Monatsh Chem (2009) 140:1489–1494
DOI 10.1007/s00706-009-0213-8

ORIGINAL PAPER

Preparation of an improved sulfonated carbon-based solid acid as a novel, efficient, and reusable catalyst for chemoselective synthesis of 2-oxazolines and bis-oxazolines

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Received: 8 February 2009 / Accepted: 14 October 2009 / Published online: 20 November 2009

Abstract A highly sulfonated carbon as an efficient, recyclable, nontoxic, and green solid acid catalyst was readily synthesized by simultaneous sulfonation, dehydration, and carbonization of sucrose in sulfuric acid and was characterized by FT-IR, TG-DTG, XRD, and CHNS analysis, neutralization potentiometric titration, and SEM techniques. This new catalyst was used for preparation of 2-oxazolines and bis-oxazolines by reaction of *β*-aminoethanol with nitriles under reflux conditions. Sonication of this system enhanced the catalytic activity of the carbon-based solid acid and led to higher product yields and shorter reaction times. Another advantage of the system under ultrasonic irradiation is the ability to carry out large-scale reactions. In two cases, the catalyst was reused several times without loss of its activity.

Keywords Nitrile · Oxazoline · Ultrasonic irradiation · Highly sulfonated carbon

Introduction

The construction of five-membered nitrogen-containing heterocycles such as oxazolines has received considerable attention because of the wide applicability of these compounds to the synthesis of biologically active compounds (e.g. *β*-hydroxy-*α*-amino acids, *α*,*β*-diamino acids, and *β*-substituted serines) [1] and their presence in the structure of several biologically active natural products, for example marine cyclopeptides [2]. 2-Oxazolines are an important class of heterocycles and are versatile intermediates in synthetic organic chemistry [3, 4]. They have been found in a variety of biologically active natural products including siderophores and postsynthetically modified nonribosomal polypeptides [5, 6]. These compounds are also used as protecting groups for carboxylic acids and hydroxylamines [7]. Chiral oxazolines have been extensively used in asymmetric synthesis as both auxiliaries and ligands [8–10]. A number of methods have been developed for preparation of 2-oxazolines from carboxylic acids [11], carboxylic esters [12], nitriles [13–15], aldehydes [16], hydroxyamides [17], and olefins [18]. Many of these procedures have several drawbacks including strongly acidic conditions, long reaction times, low yields of products, use of complex reagents, and toxic solvents [19–28]. Therefore, there is still a need to search for a better catalyst with regard to toxicity, selectivity, availability, and operational simplicity for synthesis of 2-oxazolines. The use of environmentally benign reactions is very important in view of today's eco-friendly-conscious attitude.

On the other hand the preparation of inexpensive, recyclable, and nontoxic strong solid acids is also an attractive and innovative area in green chemistry. This kind of solid acid must be as strong, active, and stable as sulfuric acid [29–38]. Traditional homogeneous acid catalysts such as H_2SO_4, HCl, H_3PO_4, or CH_3COOH are toxic, corrosive, and also are hard to remove from the reaction medium. Care of the environment a world-wide increasing problem. Recyclable solid acids can be used to solve this problem. Easy separation, handling, and recycling of the catalyst or

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the possibility of continuous operation of the reactor are attractive features for any industrial application. A good material for this purpose should have high stability and numerous strong protonic acid sites. Many inorganic-oxide solid acids (for example zeolites and niobic acid that provide acidic OH groups) and organic acids (for example cation-exchange resins and perfluorosulfonated ionomers with SO_3H groups as strong acidic sites) have been studied extensively, but these materials are expensive and the activity of the acidic sites is much lower than those of liquid inorganic acids. Therefore, adequate performance in acid-catalyzed reactions in aqueous media has not been obtained. Carbon-based solid acid is a promising alternative to sulfuric acid as catalyst. However, sulfonation of carbon in concentrated sulfuric acid is very difficult and, finally, mellitic acid is produced. Therefore, sulfonation of carbon nanotubes has been investigated for preparation of sulfonated carbon, but carbon nanotubes are very expensive and the degree of sulfonation is very low [38]. Okamura et al. used pyrolyzed D-glucose for preparation of sulfonated carbon as a solid acid. This process produces a low density of sulfonic acid groups on carbon sheets. Zong et al. used this solid acid for efficient production of biodiesel from fatty acids and waste oils. Hara et al. [31] used sulfonated naphthalene as starting material and then carbonized the naphthalene sulfonic acid under N_2 at 200–300 °C. This process is very tedious and time-consuming, and releases a lot of SO_2 as by-product.

