address this problem, fertilizer recommendations have mainly focused on measuring soil properties and regulating N nutrient supply based on the residual nitrate-N concentration in soil [4, 5]. The fertilizer recommendation could be used for quantifying crop nutrient requirements to optimize nutrient management. However, most previous studies only considered a single nutrient, thereby neglecting the interactions between more plant nutrients [6]. A site-specific nutrient management approach provides the principles and guidelines that enable farmers to apply fertilizers, which optimally match the needs of their crop in a specific field and season [7, 8]. The QUEFTS model has been applied on rice in Asia and West Africa; [7–9], wheat in India and China [10, 11], and maize in Nigeria, Kenya, Southeast Asia, and China [10, 12–16]. It provided a practical tool for site-specific nutrient management concepts for major crops [17]. Currently, the QUEFTS model has been successfully applied to different crops, including maize, rice, and wheat in countries such as Africa, the USA, India, and China [7, 9]. Either these studies have insufficient data that limit the representation for the whole barley-producing areas to estimate nutrient requirement or the experimental data are insufficient to serve as adequate nutrient management and fertilizer recommendations for current intensive barley production systems of Wolaita. Therefore, the specific objectives of this study were to (1) estimate the optimal nutrient requirements of N, P, and K uptake for a specific target yield using the QUEFTS model and (2) establish maximum and minimum nutrient uptake efficiencies.

2. Materials and Methods

2.1. Model Calibration

2.1.1. Dataset for Model Calibration. The dataset used for model calibration was collected in three field experiments conducted over 2015/16 in similar agro-ecological zones of Wolaita. The sites were Kokate, Doga Mashido, and Gurimo Koyisha in the Wolaita zone of southern Ethiopia (Figure 1). The experimental sites are located from 6°53′.03″N and 37° 48′50.60″E, 6°53′20.3″N and 37°37′40.8″E, and 6°57′15.3″N and 37°44′49.9″E, Kokate, Doga Mashido, and Gurimo Koyisha, respectively, with an altitude range of 1900–2132 meters above sea level. The average annual rainfall is 115.57 mm, and the mean annual temperature is 20°C (Table 1). Most of the major food crops in Wolaita are cultivated in this region, and they include maize, barley, teff, wheat, beans, bananas, sugarcane, coffee, cassava, cabbage, sorghum, yam, and cowpea. However, only barley farms were targeted in this study because they are one of the widely cultivated cereals in the region. The dominant soil around the Wolaita area is eutric nitisols, associated with humic nitisols, and mineralogy of the soil is kaolinite [18, 19].

2.2. Parameters for the QUEFS Model. The original version of the QUEFTS model [12] was developed as a tool for the quantitative prediction of maize yields on unfertilized tropical soils. The QUEFTS model is a combination of empirical and theoretical types of models. Calibration here is regarded as adjustment of already established indices for estimation of supply of N, P, and K to agree with the supply of the same for barley in Wolaita, southern Ethiopia, based on experiment values. Thus, for calibration of those coefficients for estimation of soil N, P, and K, kg·ha^{-1}, and parameterization of nutrient requirement of barley for Wolaita, the following procedure in QUEFTS consists of four steps (Table 2):

(i) Assessment of the potential indigenous nutrient supply on the basis of chemical soil data. Composite surface soil samples (0–20 cm) were collected from each site to determine the initial soil conditions. Air-dried soil samples were analyzed for the following parameters: soil organic carbon (OC), total nitrogen (TN), exchangeable potassium, soil texture, pH (H_2O), available phosphorus (P- Olsen), and cation exchange capacity (CEC) using the procedures described by Sahlemedhin and Taye [20]. Field experiments were then conducted in randomized complete block design with three replications per treatment of three levels of N and K and four levels of P as follows: N at 0, 23, and 46, kg·ha^{-1}; K at 0, 25, and 50 kg·ha^{-1}; and P at 0, 10, 20, and 30 kg·ha^{-1}). The size of each plot was 3 m × 3 m (9 m^2), and the space between plots and blocks was 1 m and 1.5 m, respectively. All doses of P (triple superphosphate) and K (potassium chloride) were applied as basal dressing at sowing, while N (urea) was applied in split form, one-half applied at sowing and the other half at early booting. The optimal practices treatments for barley in three sites (324 plots) were conducted during 2015 with hybrid barley 1307 being used to validate the QUEFTS model. Barley was sown at the beginning of July and harvested in November of the following year.

