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A Review of Applications of Surface-Modified Aluminum in Hydrogen Generation and Water Treatment

Yang Yang[1,*], Shu-Kuan Guo[2], Qin Yu[3]

[1]Energy Materials & Physics Group, Department of Physics, Qingdao University of Technology, Qingdao 266520, China
[2]State Key Laboratory of Functional Crystals and Devices, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 201899, China
[3]School of Mechanical Engineering and Rail Transit, Changzhou University, Changzhou 213164, China

*Corresponding author: yangyang159539@163.com; Tel: +86-0539-5797912.

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Abstract

Aluminum (Al) has been extensively studied for hydrogen generation and water treatment due to its abundance and low redox potential. However, the reductive capability of Al is hindered by the formation of a passive oxide layer on its surface. Besides the conventional Al surface treatment techniques such as acid/alkali corrosion, alloying and mechanical ball-milling, a novel Al surface modification technology that emerged in recent years has attracted significant attention and extensive research. This technology has been validated as an efficient method for Al activation, boasting both economic benefits and environment-friendly manufacturing processes.

In this review, the recent Al surface modification technologies and their applications in the fields of hydrogen generation and water treatment are comprehensively summarized. The advantages and disadvantages between Al surface modification technologies and common Al reactivity activation methods are compared, mainly focusing on their enhanced effect on Al performance in Al-water reactions for hydrogen generation and Al-contaminant reactions for water treatment. Finally, the obstacles that restrict Al surface modification processes in practical application in Al-water reactions for clean energy generation and Al-contaminant reactions for water treatment are examined. Several strategies to potentially address the obstacles in Al practical application are proposed.

Introduction

In recent years, the applications of metal Al in the fields of Al-water reactions for hydrogen evolution and Al-contaminant reactions for water treatment have gained increasing attention and intensive investigations. Al is the third most abundant element in the earth's crust and the most abundant metal element (Bokare and Choi, 2009). In comparison with the metal iron (Fe, $E_0(Fe^{2}+/Fe^{0})$ = -0.44V), Al has a lower redox potential [$E_0(Al^{3}+/Al^{0})$ = -1.662V)] (Bokare *et al.*, 2009; Bokare *et al.*, 2014; Yang *et al.*, 2016; Manilevich *et al.*, 2024) (as listed in *Table 1*),

Zero-valent metals	Standard redox potential (V)
$E_0(Al^{3+}/Al^0)$	-1.662
$E_0(Zn^{2+}/Zn^0)$	-0.762
$E_0(Fe^{2+}/Fe^0)$	-0.44
$E_0(Cu^{2+}/Cu^0)$	-0.337
$E_0(H^+/H_2)$	0

Table 1. Standard redox potential for several zero-valent metals (Yang *et al*, 2016).

which makes it a promising electron donor. In fact, Al-water reactions and Al-contaminant reactions have similar physicochemical mechanisms, both of which are based on the high reduction ability of metal Al. Distinctly, in Al-water reactions, the electrons released from inner Al are captured by water molecules to generate hydrogen molecules through reductive reaction [Eqs. (1)-(2)]. In contrast, in Al-contaminant reactions, the electrons directly attack the chemical bonds in the large contaminant compound molecules that then are decomposed into small organic fragments as shown in Eq. (3). The electrons derived from metal Al also can be captured by peroxide (hydrogen peroxide or persulfate) molecules and generate strong-oxidizing-activity radicals, and as shown in Eqs. (4)-(7), these free radicals can mineralize the organic contaminants in solution into CO_2 and H_2O.