Here, we introduce a modified, simple, and efficient procedure for synthesis of highly sulfonated carbon as a strong protonic solid acid. The process entails simultaneous sulfonation, dehydration, and carbonization of sucrose in one step. We also report use of this solid acid catalyst for selective conversion of arylnitriles to their corresponding 2-oxazolines and bis-oxazolines with β-aminoethanol under reflux or ultrasonic irradiation conditions (Scheme 1).

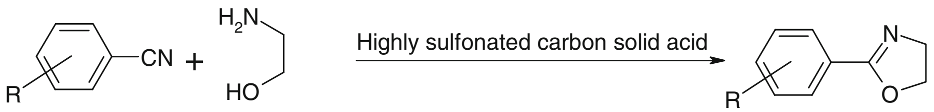
Results and discussion

In a new procedure for preparation of highly sulfonated carbon solid acid, sucrose was treated with concentrated H_2SO_4. Highly sulfonated carbon solid acid was prepared as an amorphous material by simultaneous sulfonation, dehydration, and carbonization of sucrose in one step. The catalyst obtained is a highly sulfonated carbon solid acid ($CH_{0.43}O_{0.65}S_{0.22}$). The sample was characterized by FT-IR spectroscopy, TG–DTG analysis (Figs. 1, 2), X-ray diffraction (XRD, Fig. 3), scanning electron microscopy (SEM, Fig. 4), neutralization potentiometric titration, and carbon–hydrogen–nitrogen–sulfur analysis (CHNS). A speculative structure of sulfonated carbon sheets is proposed in Scheme 2.

This solid acid catalyst was used for selective conversion of arylnitriles to their corresponding 2-oxazolines and bis-oxazolines with β-aminoethanol under reflux or ultrasonic irradiation conditions. The scope and generality of this transformation is illustrated by the various types of nitriles used; the results are summarized in Table 1. Benzonitrile (**1a**, 10 mmol) and β-aminoethanol (**2**, 40 mmol) were reacted in the presence of a catalytic amount of highly sulfonated carbon solid acid (50 mg, 0.245 mmol) under reflux conditions to afford 2-phenyloxazoline (**2a**) in 92% yield. Similarly, different types of aryl and heteroaryl nitriles were reacted and the corresponding oxazolines were obtained in 75–92% yields. After completion of the reaction, simple filtration of the reaction mixture furnished the crude product with the excess β-aminoethanol. Evaporation of the latter under reduced pressure and chromatography on an alumina column gave the product in high purity. Bis-oxazolines can also be prepared by use of the same reaction in the presence of highly sulfonated carbon solid acid. Thus reaction of 1,3-dicyanobenzene and 1,4-dicyanobenzene with β-aminoethanol in the presence of highly sulfonated carbon solid acid gave the 1,3-phenylenebis(oxazoline) and 1,4-phenylenebis(oxazoline) in 82–86% yields. The identities of the products were confirmed by mp, and by use of IR and ^{1}H NMR spectral data.

It has previously been reported that ultrasonic irradiation can be used as an efficient tool to obtain good yields, short reaction times, and mild reaction conditions [39–41]. These features prompted us to explore the effect of ultrasonic irradiation on this catalytic system. Typically, benzonitrile (**1a**, 10 mmol), β-aminoethanol (**2**, 40 mmol), and highly sulfonated carbon solid acid (50 mg, 0.245 mmol) were mixed and exposed to ultrasonic irradiation for 40 min and the corresponding oxazoline **2a** was obtained in 95% yield. The effect of ultrasonic irradiation intensity on this reaction was also investigated. The results showed that the highest yield of compound **2a** was obtained at 100% intensity.