(ii) Calculation of the actual uptakes of N, P, and K based on the potential supplies of N, P, and K. N, P, and K grain and straw contents were determined by the wet acid digestion procedure as suggested by the FAO [21]. The method used for N analysis was the Kjeldahl procedure [22], whereas the determination of P was carried out on the digest aliquot that was obtained through wet digestion. P in the solution was determined by using a colorimeter by using molybdate and metavanadate for color development, and the reading was recorded with a spectrophotometer at 460 nm wavelengths; potassium was determined by using a flame photometer FAO [21]. Nutrient use efficiency was calculated using procedures described by the authors of [23].

(iii) Identification of yield ranges as functions of the actual uptakes of N, P, and K at accumulation and dilution:

The maximum accumulation of the nutrient was calculated as follows:

$$Y(a)(kgkg-1) = \frac{GY(a)}{TU(a)}. \quad (1)$$

Here, *Y (a)* = maximum nutrient accumulation, *GY* (a) = grain yield (kg·ha^{-1}) at the maximum application rate *(a)*, and *TU (a)* = total nutrient uptake in an aboveground plant (kg·ha^{-1}) at the maximum application rate of nutrients *(a)*.

The maximum dilution of that nutrient was calculated as follows:

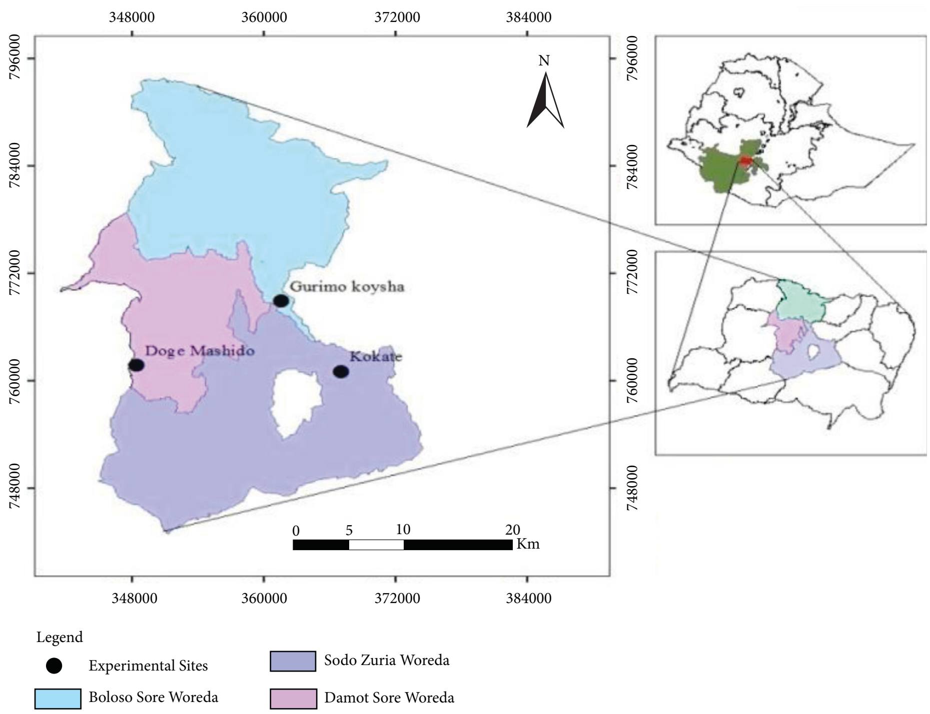

Figure 1: Location map of Wolaita zone in Ethiopia.

Table 1: Monthly average means of rainfall and temperatures of the study areas during growth season.

Year	—	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean (°C)	Total (RF)
2015/16	°C	19.3	19.2	19.6	20.1	20.7	20.5	20.7	20	
	mm	148.0	139.5	106.7	102.9	138.6	110.9	62.4		115.57

Table 2: Physicochemical properties of experiment sites.

Soil properties	Model parameterization in experimental sites		
	Kokate	Doga Mashido	Gurimo Koyisha
Sand (%)	39	28	24
Clay (%)	44	44	30
Silt (%)	17	28	46
Textural class	Clay	Clay	Clay loam
pH (H_2O)	5.5	5.3	5.6
OC(g kg^{-1})	16.0	15.2	17.0
Available P (mg kg^{-1}) (Olsen)	9.3	7.3	7.7
Total N (g kg^{-1})	1.4	1.2	12
Exchangeable K (mmol kg^{-1})	4.5	3.4	3.2
CEC (cmol kg^{-1})	20.2	23.0	20.7

$$Y(d)\,(kgkg-1) = \frac{GY(d)}{TU(d)}. \qquad (2)$$

Here, $Y(d)$ = maximum nutrient dilution, $GY(d)$ = grain yield (kg·ha^{-1}) from treatments applying no nutrient (d), and $TU(d)$ = total nutrient uptake in an aboveground plant (kg·ha^{-1}) from treatments applying no nutrient (d).