$$Al \rightarrow 3e^- + Al^{3+} \quad (1)$$

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2 \uparrow \quad (2)$$

$$\text{large organic molecule} + e^- \rightarrow \text{small organic molecule fragments} \quad (3)$$

$$2e^- + O_2 + 2H^+ \rightarrow H_2O_2 \quad (4)$$

$$e^- + H_2O_2 \rightarrow OH^- + OH^\bullet \quad (5)$$

$$6e^- + S_2O_8^{2-} + 6H^+ + 1.5O_2 \rightarrow 2SO_4^{\bullet -} + 3H_2O \quad (6)$$

$$e^- + HSO_5^- + H^+ \rightarrow SO_4^{\bullet -} + H_2O \quad (7)$$

Previous investigations demonstrated that a dense oxide film would form on the Al particle surface when Al is exposed to an oxygen-containing or a humid atmosphere, which hinders the release of electrons from inner Al and subsequently leads to a decrease in Al reduction ability (Gai *et al*., 2012; Mercati *et al*., 2013; Yavor *et al*., 2013; Swamy *et al.*, 2014). Hence, overcoming the obstacle of the Al surface dense oxide layer is critical for recovering the Al reduction ability and realizing its practical applications. Until now, a variety of Al activation methods have been developed, such as acid/alkali washing, alloying and mechanical ball milling, which could effectively reactivate Al and increase its electron-releasing ability. In recent years, a new method used in the treatment of the Al surface oxide layer that is named as Al surface modification technology has been developed. Hereafter springs a series of reports about its applications in the fields of Al-water reactions for hydrogen evolution and Al-contaminant reactions for water treatment.

Until now, there have been few detailed reports summarizing the applications of surface-modified Al in hydrogen energy evolution and water treatment. In this paper, different Al surface modification methods were reviewed and the underlying mechanisms responsible for the enhanced effect on Al electrons transferring were clarified. Furthermore, the performances of Al encountering different surface treatment processes in Al-water reactions for clean energy generation and Al-contaminant reactions for water treatment were compared. Finally, this paper elaborated upon the advantages of surface modification processes compared to the common Al surface treatment methods and pointed out the drawbacks of Al surface modification technology that should be overcome for its practical applications in the fields of hydrogen generation and water treatment.

1. Al Surface Treatment Methods

1.1. Acid/Alkali Corrosion

Due to their amphoteric properties, Al oxides or hydroxides can be easily corroded and dissolved in acid or alkaline conditions, recovering the reductive ability of metal Al as an electron donor (Kanakasabai *et al*., 2023). Belitskus *et al*. (1970) first proposed the method of the Al-NaOH reaction for hydrogen generation, which laid the foundation of Al-alkali aqueous solution reactions for hydrogen energy evolution. Pyun and Moon (2000) and Zhang *et al.* (2009) clarified the Al corrosion mechanism in alkali aqueous solutions, which proposed that OH^- ions could corrode the dense oxide film on the Al surface and then react with inner Al and generate $Al(OH)_3$. The generated $Al(OH)_3$ further combined with an OH^- ion to form $Al(OH)_4^-$ ion [Eqs. (8)-(10)]. When $Al(OH)_4^-$ ion concentration exceeds a critical value, it would inversely decompose into $Al(OH)_3$ and OH^- ions [Eq. (10)]. Consequently, the increasingly thickening $Al(OH)_3$ layer would hinder the transportation of water molecules and lead to a gradual deterioration of Al reduction ability.

$$Al_2O_3 + 2OH^- + 3H_2O \rightarrow 2Al(OH)_4^- \quad (8)$$

$$Al + 3OH^- \rightarrow Al(OH)_3 + 3e^- \quad (9)$$

$$Al(OH)_3 + OH^- \leftrightarrow Al(OH)_4^- \quad (10)$$

Soler *et al*. (2010) found that the alkaline Na_2SnO_3 aqueous solution also has a promoted effect on Al-water reactions for hydrogen generation. Furthermore, the performance of Na_2SnO_3 on activating metal Al reactivity is superior to that of NaOH and $NaAlO_2$ at the same pH values. This could be attributed to the fact that Na_2SnO_3 can be reduced by metal Al and generate metal Sn covering on the surface of Al particles. The Al-Sn galvanic cell structure would further enhance Al corrosion, increase the rate of electron release and consequently increase Al-water reaction kinetics.