Scheme 1



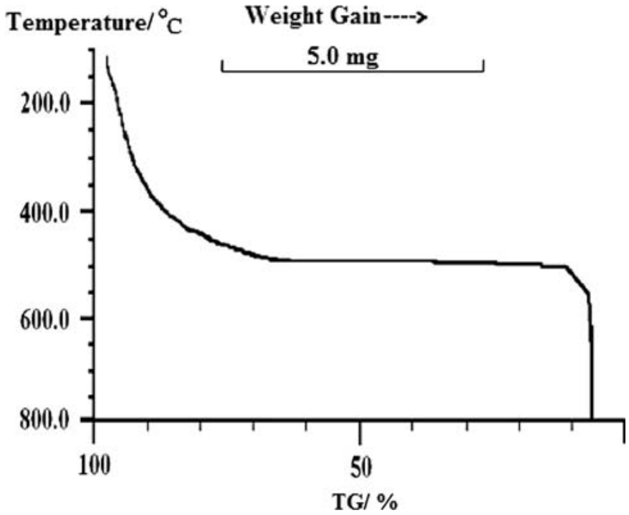


Fig. 1 TG analysis of H_2SO_4-treated sucrose

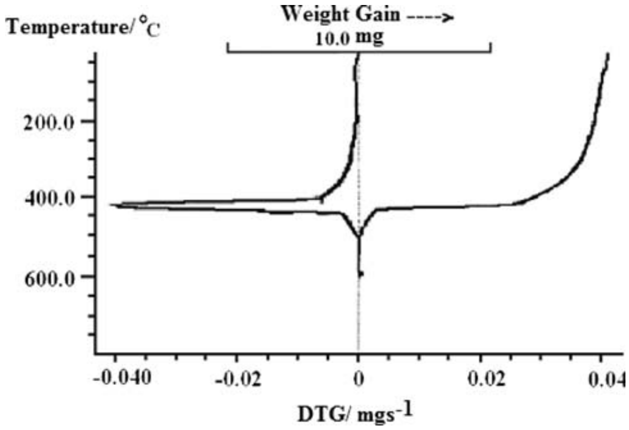


Fig. 2 DTG analysis of H_2SO_4-treated sucrose

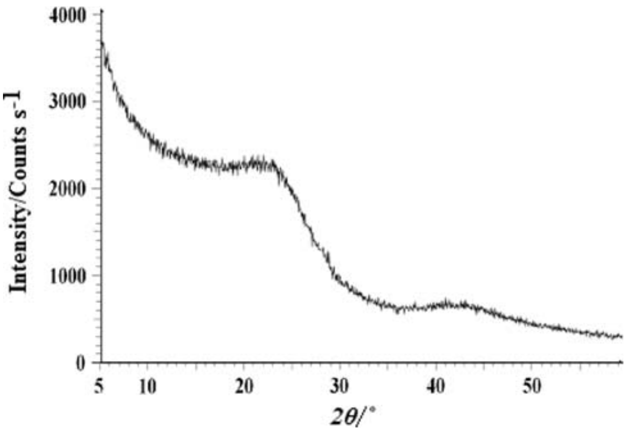


Fig. 3 XRD pattern of H_2SO_4-treated sucrose

Under the same reaction conditions, a variety of nitriles was cleanly converted to their corresponding 2-oxazolines and bis-oxazolines in 76–95% yields.

