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Straw application and soil organic carbon change: A meta-analysis

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Abstract: Straw return is considered an effective way to improve the soil organic carbon (SOC) content of farmland. Most studies have suggested that a straw application increases the SOC content; however, some suggest that a straw application reduces the SOC content when used in combination with mineral fertilisation. Therefore, a meta-analysis of the effect of a straw application on the SOC change is needed. This study comprises a meta-analysis of 115 observations from 65 research articles worldwide. Straw applications can significantly increase the proportion of the SOC in the soil. Straw applications caused a significant microbial biomass carbon (MBC) increase in tropical and warm climatic zones. The MBC increase was higher than the SOC increase. For agriculture, the most important soil functions are the maintenance of the crop productivity, the nutrient and water transformation, the biological flora and activity, and the maintenance of the microbial abundance and activity. These functions should be prioritised in order to maintain the SOC function and services. Straw applications should not be excessive, especially when combined with mineral fertilisation, in order to avoid the loss of carbon from the straw in the form of greenhouse gases. A large amount of unused fertiliser also leads to a series of environmental problems.

Keywords: mineral fertilisation; residue; SOC; stalk; straw

Many studies have shown that the continuous increase in greenhouse gases (GHGs) in the Earth's atmosphere has caused global warming (Smith & Fang 2010; Ma et al. 2019; Matysek et al. 2019; Zhuang et al. 2020). The carbon exchange between soil carbon pools and atmospheric carbon pools can significantly affect climate change (Hannam et al. 2019; Doetterl et al. 2012). Therefore, studies have proposed that soil could be utilised to store large amounts of soil organic carbon (SOC), thereby reducing the CO_2 in the atmosphere (Pan et al. 2004; Drake et al. 2019; Walker et al. 2019). When focusing on the world's environmental problems, however, we should also explore ways to solve the issue of managing food production for a rapidly increasing global population (Lawson 2013; Brain & Anderson 2019). With population growth and the development of society, the world's demand for food is increasing significantly. Based on the current trend, it is predicted that food production will need to be more than double by 2050 (Tilman et al. 2011; Brain & Anderson 2019). Therefore, scholars suggest that we should focus on the protection of soil quality in order to achieve the goal of sustainable development. Since SOC is

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closely related to soil quality, it can be utilised as an important soil quality indicator (de Paul Obade 2019).

Estimated global soil data indicate a total SOC storage of 684–724 Pg of carbon in the upper 30 cm of soils worldwide (Batjes 1996). Compared with other terrestrial ecosystems, farmland soils play an important role in global carbon and nitrogen cycling. Approximately two-thirds of the CO_2 exchanged between the terrestrial ecosystem and the atmosphere is released by soil organic matter decomposition (Post et al. 1982). The farmland ecosystem is an important source and sink of CO_2 (Dong & Ouyang 2005; Bi et al. 2019). Farmland soil is also the most active part of the global carbon pool. The farmland soil carbon pool is influenced by both natural and human factors and can be reduced by human intervention (Han et al. 2018).

Straw return is considered to be an effective way to improve the SOC content of farmlands (Fei et al. 2010; Song et al. 2019). In 2014, a meta-analysis identified the relationship between the straw return and SOC sequestration (Liu et al. 2014). Since then, more than twenty papers concerning the straw application effect on the SOC change have been published (Jiang et al. 2017; Tian et al. 2018). More importantly, two studies suggested that a straw application reduces the SOC content when used in conjunction with mineral fertilisation (Campbell et al. 2001; Yu et al. 2006). Because the focus and purpose of the 2014 meta-analysis was the straw carbon input, these two articles were excluded from that study (Liu et al. 2014), necessitating a meta-analysis of the straw application effect on the SOC change.

MATERIAL AND METHODS

Database and data extraction. The present investigation focused on published studies. Two authors independently performed electronic searches of the PubMed, Science Direct, and ProQuest bibliographic databases for the period January 1, 1970–May 31, 2020. The search terms in the title OR abstract were as follows: (straw OR straws OR stalk OR stalks OR residue OR residues) AND carbon AND organic AND (soil OR ground). Table 1 lists the studies that were excluded for various reasons. When the data required an estimation from the graphs, DataThief software was used (Maillard & Angers 2014). When two articles presented the same experiment and the same data, the older study was excluded.