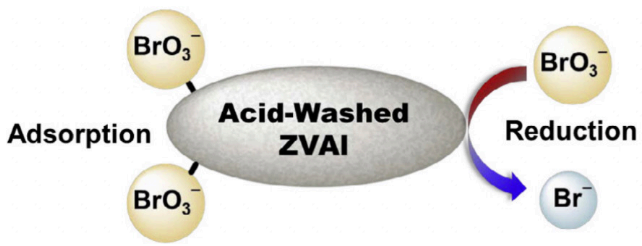

Figure 1. The schematic representation of the enhancement effect of acid washing on BrO3- removal by Al (Lin and Lin, 2016).

In 2016, Lin and Lin dissolved Al surface oxide film using hydrochloric acid. They studied the performance of the acid-corroded Al on reductively removing the aqueous BrO_3^- ions and the factors that influence BrO_3^- removal efficiency. This research laid the foundation for the application of zero-valent Al in the removal of aqueous BrO_3^- ions. Physicochemical analysis demonstrated that the enhanced effect brought about from acid corrosion on the performance of Al removing BrO_3^- ions could be attributed to two aspects. One is that as the inner fresh Al was exposed after acid washing, the direct touch between Al and BrO_3^- ions would greatly accelerate BrO_3^- ions reduction removal kinetics. The other is that the acid-corroded Al would adsorb many more BrO_3^- ions than the untreated Al because the acid corrosion process decreases the average Al particles sizes and subsequently increases the surface area of Al particles, as shown in *Figure 1*.

In 2009, Bokare and Choi studied zero-valent Al oxidatively degraded 4-chlorophenol (4-CP) in acidic aqueous solution. They found that pH value is crucial to 4-CP degradation kinetics by metal Al; a lower solution pH value would give rise to higher 4-CP degradation kinetics. Thereafter, an acidic solution is widely adopted in Al-based water treatment methods. Liu *et al*. (2011) adjusted the pH value of the reaction solution to the acidic range using $HClO_4$ and studied the performance of metal Al in the removal of aqueous bisphenol A (BPA) under acidic conditions. They found that in the reaction solution with a pH value lower than 2.5, metal Al could efficiently remove the aqueous bisphenol A (BPA) at room temperature. When the initial pH value of the reaction solution exceeded 2.5, the BPA removal efficiency using metal Al would evidently decrease as the solution pH value increased. Liu *et al*. attributed the enhanced effect of acidic conditions on the performance of metal Al in BPA removal to two aspects. On the one hand, the acidic solution promoted the dissolution of the Al surface oxide film, which made the inner Al prone to exposure and direct touch with BPA molecules. On the other hand, the acidic solution provided a suitable condition for the generation of hydroxyl radicals ($OH^\bullet$) with high oxidation ability [Eqs. (11)-(12)]. Furthermore, Liu *et al*. found that the addition of Fe^{2+} ions into the reaction solution could further increase BPA degradation kinetics, which could be attributed to the synergistic effect of the Fenton process.

$$2Al + 3O_2 + 6H^+ \rightarrow 2Al^{3+} + 3H_2O_2 \quad (11)$$

$$Al + 3H_2O_2 \rightarrow Al^{3+} + 3OH^\bullet + 3OH^- \quad (12)$$

Fu *et al*. (2016) and Chen *et al*. (2015) soaked Al powder in an acid solution with an initial pH value of ~ 2.0 for a time duration. This acid-Al system could efficiently transform high-toxic Cr(VI) ions into low-toxic Cr(III) ions through the reduction process or could mineralize the aqueous BPA in the participation of H_2O_2 through an advanced oxidation process.

Lin *et al*. (2017a) used hydrochloric acid (HCl) to wash zero-valent zinc (ZVZ); they found that the reduction ability of metal zinc in bromate removal was enhanced compared to that of untreated ZVZ. A higher ZVZ dosage and an elevated temperature had positive effects on the efficiency and kinetics of the ZVZ-bromate reduction reaction. Furthermore, pH value played a significant role in the ZVZ-bromate reduction process. Bromate removal efficiency and reaction kinetics were tremendously bolstered when the solution pH was 3 and were completely suppressed when the solution pH values were in the alkaline range. Lin *et al*. (2017b) also found that the addition of oxalic acid could further improve the bromate reduction efficiency by acid-washed aluminum. It is because oxalic acid could coordinate with the oxidized Al species (Al^{3+}) and thus suppress the formation of the passivation layer of $Al(OH)_3$.

