

# Bauxite enrichment by microwave-magnetising roasting using sawdust as reducing agent

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**Abstract:** As high grade bauxite is getting depleted in several parts of the world, bauxite with high iron content is becoming increasingly important, and this trend has called for studies into the reduction of iron in bauxite. This study investigated the use of microwave energy in the magnetising roasting of high-iron bauxite using sawdust as reducing agent. Mineralogical studies revealed gibbsite and goethite as the main constituents of bauxite. The sawdust utilised had a fixed carbon content of 7.2% and ash, 1.7%. Microwave heating responses of bauxite and sawdust were determined as a function of mass and time, and both materials proved to be active microwave absorbers as they heated rapidly. Magnetising roasting of the bauxite sample was conducted with 20-40% sawdust at temperatures between 870°C and 880°C. After magnetic separation, the major phase in the magnetic fraction was magnetite, while gibbsite and boehmite were the major phases in the non-magnetic fraction. The alumina content of the non-magnetic fraction increased to 87.5% from an as-received sample grade of 53.6%. The use of sawdust in this manner satisfies a dual role of environmental clean-up and bauxite enrichment.

**Keywords:** Bauxite, Sawdust, Microwaves, Magnetic Separation

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## 1. Introduction

Bauxite may be grouped into two major ore types, lateritic and karst, depending on the origin of formation. Lateritic bauxites originate from primary aluminosilicate rocks whilst karst bauxites originate from interbedded carbonate and aluminosilicate rocks. Depending on the binding of water molecules and structure, bauxite may be classified as gibbsite ( $\text{Al}(\text{OH})_3$ ), boehmite ( $\gamma\text{-AlO}(\text{OH})$ ), or diaspore ( $\alpha\text{-AlO}(\text{OH})$ ). In addition to alumina, bauxite contains the iron oxides; goethite ( $\text{FeOOH}$ ) and hematite ( $\text{Fe}_2\text{O}_3$ ), kaolinite, and some amounts of rutile ( $\text{TiO}_2$ ) and quartz ( $\text{SiO}_2$ ) (1, 2).

Bauxite finds application in the refractories and ceramics industry. In these industries, the bauxite must necessarily have low iron content to prevent discolourisation, and in general, hematite content should be lower than 2%. Such low iron content bauxite may be used in the production of filler, brick suitable for industrial applications, and other refractory items (3, 4).

Commercially, aluminium is mainly extracted from bauxite ores by the Bayer Process in which the metal is digested with hot caustic solution, followed by crystallization as aluminium hydroxide. The other constituents of bauxite form the leach tails, which is referred to as red mud (2). During the Bayer Process, aside aluminium, the caustic soda utilised also dissolves some iron compounds and silica in wasteful side reactions. In addition, ferrous oxides and hydroxides such as goethite present in the ore have very bad settling properties, and may interfere with solid-liquid separation after digestion. Processing of the unclear solution leads to reduction in the purity of aluminium hydroxide crystals formed (2, 5). Thus, bauxite used as feed material for the Bayer Process should have low iron content. However, as high grade bauxite is getting depleted in several parts of the world, bauxite with high iron content of about 18% is becoming increasingly important (6).

For many years, several investigators have considered

options for reducing the iron content of bauxite to make it suitable for both the refractory/ceramics industry, and also for production of aluminium (6, 7, 8, 9, 10, 11, 12, 13, 14). The alternatives proposed include hematite removal by use of High Intensity Magnetic Separators (HIMS), reduction of hematite followed by magnetic separation (4, 10, 15) and chlorination followed by leaching (16). In all these investigations, energy from conventional heat sources such as electrical resistance heating was applied.

Microwave energy has become important as a clean source of energy for many processes, and its application in heating minerals has been under investigation for many years. Microwaves can be utilised for the treatment of ores in some of the unit operations such as drying, calcination, pre-reduction, reduction and smelting processes (17, 18, 19, 20, 21, 22, 23). Some minerals such as magnetite ( $\text{Fe}_3\text{O}_4$ ) and manganese dioxide ( $\text{MnO}_2$ ) are considered hyperactive because they readily absorb microwaves and are rapidly heated. Hematite ( $\text{Fe}_2\text{O}_3$ ) is regarded as active while silica ( $\text{SiO}_2$ ) is considered inactive.