Data analysis. Since the studies were making different comparisons, the controls were considered to be conditions with no fertilisation and/or mineral fertilisation. We defined 4 datasets in this study: the SOC response to a straw application compared with an unfertilised control and a mineral fertilisation treatment (S-Z and SM-M; S – straw application; Z – unfertilised control; SM – straw application and mineral fertilisation treatment; M – mineral fertilisation treatment); a straw application compared with a mineral fertilisation treatment (S-M); and a mineral fertilisation treatment compared with an unfertilised control (M-Z).

Straw treatments and controls were classified into 3 climate zones: cool temperate (latitude > 50), warm temperate (latitude 35–50), and tropical (latitude 0–35) (Maillard & Angers 2014). We also considered straw with different compositions to allow the meta-analysis to address different straw types (Aulakh et al. 2001). Considering the wide variation in the SOC concentrations (Yu et al. 2006), the SOC contents were recalculated based on the ratio of the treatment and control in order to better reflect the effects (Liu et al. 2014). The average SOC change rate (SCR) for each of the 4 datasets was calculated using the following equation:

$$\overline{SCR} = \sum_{i=1}^{n}\left(\frac{SOC_S - SOC_C}{SOC_C}\right)\times\frac{1}{n}\times 100\%$$

Table 1. Inclusion and exclusion criteria

Inclusion	Exclusion
Straw or residue included	straw or residue not used, biochar or biogas residue is used
English	non-English
Control group included, straw treatments and controls had the same soil type and management	no control group
SOC data included	no SOC data
Original research	review

SOC – soil organic carbon

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where:

SOC_S – the SOC concentration of the straw application,

SOC_C – the unfertilised control SOC concentration.

Standard errors (SE) were calculated by

$$SE = \frac{\sqrt{\sum_{i=1}^{n}\left[\left(\frac{SOC_S - SOC_C}{SOC_C}\right)_i - \overline{SCR}\right]^2}}{n}$$

Meta-analyses were conducted by Review Manager (Ver. 5.3, Copenhagen: Nordic Cochrane Centre, Cochrane Collaboration) and the R 3.2.2 software (R Development Core Team, Auckland, New Zealand). The heterogeneity of the effect size distribution was examined using the Higgins method as well as the *P*-value and I^2 statistics (de la Cruz et al. 2017). When heterogeneity was found, the random effect model was used, whereas the fixed effects model was selected for non-heterogeneity.

The data for S-Z and SM-M were merged when conducting calculations of the different climatic zones and straw types. Since the microbial biomass carbon (MBC) is the most important part of the SOC, we also considered the change in the MBC under different climatic zones. The linear relationships between the straw application and the SOC change were determined using Microsoft Excel (Ver. 365, Microsoft Corp., Santa Rosa, CA, USA).

RESULTS

There were 3 725 findings from the literature search, which initially resulted in 62 articles (Figure S1 in the Electronic Supplementary Material (ESM)). The geographical locations of the experimental sites are

(A)

Study of subgroup	*n*	Risk difference	SE	Weight (%)	Risk Difference IV, Random, 95%CI
M-Z	16	0.2174	0.0826	19.7	0.22 (0.06, 0.38)
S-M	10	0.005	0.05	26.1	0.01 (−0.09, 0.10)
S-Z	28	0.311	0.0625	23.6	0.31 (0.19, 0.43)
SM-M	56	0.179	0.0243	30.5	0.18 (0.13, 0.23)
Total (95% CI)				100	0.17 (0.06, 0.29)

Heterogenity: $\tau^2 = 0.01$, $\chi^2 = 16.42$, df = 3 ($P = 0.0009$); $I^2 = 82\%$

Test for overall effect: Z = 2.93 ($P = 0.003$)

(B)

Study of subgroup	*n*	Risk difference	SE	Weight (%)	Risk Difference IV, Random, 95%CI
Cool temperate	5	0.0076	0.0216	34.5	0.01 (−0.03, 0.05)
Tropoical	45	0.2481	0.0408	32.7	0.25 (0.17, 0.33)
Warm temperate	30	0.2224	0.0393	32.9	0.22 (0.15, 0.30)
Total (95% CI)				100	0.16 (−0.01, 0.33)