Although acid or alkali washing is effective in activating the Al reduction ability, it poses a severe challenge to corrosion resistance of the reaction facilities, which impedes its large-scale applications in the field of clean energy generation or water treatment to some extent.

1.2. Alloying

Alloying is another widespread method for Al surface treatment. Metal Al can form alloys with other low-melting-point metals through high-temperature melting and grinding. The enhanced effect of Al alloying on activation of Al can be derived from the galvanic cell structure that effectively facilitates metal Al corrosion. Ziebarth *et al.* (2011) fabricated Al-Ga alloy through a high-temperature melting method and they proposed that liquid phase formation was essential for Al alloy-water reactions. Wang *et al*. (2021) melted the metals Ga, In, Sn, and Al, adopting the electricity arc method under an Ar atmosphere, achieving Ga-In-Sn coverage on the Al particle surface and obtaining a Ga-In-Sn-Al alloy. The alloying process not only could prevent the Al surface from passivation but could also promote the inner Al atoms' outward diffusion and contact with water molecules (Amberchan *et al*., 2022; Gao *et al*., 2021). Chen *et al*. (2014) fabricated Al-Li alloy through the ball-milling process. On one hand, metal Li could increase the brittleness of the Al-Li alloy and make it prone to fracture during the reaction. On the other hand, the metal Li-water reaction is an exothermic process, which could further accelerate the breakage of the Al surface hydrated layer and the generation of hydrogen. Fu *et al*. (2015) and Cheng *et al*. (2016) deposited an Fe layer on the Al particle surface through the Fe^{2+} ion exchange process and obtained an Al/Fe bimetal alloy. This bimetal system could be used in the effective reduction of aqueous heavy metals such as arsenate, arsenite and Cr(VI) ions, achieving the purpose of purifying the water quality. Although the alloying process could efficiently promote metal Al corrosion, this process is usually involved in the use of noble metals, which indirectly increases the cost of the alloy materials. Apart from Fe, metal Zn also could form an alloyed system with metal Al. Fan *et al*. (2010) found that metal Zn could reduce the redox potential of the Al-In alloy and efficiently accelerate the diffusion of metal In around the Al particle surface. Wang *et al*. (2014) revealed that the enhanced corrosion ability of the Mg-Al-Fe alloy mainly derived from its galvanic cell structure.

The alloying process is an effective method in preventing the Al surface from secondary passivation and increasing Al reactivity. Nevertheless, other metals and high temperature are usually required in this process, which increases power consumption and the material-fabrication cost.

1.3. Mechanical Ball-Milling

Mechanical ball milling is a common method used for Al surface modification in hydrogen generation by the Al-water reaction. Besides Al, Al powder could also be ball-milled with carbon materials, metal oxides and soluble salts used as grinding agents. Ravavi-tuousi and Szpunar (2013) ball-milled Al powder with stearic acid as a control agent under an Ar atmosphere. The ball-milling process decreased the radius of Al particles and consequently increased the surface area of Al particles. The intrinsic Al surface oxide film was fractured during the ball-milling process, which led to the generation of lattice defects. The results showed that the ball-milling time duration is crucial to the activation effect of Al. An insufficient ball-milling process would result in large Al particle sizes and would not play a satisfactory role in increasing the Al particle surface area. However, overlong ball-milling time would conversely lead to the re-blocking of lattice defects and consequently decrease Al reduction ability.