Calibration was regarded as adjustment of already established indices for estimation of supply of N, P, and K and confirmed that the yield was a combined function of N, P, and K and described the relationship between the grain yield and nutrient uptake in the above four steps.

2.3. Model Validation. The experimental sites covered (i) a wide range of soil types and climate conditions, (ii) rainfed food barley; (iii) treatments including N, P, and K fertilizers and omission plots for N, P, and K, and (iv) crop parameters, such as grain yield and N, P, and K uptakes in both straws and grains.

2.4. Model Evaluation. The model was evaluated after validation in the three sites Kokate, Doga Mashido, and Gurimo Koyisha) in Wolaita zone. The U- Theil statistical formula was used to evaluate the QUEFTS model and the deviation between the measured and simulated data. It was expressed based on the equation by Wijayanto and Prastyanto as shown in the following formula [24]:

$$U = \frac{\sqrt{(1/T)\sum_{t=1}^{T}\left(Y_1^s - Y_t^a\right)^2}}{\sqrt{(1/T)\sum_{t=1}^{T}\left(Y_t^s\right)^2} + \sqrt{(1/T)\sum_{t=1}^{T}\left(Y_t^a\right)^2}}. \quad (3)$$

Here, T is the number of samples, Y_t^s is the predicted values of the model, and Y_t^a is the actual values. If the value of U is equal to zero, then the model is perfect, and if the value of $U = 1$, then the model is poor for prediction. All the data of nutrient use efficiencies were statistically analyzed, using a generalized linear model (GLM) procedure of the Statistical Analysis System software [25], and the means were separated using the least significant difference (LSD) at the 5% probability level.

3. Results and Discussion

3.1. Calibration of QUEFTS for Barley. Assessment of soil and input supplies of available nutrients (Step 1): the results showed that Doga Mashido, Kokate, and Gurimo Koyisha had soil textures in the experimental sites to be clay and clay loam, respectively (Table 2). The soil reactions of the experimental sites were strongly acidic (Doga Mashido and Kokate) and moderately acidic in Gurimo Koyisha, accordingly [26]. According to Karltun et al. [27] classification OC, TN and available P were low in all locations. Exchangeable K in soils of Doga Mashido, Kokate, and Gurimo Koyisha ranged from medium to low, respectively. This agrees with the findings of Baligar and Fageria [28] who showed an increase in soil acidity, and the severity of acidity of the soil in cultivated land comes from intensive cultivation that results in leaching of basic cations from soil solutions. Similarly, Kebede and Yamoah [29] reported that OC levels are usually low in vertisol particularly when they are cultivated continuously with chemical fertilizer application.

3.2. Nutrient Uptake and Use Efficiency. The total N uptake by grains and straws was more prominent due to the combined application of fertilizers and neither luxurious nor deficient, meaning that the N application in Wolaita region was more rational. This finding agrees with that of Agegnehu et al. [30] who reported that the total N, P, and K uptakes were increased as the NPK fertilizer rates increased in barley. The calibration of steps iii and iv described above, using the total P uptake as input, gave a correlation coefficient of $r^2 = 0.57$ with grain yields at Gurimo Koyisha with $N_{46}P_{30}K_0$, and the lowest correlation coefficient ($r^2 = 0.07$) was observed from the nutrient omission plot at Doga Mashido, confirming nutrient deficiency. The total K uptake ranged from 18.66 to 78.13 kg ha^{-1}, and the maximum total K uptake ($r^2 = 0.59$) was observed for treatment of $N_0P_{30}K_{50}$ at Gurimo Koyisha, while minimum ($r^2 = 0.32$) for treatment of the K omission plot at the Doga Mashido site. This result is consistent with that of Dessougi et al. [31] who reported that the K content and the total K uptake were increased as K fertilizer rates increased in different cereal crops.