Heterogenity: $\tau^2 = 0.02$, $\chi^2 = 40.91$, df = 2 ($P < 0.00001$); $I^2 = 95\%$

Test for overall effect: Z = 1.80 ($P = 0.07$)

(C)

Study of subgroup	*n*	Risk difference	SE	Weight (%)	Risk Difference IV, Random, 95%CI
Maize	22	0.2549	0.0408	62.3	0.25 (0.17, 0.33)
Rice	15	0.2814	0.1	10.4	0.28 (0.09, 0.48)
Wheat	18	0.2424	0.0616	27.3	0.24 (0.12, 0.36)
Total (95% CI)				100	0.25 (0.19, 0.32)

Heterogenity: $\chi^2 = 0.11$, df = 2 ($P = 0.95$); $I^2 = 0\%$

Test for overall effect: Z = 7.89 ($P < 0.00001$)

(D)

Study of subgroup	*n*	Risk difference	SE	Weight (%)	Risk Difference IV, Random, 95%CI
Tropical	29	0.5357	0.1198	51.2	0.54 (0.30, 0.77)
Warm temperate	12	0.4883	0.1228	48.8	0.49 (0.25, 0.73)
Total (95% CI)				100	0.51 (0.34, 0.68)

Heterogenity: $\chi^2 = 0.08$, df = 1 ($P = 0.78$); $I^2 = 0\%$

Test for overall effect: Z = 5.98 ($P < 0.00001$)

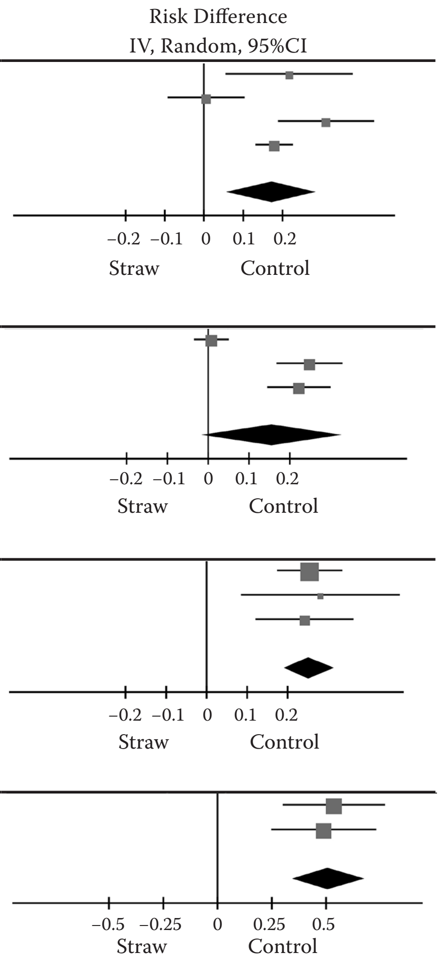

Figure 1. Forest plot of the meta-analysis: (A) straw application effect on the soil organic carbon (SOC) change for the different datasets, (B) straw application effect on the SOC change in the different climates, (C) straw application effect on the SOC change for the different straw types, and (D) straw application effect on the soil microbial biomass carbon change in the different climates; CI – 95% confidence interval; SE – standard error

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depicted in Figure S2 in the ESM. The studies meeting the criteria are listed in Table S1 in the ESM.

The 115 observations from the 65 included studies were separated into four datasets (S-Z, SM-M, S-M, and M-Z) in order to evaluate the SOC change response to the straw application (Figure 1A). There was significant improvement in the SOC content in the S-Z, SM-M, and M-Z datasets; however, there was no significant difference between the straw application and the mineral fertilisation (S-M). Overall, a straw application can significantly increase the percentage of the SOC content (95% CI (confidence interval), 0.06–0.29). The analysis also indicated that the tropical and warm climatic zones had the greatest impact on the percentage of the SOC content difference (as seen in Figure 1B), but there was little difference in the cool temperate zone. These results indicate that a straw application can increase the SOC relative to the control. In addition, all of the different types of straw were shown to have a significant improvement on the SOC content (Figure 1C; 95% CI, 0.19–0.32). In the tropical and warm climatic zones, the straw applications resulted in a significant MBC percent increase (Figure 1D; 95% CI, 0.34–0.68). In particular, the MBC percent increase (Figure 1D, 51%) was higher than that of the SOC one (Figure 1B, 16%). A straw application increases not only labile part of the SOC (MBC), but also the stable SOC (humus). Only in the cool temperature zone, it has no effect.