Huang *et al*. (2012) fabricated an Al/C composite material using graphite as a ball-milling agent. They found that

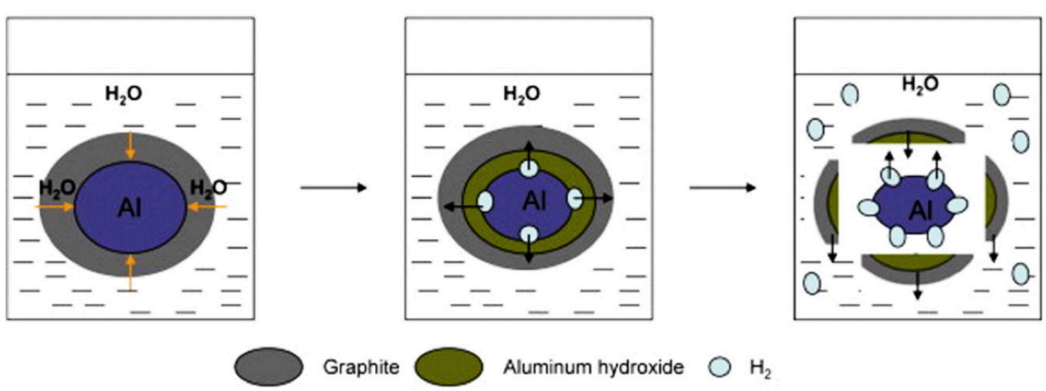

Figure 2. The schematic representation of the reaction of Al/C composite material with water (Huang *et al*., 2012).

this composite material could continuously react with water to generate hydrogen at room temperature, which is attributed to the ball-milling process that could break the Al surface oxide layer and make Al particles uniformly covered by the carbon material (Xiao *et al*., 2021). The coverage of carbon material around the Al particle surface could prevent the Al surface from secondary passivation and have a negligible effect on the contact between the inner Al and water molecules. Furthermore, the hydrogen gas bubbles, and reaction heat released in the Al-water reaction would promote the breakage of the covered carbon material layer and ensure the direct contact of the inner Al with water molecules, as illustrated in *Figure 2*.

The underlying mechanism of Al activation by metal oxides used as ball-milling agents closely depends on the oxide types used. Wang *et al*. (2011) used nano metal oxides including TiO_2, Co_3O_4, Cr_2O_3, Fe_2O_3, Mn_2O_3, NiO, CuO and ZnO as ball-milling agents. In comparison, TiO_2, Co_3O_4 and Cr_2O_3 used as ball-milling agents had a greater effect on the Al-deionized water reaction for hydrogen generation at 25ºC. Furthermore, Wang *et al.* found that the TiO_2 with average particles sizes of 14 nm were highly effective in facilitating the production of hydrogen from the reaction of Al with tap water, while other oxide nanocrystals were ineffective in promoting hydrogen generation in tap water. This is attributed to the fact that 14 nm TiO_2 nanocrystals remain in intimate contact with the surface of Al particles. The anodic polarization at the contact point of the TiO_2:Al_2O_3 layer rendered the defect species more mobile and increased reactivity.

Soluble salts, such as KCL and NaCl, could also be used as grinding agents for the treatment of the Al surface oxide layer. It is known that the crystalline salt grains have good rigidity and their sharp edges could cut and then be embedded into the Al surface oxide layer in the grinding process. Lots of micro water channels would form after the salts dissolved, which subsequently leads to the exposure of inner fresh Al. Nevertheless, some scholars attributed the promoted effect of crystalline salts on Al reactivity to that of the pit-corrosion effect by Cl^- ions in preventing the Al surface from repassivation to a great extent (Chen *et al*., 2013; Liu *et al*., 2015). If other metals exist in this case, a galvanic cell system would form and Cl^- ions would enhance the electric conductivity of the aqueous solution and the synergistic effect would further speed up the Al corrosion process (Fan *et al*., 2008).

The grinding process requires a large amount of electricity and the grinding efficiency is low. Additionally, facility abrasion is inevitable accompanying mechanical vibration and noise. These disadvantages are inconvenient for the application of the grinding process in Al surface treatment.