Recently, Lu *et al* (24) and Pickles *et al* (6) employed microwave energy and charcoal as a reducing agent to convert non-magnetic iron oxides in bauxite to magnetite. The authors determined the dielectric properties of bauxite, and the data indicated that it had appreciable microwave absorption properties. Following reduction, about 58% of the iron was removed, generating a non-magnetic fraction with alumina content of 85%. According to Pickles *et al* (6), the reduction of iron oxides in bauxite using charcoal as reducing agent may lead to the formation of several products including magnetite ( $\text{Fe}_3\text{O}_4$ ) and hercynite ( $\text{FeAl}_2\text{O}_4$ ).

In this study, microwave energy was applied in the magnetising roasting of bauxite using sawdust as a reducing agent. The previous studies reported by other investigators made use of carbon sources such as coal, activated carbon and charcoal but this investigation used a waste product generated during wood processing, which is a nuisance to the environment in several countries and communities around the world. Thus, if it is successfully applied, the process could help in environmental clean-up in addition to generating bauxite concentrates with high alumina content for the ceramics, refractories and aluminium extraction industries.

## 2. Experimental Investigations

### 2.1. Materials

The bauxite sample used in the study was obtained from the Ghana Bauxite Company in Ghana. Sawdust, a waste material generated from wood processing activities was taken from the waste pile of a wood processing factory in Tarkwa, south-western Ghana.

### 2.2. Materials Characterisation

Prior to characterisation, bauxite sample was crushed to particle size of 100% passing 2.0 mm. A representative

sample was pulverised using a Retsch pulveriser model 5657. The mineral components were determined using a Philips Xpert diffractometer while chemical analysis was done with X-ray Fluorescence SPECTROX-LAB-2000. Size analysis of the sawdust was conducted using a nest of sieves built according to the Tyler series, with 2 mm as the topmost sieve.

The concentrations of Al and Fe in subsamples obtained after microwave processing were determined by a Varian Atomic Absorption Spectrophotometer AA240FS after digestion with sulphuric acid. Thermogravimetric analysis (TGA) of sawdust was performed on a Netzsch STA-409, while carbon and sulphur were determined by the combustion volumetric technique using a LECO Titrator SC-4444DR. Proximate and other analyses aimed at characterising the sawdust used were conducted, and the results are presented in Table 1. The XRF analysis of bauxite is also presented in Table 2.

As shown in Table 1, the mean particle size of the sawdust was 500  $\mu\text{m}$  and the bulk density was 0.23  $\text{g/cm}^3$  with fixed carbon content of 7.2%. The data compares favourably well with that obtained by Rao (26) who conducted similar analysis on Indian sawdust.

**Table 1.** Characterisation of sawdust

Serial Number	Property	Value
1	Mean particle size, $\mu\text{m}$	500
2	Bulk density, $\text{g/cm}^3$	0.23
3	Moisture content, %	9.25
4	Ash content, %	1.70
5	Volatile matter, %	81.85
6	Fixed carbon, %	7.20
7	Total carbon, %	54.3
8	Sulphur, %	0.01

**Table 2.** Chemical composition of bauxite sample

Species	$\text{Al}_2\text{O}_3$	$\text{Fe}_2\text{O}_3$	$\text{SiO}_2$	$\text{TiO}_2$	$\text{P}_2\text{O}_5$
Composition %	53.60	16.20	2.40	1.80	0.23
Species	MgO	CaO	MnO	Na <sub>2</sub> O	LOI
Composition %	0.40	0.13	0.07	1.07	24.1

### 2.3. Microwave Heating and Magnetic Separation

The microwave heating apparatus utilized in the microwave heating experiments was an LG model MS-2027C with a maximum power of 1200 W. The samples were placed in a fireclay crucible which was positioned at the center of the base of the microwave chamber on a fireclay insulation board.

The microwave heating behaviour of the samples was evaluated by measuring the sample temperature after microwaving. A type K thermocouple was employed, and the temperature was measured immediately after turning the power off. In all the experiments, temperature was measured at the middle of the sample, and this is referred to as the sample temperature. Dry magnetic separation was conducted on selected samples after microwave heating using a low intensity hand-held magnet with strength  $5.0 \times 10^{-3}$  Tesla to prevent trapping non-magnetic particles.