3.3. Parameters for the QUEFTS Model. The coefficient accumulation and dilution values of N, P, and K were calculated by excluding the upper and lower percentiles of internal nutrient efficiency for barley in Wolaita (Table 3). The relationship between yield and nutrient accumulation in the aboveground parts under a potential yield of 6.0 t·ha^{-1} was calibrated with the QUEFTS model to determine the borderlines of accumulation and dilution. The average aboveground nutrient accumulation of K, P, and N was 40–44, 35–39, and 32–46 kg grain kg^{-1} K,100–171, 97–136, and 93–142 kg grain kg^{-1} P, 32–38,37–43, and36–40 kg grain kg^{-1} N for Doga Mashido, Kokate, and Gurimo Koyisha, respectively. Nutrient accumulations were less than those reported by Abegaz et al. [32] (44 for K, 182 for P, and 34 for N). The P accumulation in the grain in our study indicated a sign that P was not used efficiently. The reasons for these differences were due to different environmental conditions, soil chemical properties, and nutrient management practices imposed as treatments (nutrient omission plots, optimal treatment, and farmers' practice). The average maximum dilution of N was 46–51.9, 48.46–61.9, and 22.4–46.3 kg grain kg^{-1}, for P, 247.4–361.2, 95.8–191.3, and168.7–239 kg grain kg^{-1}, and for K, 26.6–59.7, 41–63, and57.8–105 kg grain kg^{-1} for Doga Mashido, Kokate, and Gurimo Koyisha, respectively. More points were allocated in the locations close to the nutrient dilution borderline to N, P, and K uptakes for barley, indicating that N, P, and K fertilizer applications were not in balance, not accounting for the indigenous soil nutrient supply and plant demand, and obtained yields were the highest possible in the amount of nutrient uptakes. The nutrient dilution observed in the study was less than that reported by Liu et al. [10] (64 kg grain kg-1 N, 384 kg grain kg-1 P and 90 kg grain kg-1 K); Zhang et al. [17] (87 kg grain kg-1 N, 605 kg grain kg-1 P, 210 kg grain kg-1 K) for maize. We used the constant accumulation and dilution for running the QUEFTS model calculated by excluding the upper and lower boundary line of N, P, and K nutrient internal efficiency data of barley, and it was then used to estimate the balanced nutrient uptake and the relationship between grain yields and nutrient accumulations, which were similar to those reported by Setiyono et al. [13] (the constant accumulation and dilution of N, P, and K were 40and 83 kg grain kg^{-1} N, 225 and 726 kg grain kg^{-1} P, and 29 and 125 kg grain kg^{-1} K) and Janssen et al. [12] (the constant accumulation and dilution of N, P, and K were 30 and 70 kg grain kg^{-1} N, 200 and 600 kg grain kg^{-1} P, and 30 and 120 kg grain kg^{-1} K). This finding is in agreement with that of Pathak et al. [11] who reported that wheat (YNA-YND, YPA-YPD and YKA-YKD) yielded 27-60, 162-390 and 20-50 kg of grain kg-1, respectively, and barley (YNA-YND, YPA-YPD and YKA-YKD, respectively 34-52, 182-365 and 44-127 kg grain kg^{-1} [32].

3.4. QUEFTS Model Validation. The relationship between observed and simulated nutrient uptakes was analyzed based on the current experiments conducted in 2015/16 in Wolaita. Figure 2 shows a good correlation between simulated and observed grain yields ($r^2 = 0.82$, 0.88, and 0.83) at Doga Mashido, Kokate, and Gurimo Koyisha, respectively. The calibrated yields of Doga Mashido, Kokate, and Gurimo

Table 3: Model parameterization by maximum yield accumulation and dilution in treatment and experimental sites.

Treatment	Yield accumulation (YKA) ($kg\ kg^{-1}$)		
	Doga Mashido	Kokate	Gurimo Koyisha
1. N0P0K25	44.34	39.96	46.17
2. N0P0K50	40.04	35.47	32.15
Yield accumulation (YPA)			
3. N0P10K0	171.31	136.4	142.56
4. N0P20K0	129.98	102.8	104.50
5. N0P30K0	100.32	97.28	93.514
Yield accumulation (YNA)			
6. N23P0K0	38.18	43.647	40.50
7. N46P0K0	32.25	37.341	36.30
	Yield dilution (YND) ($kg\ kg^{-1}$)		
Treatment	Doga Mashido	Kokate	Gurimo Koyisha
1. N0P10K25	48.13	54.31	46.275
2. N0P10K50	47.82	48.46	35.843
3. N0P20K25	51.96	48.96	31.467
4. N0P20K50	49.86	52.01	29.394
5. N0P30K25	49.02	61.93	29.394
6. N0P30K50	46.54	49.29	22.401
Yield dilution (YPD)			
1. N23P0K25	361.2	191.31	239.04
2. N23P0K50	329.42	167.82	239.04
3. N46P0K25	295.16	95.854	199.07
4. N46P0K50	247.63	96.673	168.77
Yield dilution (YKD)			
1. N23P10K0	31.86	41.05	80.04
2. N23P20K0	26.62	50.58	105.4
3. N23P30K0	36.33	63.05	61.01
4. N46P10K0	31.96	42.25	70.31
5. N46P20K0	49.24	42.45	102.70
6. N46P30K0	59.72	47.11	57.83