1.4. Surface-Modified Al Powder (SMAP)

In 2005, Deng *et al*. (2005a) first adopted the ceramic-fabrication technique, which involved the mixing of $Al(OH)_3$ with Al powder, tableting, sintering, smashing and sieving, and finally obtained γ-Al_2O_3 modified Al powder. This modified Al powder could be used in hydrogen generation from Al-water reactions or be used in aqueous contaminant removal under mild conditions, which would provide a promising functional metal material for clean energy evolution and water treatment. In fact, the essential mechanism of Al surface modification is attributed to crystalline phase transformation (Deng *et al*., 2001a; Deng *et al*., 2001b; Deng *et al*., 2001c). After heat treat-

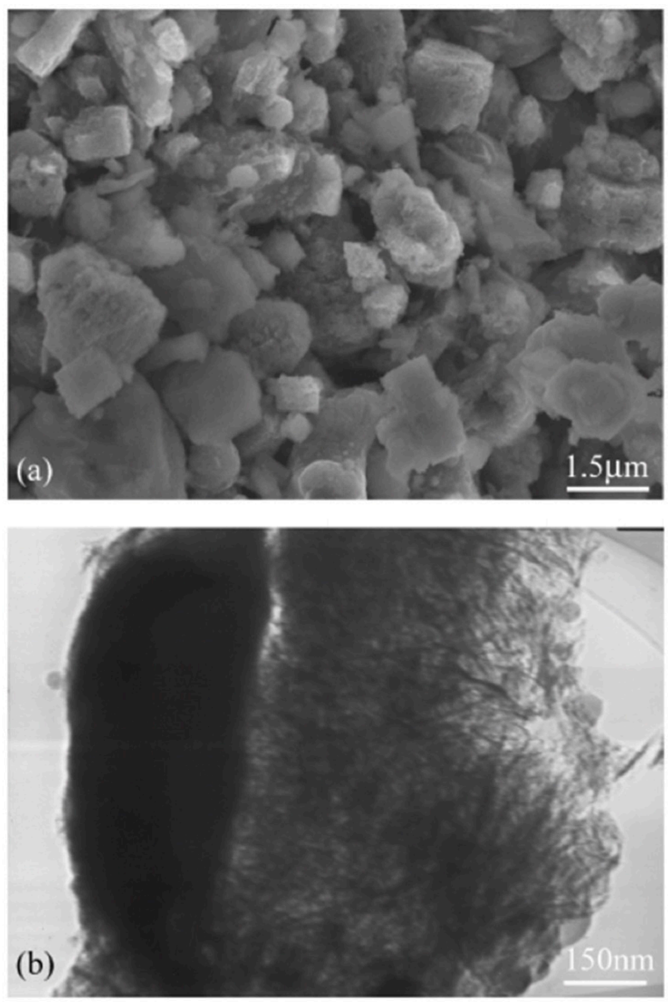

Figure 3. SEM micrographs (a) and TEM micrographs (b) of the SMAP with composition of 72 wt% Al + 28 wt% γ-Al_2O_3 (Deng *et al.*, 2005b).

ment for a time length, the intrinsic Al particle surface oxide or hydroxide layer would transform into γ-Al_2O_3 grains with fine-crystallite structures (as shown in *Figure 3*). The SMAP could continuously react with water and generate hydrogen at room temperature and under atmospheric pressure, demonstrating that SMAP is a kind of potential material for clean energy generation. The mechanism responsible for the promoted effect of γ-Al_2O_3 modification on Al-water reaction will be explained in detail in the following section.