### 3. Results and Discussion

#### 3.1. Analysis of Sawdust

Thermogravimetric Analysis (TGA) and Derivative Thermogravimetric Analysis (DTGA) of sawdust are presented in Fig. 1. The results of TGA indicate a mass loss of about 9.25% in the temperature range of 25°C to 100°C, and this may be attributed to free moisture. By 300°C, the mass loss was 82%, and this can be ascribed to the combustion of cellulose to form volatile products. Between 300°C and 525°C, there was an additional loss of 16.3% bringing the total loss to 98.3%, and an ash content of 1.7%. The ash content of wood is generally determined at a temperature of 525°C (25). Beyond 525°C, the change in mass was 0.7% which may be due to decomposition of some components in the ash. The corresponding DTGA shows that the maximum volatilisation rate was at 150°C.

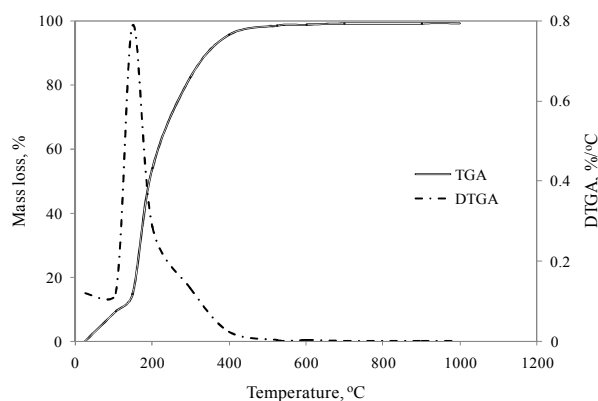


Fig 1. TGA and DTGA of sawdust

#### 3.2. Mineralogical and Chemical Analysis of Bauxite

The X-Ray diffraction pattern of bauxite in Fig. 2 shows that the main phase was gibbsite though goethite was also present. The XRF analysis presented in Table 2 indicates that the alumina content was 53.6% and the main impurities were hematite, quartz and titanium dioxide. Though alumina does not interact strongly with microwaves, hematite and goethite are microwave-active minerals (27, 28). Thus their presence in bauxite indicates that the material would respond to microwave irradiation.

#### 3.3. Microwave Heating Behaviour of Sawdust and Bauxite

Various amounts of sawdust were subjected to microwave heating over a 40 minute period, and the data is presented in Fig. 3. For a sample mass of 5 g, the maximum sample temperature attained was 450°C, and this was accomplished after 20 minutes. Beyond this period, the temperature dropped reaching 130°C after 40 minutes. This presupposes that the combustible material was exhausted after 20 minutes.

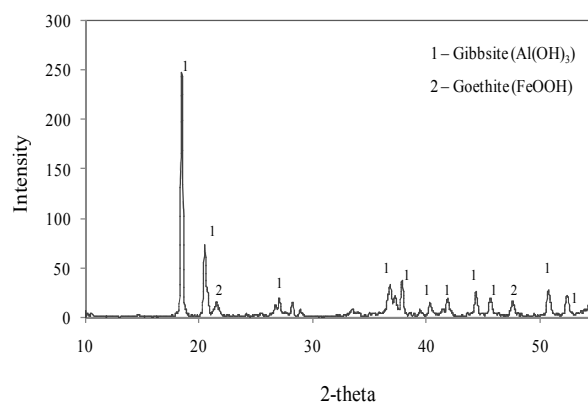


Fig 2. X-ray diffractogram of bauxite showing gibbsite and goethite peaks

For the other sample masses, the sample temperatures increased consistently over 30 minutes reaching 700°C, 850°C and 960°C for the 10 g, 20 g and 30 g samples respectively. These values show that in microwave heating, the sample mass plays a dominant role as explained earlier by Amankwah and Pickles (29). Between 30 minutes and 40 minutes, there was a reduction in temperature of all sample masses indicating reduction of combustible materials, and hence, heat generation.