Our analysis uncovered a significant quadratic relationship between the straw application and the SOC content in the S-Z (Figure 2A, n = 26) and SM-M (Figure 2B, n = 74) datasets. The straw application and MBC percent also had a quadratic relationship (Figure 2C, n = 38). A straw application at 4–8 Mg/ha produced the highest SOC or MBC increase rate (Figures 2A–C).

DISCUSSION

The transformation and deposition mechanism of SOC was considered to include the following four aspects: (1) physical protection, including the formation of macroaggregates by microaggregates under the bonding of organic matter, the inclusion of organic matter by macroaggregates, and the establishment of physical barriers between microorganisms, enzymes, and their substrates to protect organic matter from decomposition (Schnecker et al. 2015); (2) chemical protection, which changes the original structure of the organic matter through the interaction of organic and inorganic molecules, thus reducing the availability of the organic matter (Guggenberger & Kaiser 2003); (3) the fact that the structure of the SOC is not easily decomposed by biochemical processes (Poirier et al. 2003); and (4) the microbial metabolic mechanism, in which the organic carbon cycle is driven by microorganisms, firstly through utilisation for their own growth (i.e.,

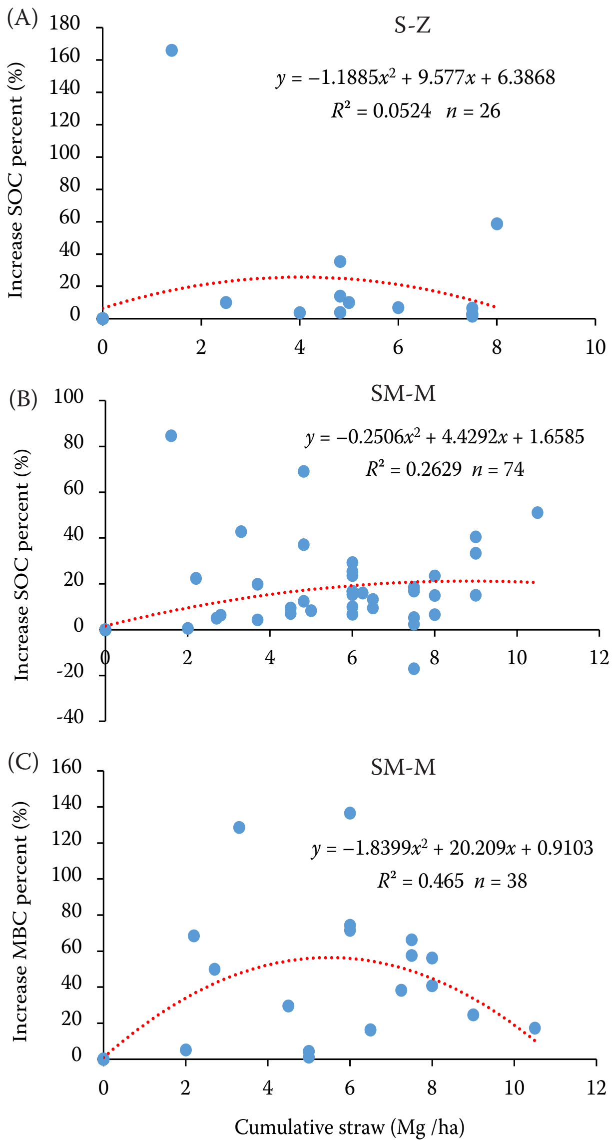

Figure 2. Relationships between the straw application and the soil organic carbon change for the (A) S-Z and (B) SM-M datasets, and (C) the relationship between the straw application and the soil microbial biomass carbon change in the SM-M dataset

S – straw application; Z – unfertilised control; SM – straw application and mineral fertilisation treatment; M – mineral fertilisation treatment

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the immobilisation of organic carbon) and secondly through conversion into CO_2 and arsenic through respiration (i.e., the mineralisation of organic carbon) (Menendez-Serra et al. 2019). Our results revealed that straw applications can increase the SOC relative to the control (S-Z and SM-M).