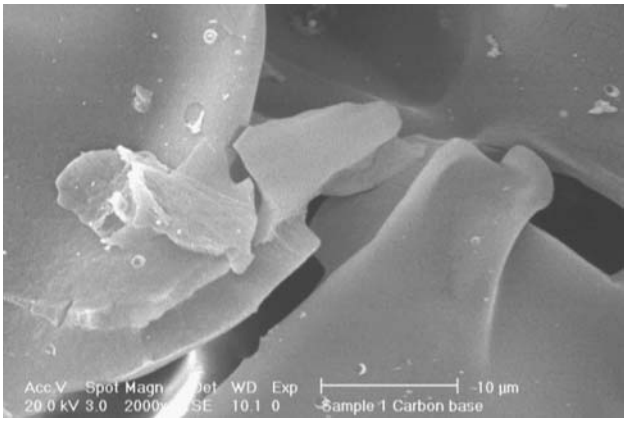


Fig. 4 SEM image of H_2SO_4-treated sucrose

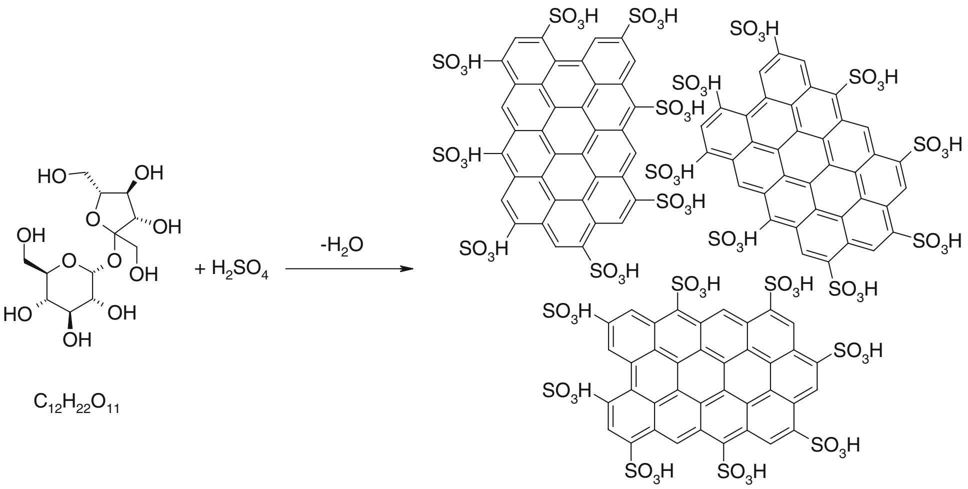
In all of these experiments no weight loss or leaching were observed, showing that the highly sulfonated carbon solid acid is insoluble in organic solvents.

The amount of catalyst was optimized by studying the reaction of benzonitrile (**1a**, 10 mmol) and β-aminoethanol (**2**, 40 mmol) to afford 2-phenyloxazoline (**2a**) under reflux condition. The best results were obtained with 50 mg (0.245 mmol) catalyst. Highly sulfonated carbon solid acid is superior in terms of reaction time, yield of product, and toxicity (LD_{50}). In comparison with other solid acid catalysts, our sulfonated carbon had a very high density of acidic sites on the amorphous carbon. Our procedure is very easy and simple and produces a stable, inexpensive, insoluble, recyclable, and environmentally friendly strong solid acid. The sulfonated carbon has good potential as replacement for sulfuric acid in catalytic reactions; this can be attributed to the high density of SO_3H groups with strong acidity (Table 2).

It is also interesting to note that alkylnitriles did not afford the corresponding 2-oxazolines under the same reaction conditions. These results indicate that this procedure is potentially applicable to chemoselective conversion of arylnitriles to 2-oxazolines in the presence of alkylnitriles.

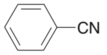
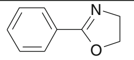
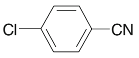
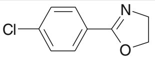
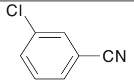
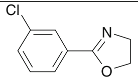
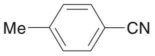
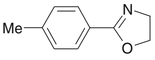
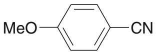
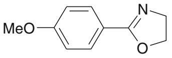
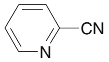
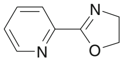
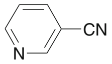
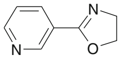
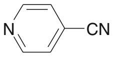
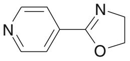
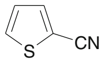
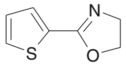
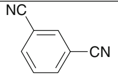
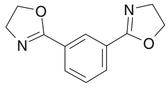
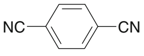
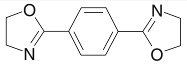
Conclusion

We have demonstrated that highly sulfonated carbon solid acid can be used as a green and reusable catalyst for efficient synthesis of oxazolines and bis-oxazolines under heterogeneous conditions. Moreover, the environmentally friendly, inexpensive, and reusable catalyst, the easy availability of the reagent, and the easy and clean workup make this method attractive for organic chemists. Ultrasonic irradiation of the liquid may enhance liquid–solid mass transfer. An additional advantage of this method with ultrasonic irradiation is its large-scale applicability. Oxazolines and bis-oxazolines



Scheme 2

Table 1 Preparation of 2-oxazolines and bis-oxazolines from nitriles under reflux and ultrasonic conditions[a]