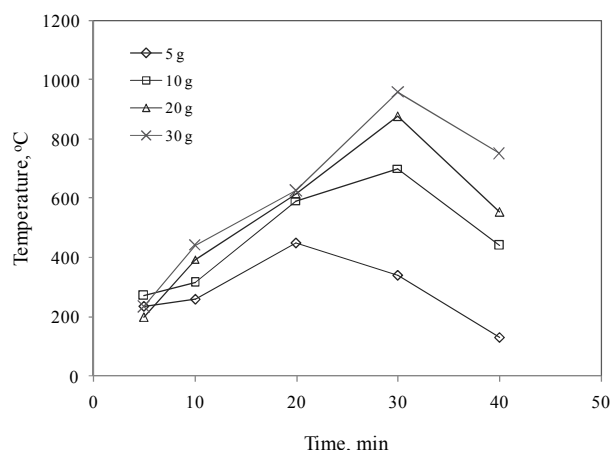
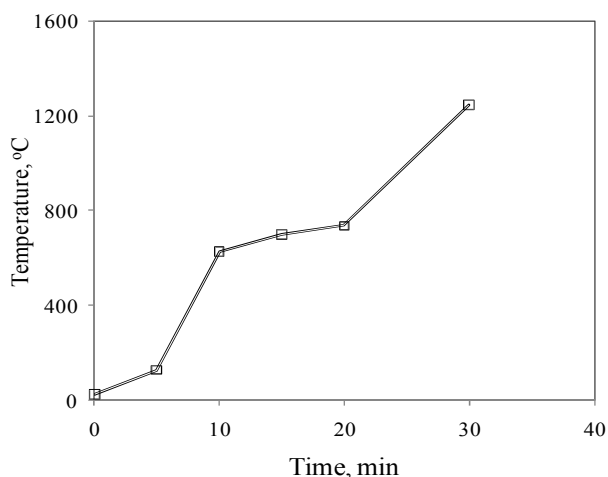


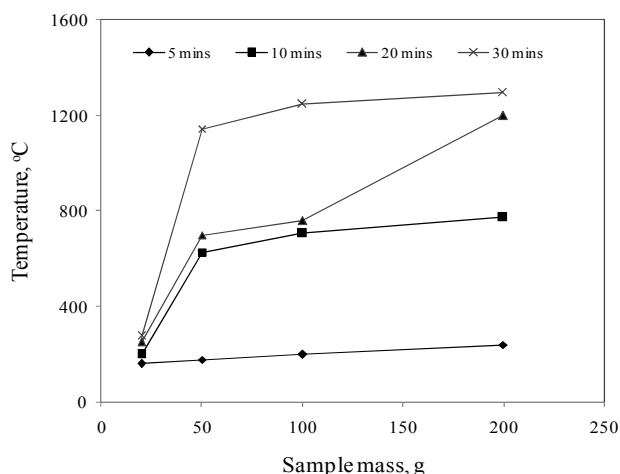
Fig 3. Microwave heating response of sawdust at different sample masses and processing times. Microwave power was 900 W

The microwave heating behavior of the bauxite utilised was observed as a function of time. Fig. 4 presents the heating profile of a 50-g sample over a 30 minute period. From a sample temperature of 25°C, the temperature increased slightly to 95°C after the initial 5 minutes and rose sharply to 650°C at 10 minutes. Between 10 and 20 minutes, there was an insignificant rise in sample temperature of 50°C followed by a sharp increase in the next 10 minutes ending at 1265°C.



**Fig. 4.** The influence of processing time on the microwave heating response of 50 g bauxite. Microwave power was 900 W.

Fig. 5 shows that both microwave processing time and sample mass had strong influence on the sample temperature. For a processing time of 5 minutes, all samples from 25 g to 200 g recorded relatively low sample temperatures below 200°C. For a processing time of 10 minutes, the sample of mass 25 g attained a low temperature of 195°C.



**Fig. 5.** Microwave heating response of bauxite at different sample mass and processing times. Microwave power was 900 W.

As the mass increased to 50 g, the sample temperature rose sharply to about 650°C, and for sample mass of 200 g, the temperature rose to 800°C. For a processing time of 20 minutes, the sample temperatures attained were similar to those of 10 minutes, except for the 200 g sample that had a much higher sample temperature of 1200°C. From 300°C, the sample temperature increased dramatically to 1175°C when the mass was increased from 25 g to 50 g for a microwave processing time of 30 minutes. For the same time, further increase in mass did not alter the sample temperature significantly. In general, the microwave heating response of the bauxite utilised was higher than that used by Lu *et al.* (24), and this could be attributed to the higher content of iron minerals (16.2%) in the bauxite used as against 13.7% reported by Lu *et al.* (24).