Koyisha, however, were the highest simulated grain yields (3650, 3134, and 3434 $kg{\cdot}ha^{-1}$) recorded in treatment of $N_{46}P_{30}K_{50}$, whereas the observed yields were 3090, 2800, and 2858 $kg{\cdot}ha^{-1}$, which can be attributed to soil nutrient supply, textural class, available P, exchangeable K and OC content, and soil pH in different locations. However, for all experiments, the observed N, P, and K uptake in the aboveground plant dry matter was scattered more or less equally around the line regression, suggesting that the observed values agreed well with the simulated nutrient uptake and there were no significant deviations between each other, and the simulated yield by QUEFTS tended to increase with increasing rates with respect to these soil fertility and management factors. It confirmed that the QUEFTS model could be used to calibrate the simulated yield and to improve fertilizer recommendations. To that end, we found that the QUEFTS model equations (1–5) fitted the simulated QUEFTS model outputs well ($r^2 = 0.82$, 0.88, and 0.83) for both simulated and observed yields. Janssen et al. [12] reported that the yield correlation between simulated and observed grains was ($r^2 \geq 70$) recommended for crops. This was confirmed by the increase as the simulated yield increased above 60–70% of the yield potential of wheat ([10] Abegaz et al., 2008 [9, 33]).

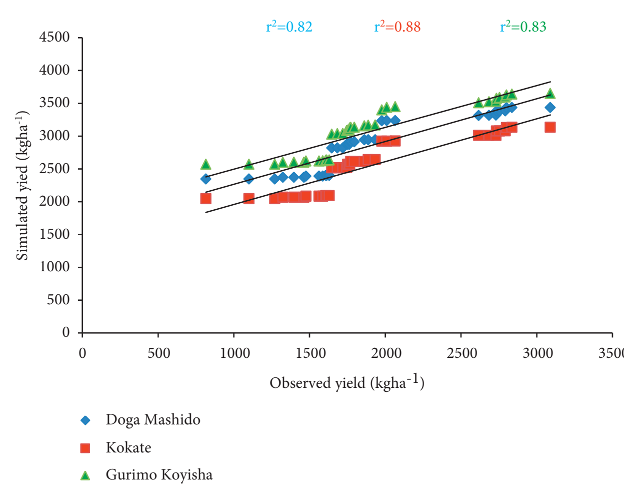

Figure 2: Relationships between the simulated and observed yields in the three sites.

3.5. Model Evaluation. The U-Theil values were 0.04, 0.16, and 0.28 at Doga Mashido, Kokate, and Gurimo Koyisha, respectively, indicating that the simulated and observed yields had significant variations among sites.

Notwithstanding, for all experiment sites, the simulated and observed yields were less than 1, suggesting that the U-Theil values were consistent with the simulated yield and there was a regression line between each other (Figure 2), similar to the results of Liu et al. [10] and Das et al. [9]. The results indicated that the QUEFTS model can be used to predict the optimal nutrient uptake, which is used to make fertilizer recommendations for barley.

4. Conclusions

In this study, a model has been established to estimate indigenous nutrient supplying capacity of soil N, P, and K requirements for barely and their use efficiencies of nutrients as affected by fertilizer levels for barley in Wolaita zone, southern Ethiopia. Data collected from different field experiments conducted in major barley production regions of Wolaita during 2015 were used to calibrate the model. Calibration of the QUEFTS model for barley required estimating slopes of two boundary lines describing the maximum accumulation and dilution of N, P, and K in relation to grain yields. The constant accumulation and dilution of N, P, and K were 32–51.9, 93–361.2, and 32–46.3 kg grain kg^{-1} for Doga Mashido, Kokate, and Gurimo Koyisha, respectively. Parameterization indicated that balanced nutrient requirements estimated by the QUEFTS model had a good correlation between simulated and observed grain yields ($r^2 = 0.82$, 0.88 and 0.83) at Doga Mashido, Kokate, and Gurimo Koyisha, respectively, while evaluation of the QUEFTS model in three different districts showed a first-rate agreement (U-Theil = 0.04, 0.16, and 0.28 for Doga Mashido, Kokate, and Gurimo Koyisha, respectively) between observed and simulated yields. As a result, these results would help to optimize barley yield and avoid nutrient depletion or excess application and also could improve nutrient use efficiency, economic benefits, and environmental sustainability.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Mesfin Kassa, Wasie Halie, and Fassil Kebede contributed equally to this study.

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