2. Application of SMAP in Al-Water Reactions for Hydrogen Generation

SMAP was initially proposed in the study of Al-water reactions for hydrogen generation. Deng *et al*. (2005a) put forward a hypothesis that the enhancement effect of Al surface modification processes on Al-water reactions mainly derives from the generation of γ-Al_2O_3 with fine-crystallite structures, which provided a reasonable explanation for Al-water reactions or Al-contaminant reduction removal. According to the hypothesis, there is an intrinsic dense oxide film on the Al surface (Fu *et al*., 2024; Li *et al*., 2024; Yang *et al*., 2023; Wang *et al*., 2024) when Al powder is exposed to a humid environment and a hydration reaction occurs in this oxide film, which involves the breakage of the Al-O-Al bond and the generation of Al-OH pieces. Two Al-OH pieces would be generated accompanying the breakage of one Al-O-Al bond. As the hydration process proceeds, a layer of AlOOH or $Al(OH)_3$ would consequently generate on the Al particle surface [as Eq. (13)]. When the hydrated oxide layer contacts the inner fresh Al, it will react with Al and generate molecules [as Eq. (14)] (Deng *et al*., 2007). Since H atoms have a limited solubility in Al particles, hydrogen molecules would immediately accumulate at the hydrated oxide layer-Al surface interface. The hydrated oxide layer will be broken when the hydrogen gas pressure exceeds the critical pressure that the hydrated layer can sustain (Kumar *et al*., 2023; Mutlu *et al*., 2024; Chen *et al*., 2024). From the above analysis, it can be deduced that an induction period is needed before the Al-water reaction for hydrogen generation, as shown in *Figure 4*.

$$Al_2O_3 + H_2O \rightarrow 2AlOOH \tag{13}$$

$$6AlOOH + 2Al \rightarrow 4Al_2O_3 + 3H_2\uparrow \tag{14}$$

After modification, the intrinsic dense oxide film on the Al surface will be transformed into a loose structure (as shown in *Figure 3*), and the maximum pressure that the surface oxide layer can sustain decreases. Simultaneous-

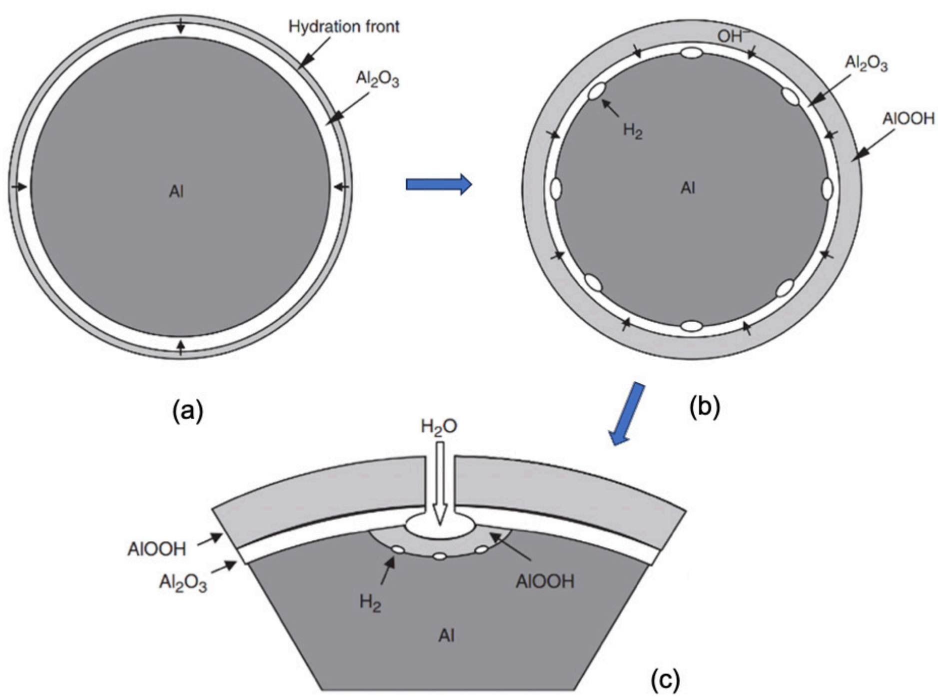

Figure 4. Several processes in Al-water reaction: (a) hydration of passive oxide film, (b) accumulation of hydrogen molecules, (c) Al-water reaction (Deng *et al.*, 2007).

ly, as the critical hydrogen gas pressure is proportional to the tension of surface oxide film (Deng *et al*., 2007), it can be inferred that the SMAP surface oxide layer is more easily broken by the accumulated hydrogen gas bubbles. Then, continuous hydrogen generation at room temperature and atmospheric pressure can be achieved.