### 3.4. Reduction and Deironation Studies

Due to the temperatures generated and the limiting oxygen conditions, the heating of bauxite and sawdust together is supposed to generate two reducing agents; carbon and carbon monoxide. These reducing agents will react with iron oxides present and reduce them to magnetite. From the XRD, the most predominant iron mineral was goethite, and this oxyhydroxide may be thermally transformed into magnetite sequentially as presented in Equations 1 and 2 (30). The magnetic material produced during the processing of sawdust and bauxite was removed by dry magnetic separation after microwaving.

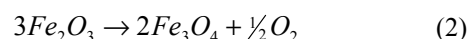
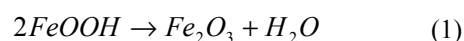
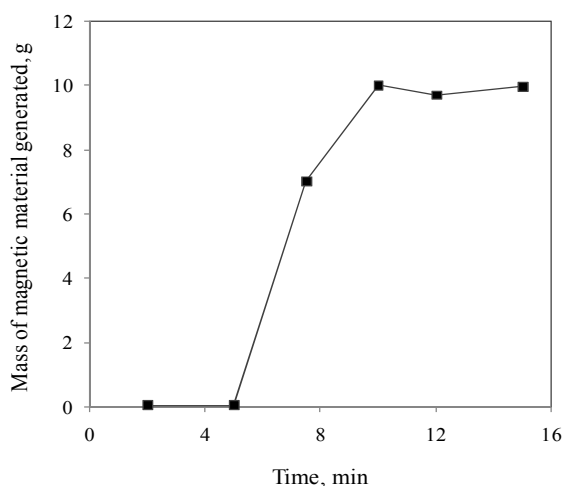
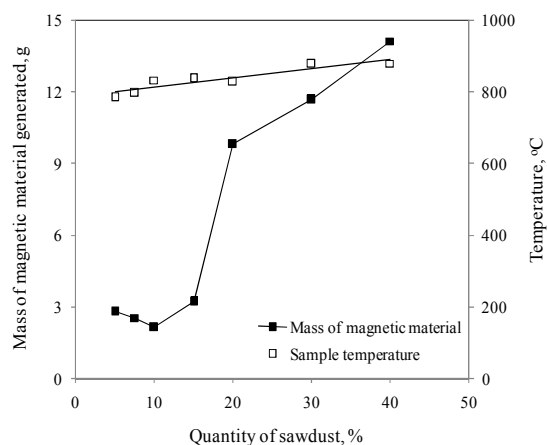


Fig. 6 shows the amount of magnetic material removed when 50 g of bauxite was heated with 20% by mass of sawdust. The mass of magnetic material removed after heating for up to 5 minutes was relatively low and below 0.2 g. As processing time increased, the mass of magnetic material removed increased to a high of 10.5 g after 10 minutes.



**Fig. 6.** Effect of processing time on the generation of magnetic materials. The mass of bauxite utilised was 50 g and sawdust addition was 10 g.

For the same mass of bauxite and a processing time of 10 minutes, an increase in the percentage of sawdust up to 50% resulted in the data presented in Fig. 7. For sawdust concentrations below 15%, the magnetic materials generated were below 6 g. However, from 20% to 40% sawdust concentration, the mass of magnetic materials produced were between 10 and 14 g. The phase transformation from hematite to magnetite results in 1.4% increase in mass and thus, for a 50 g sample containing 16.2%  $\text{Fe}_2\text{O}_3$ , the maximum amount of magnetite likely to be generated is 11.34 g. This indicates that some non-magnetic fractions were entrained in the magnetic materials produced. The temperature range for the reactions was 780°C to 880°C (Fig. 7).



**Fig 7.** Effect of mass of sawdust on the generation of magnetic material. 50 g sample mass was used and the microwave processing time was 10 min.

The higher masses of magnetic material were generated with 20% to 40% sawdust where the temperatures were between 870°C and 880°C. In studies by Pickles et al (6), maximum magnetite formation was achieved at 877°C.