At present, SOC is generally divided into: (1) active organic carbon pools (mainly microbial biomass carbon, soluble organic carbon, mineralisable carbon, and carbohydrates), which move easily through the soil, have poor stability, and are closely linked with the ability of the soil fertiliser supply; (2) stable organic carbon pools (mainly particulate organic carbon and carbohydrates), in which the carbohydrates and lipids are dominant and the conversion rate of the organic carbon is relatively slow; and (3) inert organic carbon pools, which are dominated by carbon fractions such as lignin, humus, polyphenols, and polysaccharides that have very slow organic carbon decomposition rates (Paul 2016). Figure 3 describes the relationship between the straw application and the greenhouse gas emissions.

The application of a mineral fertiliser is an important measure used to ensure the grain yield (Ying et al. 2017). When a mineral fertiliser is applied to increase the crop yield, it will also promote the growth of the entire plant (Bending & Turner 2009), thereby improving the SOC content of the soil (Liu et al. 2011). Previous studies found that the SOC content in the 0–20 cm soil layer increased significantly with the long-term application of mineral fertilisers (Guo et al. 2011). Our results revealed that mineral fertilisation can increase the SOC relative to the control (M-Z).

Surprisingly, the straw return improved the MBC far more than the SOC. The studies in this review suggested that straw may provide more metabolic substrates for the soil microorganisms. The straw return can change the soil porosity and soil water movement (Singurindy et al. 2006; Skiba & Ball 2010). It is believed that the SOC mainly derives from the input of animal and plant residue. This process is dominated by microorganisms (bacteria, archaea, protozoa, fungi, and viruses) that circulate the organic carbon in complex terrestrial environments (Jia et al. 2017). ^{13}C-labeled straw has been used to study the composition of soil microbial communities involved in the process of straw carbon transformation (Bernard et al. 2007). The results showed that Betaproteobacteria and Gammaproteobacteria are the main bacteria involved in the early stage of carbon transformation of wheat straw, of which *Janthinobacterium*, *Massilia*, *Variovorax*, *Xanthomonas*, and *Pseudomonas* are the main genera.

The soil microbial community structure and microbial diversity were significantly positively correlated with the SOC. This also indicated that the growth and metabolism of the microorganisms in the soil ecosystem were significantly affected by the quantity and quality of the SOC, thus affecting the transformation and decomposition of the SOC (Li et al. 2014). Soil microorganisms are widely involved in most soil processes and the abundance and structure of the microorganisms are generally considered to be essential for the fixation, transport, and accumulation of the SOC (Denef et al. 2009). Soil microorganisms are inactive at low temperatures. Our results also

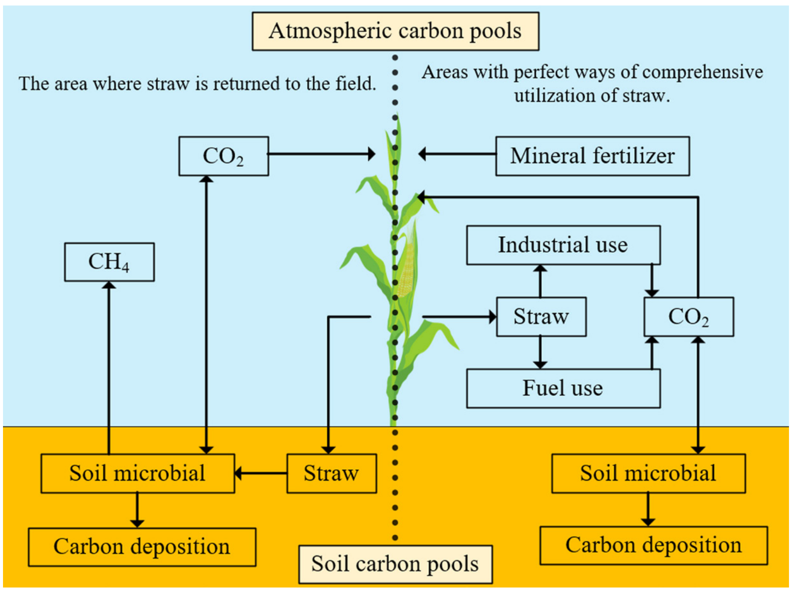

Figure 3. Relationship between the straw application and greenhouse gas emissions

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showed that there was no impact of the straw application on the SOC change in cool climates.

