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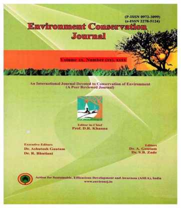

Profile distribution of soil organic carbon fractions under different landforms in the Meghalaya plateau of India

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ABSTRACT

Assessment of organic carbon fractions in soil provides the basis to ascertain vulnerability of an ecosystem to climate change. In the present study, we assessed SOC fractions in four pedons under contrasting landforms i.e., denudational low hill, upper plateau, lower plateau and valley in the Meghalaya plateau, India. Results indicated that soils of the studied pedons were acidic in nature, low in cation exchange capacity and base saturation. Further, surface (0-30 cm) soils were high in Walkley Black C (WBC) content (0.83-1.13%) in the studied pedons located under different landforms. The density of very labile carbon (VLC) fraction up to a depth of 150 cm was highest (49.22 Mg ha^{-1}) in pedon 2 (P2) located in the upper plateau under shifting cultivation while that of less labile carbon (LLC) was highest (50.25 Mg ha^{-1}) in pedon 4 (P4) in the valley under paddy cultivation. Higher densities of WBC and LLC in the valley (P4) as compared to other landforms in the study area indicate higher carbon sequestration potential of valley soil.

Introduction

Soil organic carbon (SOC) forms the largest terrestrial pool which plays an important role in soil fertility and carbon sequestration. The global SOC stock is estimated at 1500 Pg in the upper 1m soil depth and it is three times of the atmospheric pool and two times of the biotic pool (Lal, 2008). The SOC plays an important role in carbon cycling, soil aggregate formation, water retention and soil biodiversity; and affects various physical, chemical, and biological properties of soil (Smith *et al.,* 2008; Singh *et al*., 2018). It has been recognized that any small change in the SOC stock can significantly affect the atmospheric CO_2 concentration and leads to global warming (Dhillon and von Wuehlisch, 2013). The SOC stocks in soils are influenced by soil types, climate, vegetation, topography and land use management (Singh *et al.,* 2011; Singh and Benbi, 2018; Reza *et al*., 2019). Conversion of forest and grassland into agricultural lands may lead to depletion of SOC stock (Chaudhury *et al*., 2016; Ghosh *et al*., 2020) mainly due to less organic matter input (Singh *et al*., 2011) and exposure of protected SOC by tillage operations to microbial decomposition (Pandey *et al*., 2010). It is

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reported that adoption of appropriate land use and soil management practices may augment C sequestration in soil (Powlson *et al*., 2011; Singh and Benbi, 2018). Therefore, identification of appropriate land use system under appropriate landscape position with high carbon sequestration potential is of tremendous importance in view of climate change.

Soil organic matter (SOM) is composed of various materials of different biochemistry which vary in their rate of decomposition by microorganisms. Therefore, quantitative knowledge of SOC fractions is important to understand the SOM decomposition and stabilization process in the soil (Poeplau *et al.,* 2018). Based on residence time, SOC is categorized into labile and non-labile carbon fractions (Chan *et al.,* 2001). The easily decomposable organic matter which has rapid turnover rates called labile carbon fraction and it plays an important role in nutrient cycling (Majumdar *et al.,* 2008). On the other hand, non-labile or recalcitrant fraction of SOC is highly resistant to microbial decomposition and remains unaffected by management changes. This fraction is considered to be important for the soil carbon sequestration (Paul *et al.,* 2001). Among different physical, chemical and biological methods of separation of SOC fractions, chemical methods are the most common. Chemical methods use different concentrations of acids to hydrolyse the carbon (Paul *et al.,* 2001), digest the soil with permanganate (Weil *et al.,* 2003) or extract it with hot water (Gregorich *et al.,* 2003). Chemical methods are based on the principle that SOM fraction which is readily decomposed by the microbial enzyme is also easily hydrolyzed by acids or solubilized by hot water (McLauchlan *et al.,* 2004). Several studies have reported that subsurface layer (below 15 cm) store more than 70 % of SOC (Jobbagy and Jackson, 2000) and considered more important for C sequestration due to the fact that SOC in subsoil is more stable and resistant to microbial decomposition (Datta *et al*., 2015; Ghosh *et al.,* 2020). Thus, the details of SOC distribution within the soil profile are important for carbon budgeting and for the management of ecosystem services (Kukal *et al.,* 2014). Besides, quantification of SOC stocks and its fractions under differential landforms and land uses helps in identifying the suitable and potential niche area for sequestration of SOC. Earlier, Gupta and Rao (1994) quantified the SOC stock of Indian soils utilizing the data from 48 benchmark soil series across the country and reported the SOC stock at 24.3 Pg ranging from surface to average depth of 0.44 – 1.86 m. Bhattacharyya *et al.* (2000) estimated the SOC stock of Indian soils to 29.97 Pg in the 0-150 cm depth from 60 Agro-Ecological Sub Regions (AESRs) using the point data from benchmark soils and other soils reported in the literature in the AESRs.