Both magnetic and non-magnetic materials obtained for samples processed for 10 min with sawdust concentration between 20% and 40% were subjected to chemical analysis, and Table 3 presents the data obtained for 20% sawdust which gave the best results.

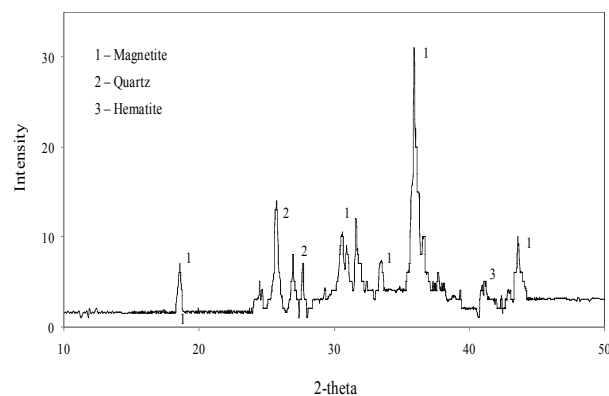
The alumina concentration in the non-magnetic fraction was 87.5% which is a substantial enrichment from an as-received concentration of 53.6%. The iron content of the magnetic fraction was 68.4% from an as-received assay of 9.1% while that in the non-magnetic fraction was low at 1.8%. Figures 8a and 8b show the XRD of both the magnetic and non-magnetic fractions.

**Table 3.** Partial chemical analysis of products obtained after processing with 20% sawdust for 10 min

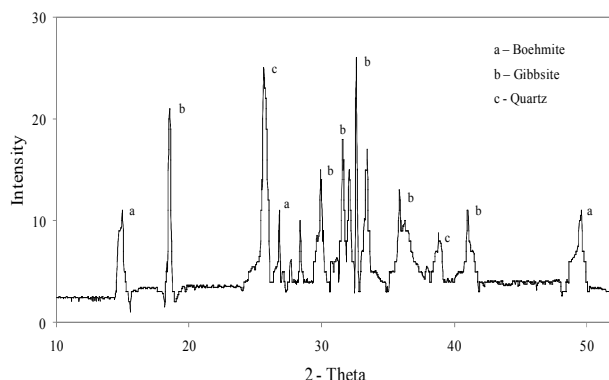
Species	Original	Magnetic material	Non-magnetic material
Al <sub>2</sub> O <sub>3</sub>	53.6	87.5	16.4
Fe	9.1	1.8	68.4

The main phase in the magnetic fraction was magnetite, however, hematite and quartz were also present. For the non-magnetic fraction, the main phases were gibbsite (Al(OH)<sub>3</sub>) and boehmite (AlO(OH)). Work done by Lu et al (24) shows that gibbsite is transformed to boehmite between 250°C and 350°C and subsequently into  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> beyond 350°C.

It was therefore expected that more alumina peaks will be identified instead of those of boehmite. The major presence of boehmite and gibbsite in the non-magnetic fraction suggests that there was differential heating of the sample during the reduction process. Thus, iron oxides and sawdust, being more active in their responses to microwaves, reached higher temperatures in preference to the aluminium hydroxides.



**Fig 8a.** X-ray diffractogram of the magnetic fraction obtained after microwaving and magnetic separation.



**Fig 8b.** X-ray diffractogram of the non-magnetic fraction obtained after microwaving and magnetic separation.

## 4. Conclusions

This study considered enrichment of bauxite to generate suitable feed material for the ceramics, refractories and aluminium extraction industries. The main phase in the bauxite used for this study was gibbsite with alumina content of 53.6% and iron content of 9.1%. The sawdust used as a reducing agent had a fixed carbon content of 7.2% and ash, 1.7%.

The sample temperature attained during microwave heating of bauxite and sawdust as separate samples increased with increase in sample mass and time. Microwaving bauxite and sawdust together in varying percentages led to the production of magnetite, which could be separated. The sample microwaved for 10 min with 20% sawdust content gave the best iron removal. The major phases in the non-magnetic fraction were gibbsite and boehmite while that in the magnetic fraction was magnetite. The alumina concentration in the non-magnetic fraction was 87.5%. The application of sawdust in this way, serves in both environmental clean-up and enrichment of bauxite.

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