Limitations. There are many types of tillage management. Traditional tillage practices can mix the topsoil evenly (Campbell et al. 2000). Conservation tillage, such as no-tillage or reduced tillage, reduces the disturbance to the soil and easily results in the saturation of organic carbon in the surface soil (Baker et al. 2007), leading to a large amount of straw carbon loss after the degradation of the surface straw (Petersen et al. 2008). Since this meta-analysis merged all the tillage data, the effect of tillage on the SOC was ignored.

Soil microorganisms play an important role in the global carbon cycle, supporting and shaping the effectiveness and mechanism of soil organic matter utilisation (Bowles et al. 2014), and also in global climate change. We did not classify and analyse soil microorganisms, which is also a limitation of this research.

Our meta-analysis omits the significant effect of the soil moisture on the rate of the straw decomposition. Soil moisture can be a limiting factor for straw decomposition (Wang et al. 2017). On the other hand, the straw return can increase the soil moisture (Wang et al. 2019). In particular, repeated fertilisation with straw in dry conditions can lead to the accumulation of undecomposed straw in the soil. Straw that remains on the soil surface or is only shallowly incorporated into the soil decomposes very slowly and phytotoxic substances may be formed during such decomposition (Xiao et al. 2020).

Implications. Our results show that MBC is the key to the straw application effects on the SOC change. A straw application increases the MBC, causing the SOC to rise accordingly. However, a straw application greater than 6 Mg/ha will decrease the SOC. It has been shown that the soil respiration can rapidly increase the concentration of CO_2 in the soil air, reaching 10–45 times that in the atmosphere (Tans et al. 1990). With the straw return, the soil carbon storage will not increase continuously, but will reach saturation at a certain level (Stewart et al. 2007). Research has shown that the SOC will reach saturation after 12 years of straw return (Liu et al. 2014). Modelling studies show that saturation occurs when the carbon density of the soil at a depth of 0–20 cm is 32 Mg/ha (Qin & Huang 2010). For agriculture, the most important soil functions should be the maintenance of the crop productivity, nutrient and water transformation, and microbial abundance and activity, with the maintenance of the microbial abundance and activity exerting dominant control on the SOC function and service (Bardgett & van der Putten 2014). Therefore, excessive straw applications should be avoided.

Moreover, it has been shown that excessive carbon applied to grasslands cannot improve the SOC content, and is released rapidly in the form of CO_2 (Lenhart et al. 2016). Agricultural production is the main source of CH_4 emissions, accounting for 50% of the total global emissions (Netz et al. 2007). Changes in the CH_4 emissions in the soil are mainly due to the processes of methanogenic and methane-oxidising bacteria (Menendez-Serra et al. 2019). A large amount of unused fertiliser leads to a series of environmental problems, such as greenhouse gas emissions (Zhao et al. 2017), ammonia volatilisation (Chen et al. 2014), soil nitrogen leaching (Cameron et al. 2013), air pollution (Hickman et al. 2017), and soil acidification (Duan et al. 2019).

CONCLUSION

In areas where fertilisers are expensive, a straw return is a common fertilisation method. In some areas, straw is often burned, which causes environmental pollution. At present, it is generally believed that the most reasonable approach is to use straw for industrial and fuel purposes, and then, after a period of cycling, release it into the atmosphere as CO_2. The return of matter to the soil reduces the carbon emissions from forestry resources and also reduces the energy consumption (Grigoriou 2000; Badve et al. 2014; Hu et al. 2019). However, if the amount of straw added to a field is greater than the amount of fertiliser needed, the straw will decompose into CO_2 and be discharged into the air (Wang et al. 2018).

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