North Eastern Region (NER) of India has wide variations in climate and physiography which supports the growth of dense vegetation. Soils of the NER are very high in SOC content and estimated to >1 % in 98.54 % area and > 2.5 % in 14.4% area in the surface layer. Similarly, 76.5% area had SOC density of 20– 40 Mg/ha, and 8% area had a very high SOC density of 40–60 Mg/ha (Chaudhuri *et al.,* 2013). The NER is considered as green belt due to its relatively high SOC content (Bhattacharyya *et al.,* 2008). However, accelerated deforestation, unscientific land-use, and reduced fallow period under shifting cultivation are of major concern in relation to their effects on SOC stocks of NER (Ray *et al*., 2021a). Erosion and redistribution of soil particles influence not only the quantity of SOC but also its quality along hill slopes (Singh and Benbi, 2018). At the erosional portions of the landscape, exposed mineral surfaces accumulate fresh and labile C which become part of new top soil (Fissore *et al*., 2017) whereas at depositional portions C is protected from decomposition with longer mean residence time (Doetterl *et al*., 2012). Bhattacharyya *et al.* (2010) suggested for maintaining the threshold level of SOC stocks ranging from 50 – 60 Mg/ha in the areas under the green belt for the protection of natural ecosystem. However, information is very limited on the depth distribution of SOC and its fractions under different landform positions in the NER. Therefore, the present study was undertaken to quantify the profile distribution of different SOC fractions under contrasting landforms in a part of the Meghalaya plateau, Northeastern India.

Material and Methods

The study area comes under per-humid sub-tropical Northeastern hill region of India. For the present research work, soil samples were collected from different soil depth up to a depth of 150 cm from representative pedons in contrasting landforms in the Jirang block of Ri-Bhoi district, Meghalaya. Detailed site characteristics of the soils are given in Table 1. For determining bulk density (BD) of soil, samples were collected from each depth using the soil core sampler during soil sampling. The collected soil samples were air-dried, grounded, passed through a 2 mm sieve and used for characterization of different physical and chemical properties of soil. A part of the soil sample was finely grounded and completely passed through 100 mesh sieves for the determination of SOC. Soil BD was determined by undisturbed core method (Blake and Hartge, 1986). The soil samples were analyzed for important physical and chemical properties following standard procedures (Jackson, 1973). The concentration of SOC (WBC) of each of the soil samples was determined through the wet oxidation method (Walkley and Black, 1934). The concentration of organic carbon fractions was determined by using 5, 10, and 20 mL of concentrated H_2SO_4 which corresponds to the acid-aqueous solution of 12 N, 18 N, and 24 N H_2SO_4 (Chan *et al.,* 2001). Organic C oxidized by 12 N H_2SO_4 has been considered as a very labile C (VLC) fraction; whereas the difference between C oxidized by 18 N H_2SO_4 and 12 N H_2SO_4 has been considered as labile C (LC) fraction. Besides, the difference between C oxidized by 24 N H_2SO_4 and 18 N H_2SO_4 has been considered as less-labile C (LLC) fraction. The depth-wise density of each SOC fraction was calculated using the following equation:

$$\text{SOC density (Mg ha}^{-1}) = \text{SOC (\%)} \times \text{BD (Mg m}^{-3}) \times \text{soil depth (m)} \times 100$$

SOC density for entire soil profile (up to 150 cm depth) was determined by summing up the SOC density of all the soil horizons of the profile.