Entry	Nitrile		Oxazoline[b]	Reflux conditions		Ultrasonic conditions	
				Time (h)	Yield (%)[c]	Time (min)	Yield (%)[c]
1a		**2a**		3.5	92	40	95
1b		**2b**		2	90	30	94
1c		**2c**		2.5	89	30	93
1d		**2d**		3.5	80	40	85
1e		**2e**		4	76	45	80
1f		**2f**		2.5	87	35	91
1g		**2g**		2	90	35	92
1h		**2h**		2	85	40	90
1i		**2i**		2.5	81	40	85
1j		**2j**		5.5	76	40	80
1k		**2k**		7	75	45	76

[a] Reaction conditions: nitrile **1a**–**1k**(10 mmol), *β*-aminoethanol (**2**, 40 mmol), and highly sulfonated carbon solid acid (50 mg, 0.245 mmol) for system under reflux and ultrasonic conditions

[b] The identities of products were confirmed by mp, and by use of IR and ^{1}H NMR spectral data [13, 15, 19–28]

[c] Isolated yields

were prepared on a 100 mmol scale, and the results were comparable with those from small-scale experiments.

Experimental

Melting points were measured on an Electrothermal 9100 apparatus. All chemicals were commercial products. All reactions were monitored by TLC and all yields refer to isolated products. ^{1}H NMR spectra were recorded on a Bruker–Avance AQS 300-MHz instrument using tetramethylsilane (TMS) as internal standard. Fourier transform infrared spectra (FT-IR) were recorded on a Nicolet Impact 400D instrument. Thermal gravimetric and differential thermal gravimetric analyses (TG-DTG) were carried out using a Mettler TG 50 instrument. X-ray diffraction patterns (XRD) were obtained on a Bruker D8 Advance instrument. Scanning electron microscopy images

Table 2 Acidity characterization and surface area properties of solid acids

Acid	Acid density (mmol g^{-1})	Surface area (m^2 g^{-1})	Refs.
H_2SO_4-treated sucrose (highly sulfonated carbon)	7.3	9.25	
H_2SO_4-treated naphthalenes	4.9	24	[31]
H_2SO_4-treated carbon nanotubes	1.90	150	[38]
H_2SO_4-treated carbonized D-glucose	1.34	2	[30]
H_2SO_4-treated carbonized resin	0.08	19	[31]
H_2SO_4-treated glassy carbon	0.05	26	[31]
H_2SO_4-treated activated carbon	0.15	1250	[31, 38]
H_2SO_4-treated natural graphite	0.05	25	[31]
Protonated nafion (NR50)	0.93	<0.1	[31]
H_2SO_4	20.4	–	[31]

(SEM) were taken on a Philips XL30 SEM. The specific surface area and mean pore diameter (dp) were calculated from adsorption isotherms of nitrogen at 77 K using the standard Brunauer–Emmett–Teller (BET) equation and were obtained on a Quantachrome Nova 2200 Version 7.11 instrument. All of the products were characterized by a comparison of their spectral and physical data with those of authentic samples.

Typical procedure for preparation of highly sulfonated carbon solid acid

In a typical procedure for preparation of highly sulfonated carbon solid acid, 25 g sucrose was ground and gradually added to 75 cm^3 concentrated H_2SO_4 (98 wt%). The solution was stirred vigorously and then heated for 2 h at 250 °C. Some of the carbon atoms in hot sulfuric acid were oxidized to CO_2 and much foam was formed during heating of the mixture, but heating was necessary for decomposition of C–O–SO_3H esters which were produced during preparation of the catalyst. After cooling to room temperature, the mixture was filtered through sintered glass and the solid was washed with distilled water until no sulfate ions were detected in the filtrate on addition of $BaCl_2$. The product was dried in an oven at 100 °C and then heated at 350 °C to remove any trapped sulfuric acid. The highly sulfonated carbon solid acid was an amorphous material.

Characterization of the highly sulfonated carbon

The FT-IR spectrum of H_2SO_4-treated sucrose contains a broad band at 3,300–3,500 cm^{-1}, which is assigned to OH groups (3,442 cm^{-1}). Strong and sharp bands at 1,719 and 1,613 cm^{-1} and a broad band at 1,164 cm^{-1} are attributed to the stretching vibration modes of sulfate groups. The strong and sharp bands indicate that sucrose can be easily sulfonated, dehydrated, and carbonized for attaching –SO_3H groups to graphite rings with a high density of acid sites.