Table 1: Soil type and site characteristics of the studied pedons (Jena *et al.,* 2015)

Pedon No	Soil type	Landform	Slope gradient (%)	Drainage	Present land use
P1	*Typic Hapludults*	Denudational low hill	25-33	Well	Forest
P2	*Typic Kandiudults*	Upper plateau	10-15	Well	Shifting cultivation
P3	*Fluventic Endoaquepts*	Lower plateau	5-8	Imperfectly drained	Paddy
P4	*Typic Endoaqualfs*	Valley	1-3	Imperfectly drained	Paddy

Results and Discussion

Soil physical and chemical properties: Data on important soil physical and chemical properties are presented in Table 2. The sand content in the soils under different landforms varied from 11.36 % to 42.13 % in surface layers (0-30 cm) whereas it varied from 7.78 % to 70.96 % in the sub-surface layers. Sand content decreased with depth in the highly weathered soil of pedon P1 on the denudational low hill and pedon P2 on the upper plateau and increased with depth in the pedon P3 on the lower plateau and irregular pattern was recorded in pedon P4 on the valley. Silt content in the surface layer varied from 19.37 % to 45.07 %, whereas in sub-surface layers it varied from 10.57 % to 43.63 %. The clay content in soils under different landforms varied from 38.50 % to 43.87 % in 0-30 cm depth; 36.50 % to 60.00% in 30-60 cm; 23.45% to 57.30 % in 60-90 cm; 18.48% to 60.47 % in 90-150 cm soil depth. An increase in the clay content with depth in the pedons P1 and P2 indicated the illuviation of clay in the denudational low hill and upper plateau (Jena *et al.,* 2016).

In the 0-30 cm soil depth, variation in bulk density (BD) was not observed among the soils under different landforms while at subsurface BD varied from 1.18 Mg m^{-3} to 1.54 Mg m^{-3}. An increase in the bulk density with depth was observed in pedon P3 on the lower plateau; the irregular pattern was observed in pedon P2 on the upper plateau and P4 on the valley, while subsurface has a lower bulk density in pedon P1 on the denudational low hill. An increase in the soil bulk density in the lower depth of soil profile was due to the low organic matter content and compaction from the pressure of upper layers (Singh and Agrawal, 2005). Soil reaction (pH 1:2.5 soil:water ratio) of the pedons

Table 2: Important physical and chemical properties of the studied pedons

Pedon No	Sand (%)	Silt (%)	Clay (%)	BD (Mgm^{-3})	pH	WBC (%)	CEC ($cmol_c kg^{-1}$)	Clay CEC ($cmol_c kg^{-1}$)	BS (%)
0-30 cm									
P1	22.03	34.10	43.87	1.32	5.3	0.83	9.22	22	37.56
P2	42.13	19.37	38.50	1.33	4.8	1.00	7.61	20	13.76
P3	11.36	45.07	43.57	1.35	5.1	1.13	11.92	27	31.56
P4	16.80	44.70	38.50	1.33	4.9	1.00	10.19	26	40.13
Mean	23.08	35.81	41.11	1.33	5.0	0.99	9.73	24	30.75
30-60 cm									
P1	10.12	29.88	60.00	1.25	5.6	0.47	10.35	17	40.12
P2	35.00	17.90	47.10	1.27	4.8	0.51	7.07	15	12.64
P3	14.63	41.87	43.50	1.43	5.5	0.50	10.29	24	44.33
P4	23.30	40.20	36.50	1.54	5.9	0.38	9.41	26	55.00
Mean	20.76	32.46	46.78	1.37	5.4	0.47	9.28	20	38.02
60-90 cm									
P1	7.78	34.92	57.30	1.25	5.5	0.37	10.23	18	38.85
P2	33.94	19.26	46.80	1.18	4.8	0.35	6.76	14	12.70
P3	55.60	20.95	23.45	1.46	5.5	0.24	5.79	24	51.26
P4	10.70	43.63	45.67	1.50	5.6	0.41	10.68	23	76.73
Mean	27.01	29.69	43.30	1.35	5.3	0.34	8.37	20	44.89
90-150 cm									
P1	8.13	31.40	60.47	1.25	5.5	0.32	10.65	18	46.22
P2	37.22	19.57	43.21	1.23	5.2	0.25	6.19	14	11.87
P3	70.96	10.57	18.48	1.54	5.5	0.20	4.83	25	43.36
P4	11.53	42.63	45.83	1.48	5.7	0.28	11.20	24	64.66
Mean	31.96	26.04	42.00	1.38	5.5	0.26	8.22	20	41.53

varied from 4.8 to 5.3 in 0-30 cm; 4.8 to 5.9 in 30-60 cm; 4.8 to 5.6 in 60-90 cm and 5.2-5.7 in 90-150 cm soil depth. In general, the soil pH increased in all the pedons with depth which might be due to the leaching and accumulation of basic cations in the lower depth (Datta *et al.,* 2015). Soil reaction was acidic in all the studied pedons on different landforms. High annual rainfall in the study area under per-humid climatic condition and associated leaching of bases from soil are attributed to the acidic soil reaction (Bandyopadhyay *et al*., 2018). Highest content of WBC for surface soil (0-30 cm) was observed in pedon P3 on the lower plateau and the mean value was 0.99 % indicating accumulation of carbon in the surface layer. The WBC content decreased in all the pedons with depth and mean values from surface to subsoil were 0.99, 0.47, 0.34 and 0.26% for 0-30, 30-60, 60-90 and 90-150 cm soil depth, respectively. Jena *et al.* (2015) also reported medium (40% area) to high (60% area) WBC content in the surface layer of Jirang block of Ri-Bhoi district of Meghalaya. A decrease in the WBC with depth in all the pedons might be due to the less organic matter input in the lower layers (Jobbagy and Jackson, 2000). Cation exchange capacity (CEC) varied from 7.61 to 11.92 $cmol_c kg^{-1}$ in 0-30 cm; 7.07 to 10.35 $cmol_c kg^{-1}$ in 30-60 cm; 5.79 to 10.68 $cmol_c kg^{-1}$in 60-90 cm; and 4.83 to 11.20 $cmol_c kg^{-1}$ in 90-150 cm soil depth. The values of CEC decreased with depth in pedons P2 and P3; increased with depth in pedon P1 and the irregular pattern was observed in case of pedon P4. Variation in CEC might be due to the variation in clay content, presence of pseudo-aggregates of sesquioxides, and coating of clay minerals with amorphous oxides of iron and aluminium (Liu *et al.,* 2020). Clay CEC ranged from 14 to 27 $cmol_c kg^{-1}$ clay in the studied pedons. The clay CEC values less than 16 indicates the dominance of low activity clay in soil (Sarkar *et al*., 2002; Ray *et al*., 2021b), which was associated with pedon P2. Base saturation (BS) varied from 13.76 to 40.13 % in 0-

30 cm; 12.64 to 55.00 % in 30-60 cm; 12.70 to 76.73 % in 60-90 cm; and 11.87 to 64.66 % in 90-150 cm soil depth. BS increased with depth in pedons P3 and P4 up to 90 cm; decreased with depth in pedon P2 while irregular pattern was observed in pedon P1.

SOC fractions: Data of the SOC fractions is presented in the Table 3. The mean values of VLC, LC and LLC in the studied pedons were 0.41, 0.15 and 0.43 %, respectively in the surface (0-30 cm) layer and decreased to 0.11, 0.04 and 0.12 %, respectively in 90-150 cm soil depth. Among the different SOC fractions LC was lowest in all the studied pedons. A decrease in SOC fractions with depth might be due to the less organic matter input in the lower layers (Jobbagy and Jackson, 2000). Slope of the landforms is one of the important factors governing runoff and soil erosion, and thereby affecting SOC fractions in soils under different landforms (Reza *et al.,* 2020).

Table 3: Depth wise soil organic carbon (SOC) fractions in the studied pedons

Pedon No	**0-30 cm**			**30-60 cm**		
	VLC (%)	**LC (%)**	**LLC (%)**	**VLC (%)**	**LC (%)**	**LLC (%)**
P1	0.31	0.11	0.41	0.20	0.08	0.19
P2	0.52	0.05	0.43	0.29	0.08	0.14
P3	0.43	0.24	0.45	0.14	0.13	0.23
P4	0.38	0.19	0.43	0.15	0.06	0.17
Mean	0.41	0.15	0.43	0.19	0.09	0.18
	60-90 cm			**90-150 cm**		
P1	0.17	0.07	0.14	0.15	0.01	0.16
P2	0.21	0.05	0.09	0.14	0.07	0.04
P3	0.08	0.05	0.11	0.05	0.03	0.11
P4	0.13	0.04	0.24	0.09	0.03	0.16
Mean	0.15	0.05	0.14	0.11	0.04	0.12