The density of –SO_3H groups on the sulfonated carbon was determined by potentiometric titration with NaOH (0.01 N) and was in agreement with CHNS analysis ($CH_{0.43}O_{0.65}S_{0.22}$). The neutralization titration showed that the amount of SO_3H which is attached to carbon is 7.23 mmol g^{-1} (Table 2). The surface area of catalyst was 9.25 m^2 g^{-1} and the dp was 56 Å.

The thermal stability of carbon-based solid acid was examined by TG (Fig. 1) and DTG (Fig. 2) analysis under a flow of nitrogen at a heating rate of 10 K min^{-1}. The results showed that the sample weight decreases as temperature increases. Weight loss of the sample occurred in the temperature range of 673–804 K (400–531 °C, peak temperature at 421 °C). On the basis of DTG analysis it seems that no sulfuric acid (free or bound as an ester) was trapped in pores of the char-like material. The weight loss can be attributed to thermal decomposition of carbon-based solid acid to C, SO_2, H_2O, and CO.

The XRD pattern (Fig. 3) contains two broad and weak diffraction peaks ($2\theta = 10°–30°$, $35°–50°$), which are attributed to amorphous carbon. The X-ray diffractogram is similar to that of char because the sulfonic acid groups were attached to edges of isotropic carbon sheets and the solid acid exhibits broad diffraction peaks of amorphous carbon.

The SEM image of H_2SO_4-treated sucrose (Fig. 4) reveals the morphology and structure of amorphous carbon. The sample was gold coated before scanning.

General procedure for synthesis of 2-oxazolines under reflux conditions or under ultrasonic irradiation

In a 50 cm^3 round-bottomed flask, 50 mg highly sulfonated carbon solid acid (0.245 mmol) was added to a mixture of benzonitrile (**1a**, 10 mmol) and β-aminoethanol (**2**, 40 mmol). The reaction mixture was heated under reflux or exposed to ultrasonic irradiation. The progress of the reaction was monitored by TLC (EtOAc–*n*-hexane 1:2). At the end of the reaction the mixture was diluted with $CHCl_3$ and filtered. The solid material was washed with 10 cm^3 $CHCl_3$. The filtrate was evaporated and the residue was purified on an alumina column to afford the pure 2-phenyloxazoline.

Catalyst recovery and reuse

Recovery and reusability of the catalyst are very important practically and economically. Therefore, the reusability of

Table 3 Reusability of catalyst recovered in the synthesis of 2-phenyloxazoline (**2a**) from reaction of benzonitrile (**1a**, 10 mmol) and *β*-aminoethanol (**2**, 40 mmol)

Recycling No	Reflux conditions		Ultrasonic conditions	
	Yield (%)[a]	Time (h)	Yield (%)[a]	Time (min)
1	92	3.5	95	40
2	91	3.5	95	40
3	91	3.5	94	40
4	92	3.5	94	40
5	90	3.5	95	40
6	91	3.5	94	40
7	91	3.5	95	40
8	91	3.5	95	40

[a] Isolated yield based on starting benzonitrile

highly sulfonated carbon solid acid was investigated by performing multiple sequential syntheses of 2-phenyloxazoline (**2a**) by reaction of benzonitrile and *β*-aminoethanol under reflux conditions and under ultrasonic irradiation. At the end of the reaction, the catalyst was isolated by filtration, washed exhaustively with chloroform and ethanol, successively, and dried before being used with fresh benzonitrile and *β*-aminoethanol. Under reflux conditions and ultrasonic irradiation, the catalyst was consecutively reused eight times without significant loss of its activity (Table 3). Initial experimental studies of leaching were conducted by boiling highly sulfonated carbon solid acid in various organic solvents and hot filtration after boiling. In all of these experiments no weight loss or leaching were observed. On the other hand, addition of fresh nitrile and *β*-aminoethanol to the filtrates and execution of the reaction under the same condition resulted in no product.

Acknowledgement We are grateful to the Graduate Studies and Center of Excellence of Chemistry of University of Isfahan for financial support of this work.

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