VLC-very labile C; LC-labile C; LLC-less labile C

The density of the SOC fractions varied with landform and soil depth (Table 4). In the 0-30 cm soil depth VLC density varied from 12.40 Mg ha^{-1} in the pedon P1 on the denudational low hill to 20.67 Mg ha^{-1} in case of pedon P2 on the upper plateau. The density of LC fraction varied from 2.13 Mg ha^{-1} in pedon P2 on the upper plateau to 9.80 Mg ha^{-1} in pedon P3 on the lower plateau. The density of the LLC fraction varied from 16.15 Mg ha^{-1} in pedon P1 on the denudational low hill to 18.09 Mg ha^{-1} in pedon P3 on the lower plateau. The WBC density in the surface layer varied from 33.05 Mg ha^{-1} in pedon P1 on the denudational low hill to 45.44 Mg ha^{-1} in the pedon P3 on the lower plateau. In the 30-60 cm soil depth density of VLC varied from 5.93 Mg ha^{-1} in case of pedon P3 on the lower plateau to 10.90 Mg ha^{-1} in the pedon P2 on the upper plateau. The density of LC varied from 2.77 Mg ha^{-1} in pedon P4 on the valley to the 5.47 Mg ha^{-1} in pedon P3 on the lower plateau. The density of LLC varied from 5.49 Mg ha^{-1} in pedon P2 on the upper plateau to the 10.04 Mg ha^{-1} in pedon P3 on the lower plateau. WBC density varied from 17.54 Mg ha^{-1} in pedon P4 on the valley to the 21.44 Mg ha^{-1} in pedon P3 on the lower plateau.

In the 60-90 cm soil depth density of VLC varied from 3.55 Mg ha^{-1} in pedon P3 on the lower plateau to 7.34 Mg ha^{-1} in pedon P2 on the upper plateau. The density of LC varied from 1.65 Mg ha^{-1} in pedon P4 on the valley to 2.48 Mg ha^{-1}in pedon P1 on the denudational low hill. The density of LLC varied from 3.25 Mg ha^{-1} in pedon P2 on the upper plateau to 10.66 Mg ha^{-1} in pedon P4 on the valley. WBC density varied from 10.44 Mg ha^{-1} in pedon P3 to 18.32 Mg ha^{-1} in pedon P4 on the valley. In the 90-150 cm soil depth density of VLC varied from 5.03 Mg ha^{-1} in pedon P3 on lower plateau to 11.28 Mg ha^{-1} in pedon P1 on the denudational low hill. The density of LC varied from 0.85 Mg ha^{-1} in pedon P1 on the denudational low hill to 5.27 Mg ha^{-1} in pedon P2 on the upper plateau. LLC density varied from 3.16 Mg ha^{-1} in pedon P2 on the upper plateau to the 14.54 Mg ha^{-1} in pedon P4 on the valley. WBC density varied from 18.23 Mg ha^{-1} in

Table 4: Depth wise density of soil organic carbon (SOC) fractions in the studied pedons

Pedon No	0-30 cm				30-60 cm			
	VLC (Mg ha^{-1})	LC (Mg ha^{-1})	LLC (Mg ha^{-1})	WBC (Mg ha^{-1})	VLC (Mg ha^{-1})	LC (Mg ha^{-1})	LLC (Mg ha^{-1})	WBC (Mg ha^{-1})
P1	12.40	4.51	16.15	33.05	7.43	3.15	7.05	17.63
P2	20.67	2.13	17.07	39.87	10.90	3.05	5.49	19.44
P3	17.55	9.80	18.09	45.44	5.93	5.47	10.04	21.44
P4	15.20	7.60	17.20	40.00	6.92	2.77	7.85	17.54
Mean	16.45	6.01	17.13	39.59	7.79	3.61	7.61	19.01
	60-90 cm				90-150 cm			
P1	6.30	2.48	5.25	14.03	11.28	0.85	11.99	24.11
P2	7.34	1.76	3.25	12.35	10.31	5.27	3.16	18.74
P3	3.55	2.24	4.65	10.44	5.03	2.77	10.43	18.23
P4	6.01	1.65	10.66	18.32	7.86	2.67	14.54	25.07
Mean	5.80	2.03	5.95	13.78	8.62	2.89	10.03	21.54

VLC-very labile C; LC- labile C; LLC-less labile C; WBC- Walkley Black C

Table 5: Density of SOC fractions in the studied pedons up to 150 cm depth

Pedon No	VLC (Mg ha^{-1})	LC (Mg ha^{-1})	LLC (Mg ha^{-1})	WBC (Mg ha^{-1})
P1	37.40	10.98	40.44	88.81
P2	49.22	12.22	28.96	90.40
P3	32.06	20.28	43.21	95.55
P4	35.99	14.69	50.25	100.93
Mean	38.67	14.54	40.71	93.92

VLC-very labile C; LC- labile C; LLC-less labile C; WBC- Walkley Black C

pedon P3 on the lower plateau to 25.07 Mg ha^{-1} in pedon P4 on the valley. The overall distribution of VLC, LC, LLC and WBC density up to 150 cm soil depth is presented in the Table 5. The density of VLC ranged from 32.06 Mg ha^{-1} in case of pedon P3 on the lower plateau to 49.22 Mg ha^{-1} in pedon P2 on the upper plateau with the mean value of 38.67 Mg ha^{-1}. The density of LC varied from 10.98 Mg ha^{-1} in pedon P1 on the denudational low hill to 20.28 Mg ha^{-1} under pedon P3 on the lower plateau. The density of LLC varied from 28.96 Mg ha^{-1} in pedon P2 on the upper plateau to 50.25 Mg ha^{-1} under the pedon P4 on the valley with the mean value of 40.71 Mg ha^{-1}. The density of WBC ranged from 88.81 Mg ha^{-1} in case of pedon P1 on the denudational low hill to the 100.93 Mg ha^{-1} in pedon P4 on the valley with the mean value of 93.92 Mg ha^{-1}. The mean value of the density of the different OC fractions followed the order as WBC>LLC>VLC>LC across different landforms.

The slope of the landform affects the amount and quality of SOC due to variation in hydrology, solar radiation, and vegetation. In the humid subtropical climate, erosion from the steep slope positions and deposition at the gentle slopes and valley positions are the important factors for redistribution of SOC and other plant nutrients (Reza *et al.,* 2014). Shifting cultivation at the steep slopes in the study area further aggravates the soil erosion. Relatively lower values of WBC density and LLC density in soils on the denudational low hill and upper plateau with higher slope classes might have been due to accelerated erosion (Singh *et al.,* 2011). Shifting cultivation at upper plateau might have exposed the protected carbon for the microbial decomposition due to accelerated soil erosion (Fierer *et al.,* 2003) and dominance of low activity clays in such soil might have hindered the process to form clay humus complex (Singh *et al*., 2018), which resulted in lower value of LLC density in pedon P2. Relatively higher densities of WBC and LLC in the pedon P4 on valley might be due the deposition and burial of SOC, and reduced microbial activity under anaerobic condition in paddy cultivation (Fissore *et al.,* 2017). Sahrawat (2004) also reported the accumulation of OC in the valley under paddy cultivation under temperate climate and poor drainage condition. The revegetation of degraded slopes with increased fallow period under shifting cultivation is one of the important strategies to control soil erosion with the recovery of the degraded ecosystem through build-up of recalcitrant pool of organic carbon in soil (Singh and Benbi, 2018).

Conclusion

Results showed that soils of the studied pedons were high in SOC (WBC) content in the surface layer, acidic in reaction, and have low cation exchange capacity with low base saturation across the landforms. Different SOC fractions were influenced by landform positions and land uses. Relatively higher densities of less labile carbon (LLC) and WBC of soils under lower plateau and valley as compared to the soils under denudational low hill and upper plateau indicate that the soil organic carbon in the valley and lower plateau are more protective. Further, relatively higher density of very labile carbon (VLC) in shifting cultivated soils under upper plateau indicates the potential vulnerability of the ecosystem to climate change.

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