Surface modification technology attracted wide attention once it was proposed. This is mainly because the reaction of SMAP with water has no induction process, in contrast to commercial Al powder (*Figure 5*). SMAP is becoming a promising on-spot clean energy-generation material owing to its relatively low cost and its ability to continuously react with water at mild temperature and under atmospheric pressure.

The enhancement effect of γ-Al_2O_3 modification on the Al-water reaction closely relies on the percentage of γ-Al_2O_3 in Al/γ-Al_2O_3 mixed powder. As γ-Al_2O_3 content increased from 27% to 70%, Al-water reaction kinetics became re-

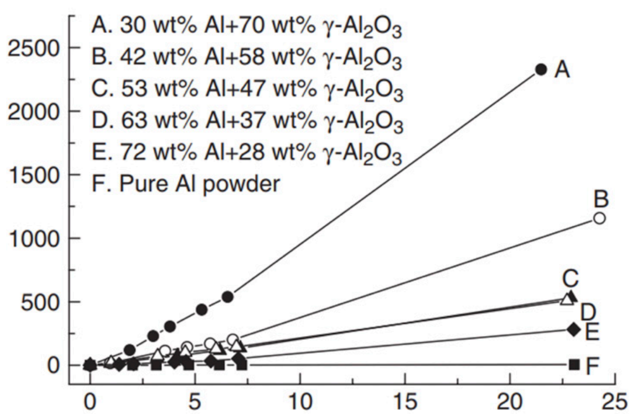

Figure 5. Hydrogen generation from water using SMAP with different γ-Al_2O_3/Al composition (Deng *et al.*, 2005a).

markably more rapid, and the hydrogen yield increased by nearly six times in the same length of time. Besides, Al-water reaction kinetics are positively proportional to the reaction temperature (Deng *et al*., 2005b). Deng *et al*. (2010) and Liu *et al*. (2012) found that the enhancement effect of γ-Al_2O_3 modification has a positive correlation with the uniformity of γ-Al_2O_3 coverage on Al particles surface. Later, Gai *et al*. (2015) supplemented the mechanistic explanation for the enhancement effect of γ-Al_2O_3 modification on the Al-water reaction for hydrogen generation (*Figure 6*): the γ-Al_2O_3 grain acts like a "reactive sponge" that can store and release water molecules in a reactive way (Sohlberg *et al*., 1999; Yang *et al*., 2014). This means that water molecules could be dissociated into H^+ and OH^- ions when they contact γ-Al_2O_3 grains. When γ-Al_2O_3 grains contact Al particles in aqueous solution, the OH^- ions dissociated from water molecules on γ-Al_2O_3 surfaces are easy to hydrate with the passive oxide film on the Al particle surface, which greatly accelerates the hydration process in the Al surface oxide layer. Consequently, the induction time length at the beginning of the Al-water reaction would be greatly shortened. *Table 2* lists several different Al surface process methods.

Apart from the γ-Al_2O_3 modification, Gai *et al*. (2014) found that direct addition of γ-Al_2O_3, $Al(OH)_3$, α-Al_2O_3 or TiO_2 powder could also remarkably shorten the induction period time of the Al-water reaction (*Figure 7*), and γ-Al_2O_3 exhibited the most remarkable improvement. This study discovered that the phase constituents of these oxides remain nearly unchanged compared to their pristine ones, indicating that these oxides or hydroxides just acted as reaction catalysts that effectively promoted the hydration process in the Al surface oxide film. This is probably re-

Processing methods	**Reaction condition**	**Hydrogen generation efficiency and time**	**Ref.**
Alkaline additive	0.25 M Na_2SnO_3, pH = 12.0, 75°C, 1atm	35%, ~ 0 h	(Soler *et al*., 2010)
Alloys	50 wt% Al-34 wt% Ga-11 wt% In-5 wt% Sn, 55°C, 1atm	85%, ~ 0 h	(Ziebarth *et al*., 2011)
Ball-milled alloys	Al-5wt%Li-5wt%NaCl, 25°C, 1atm	100%, ~ 16.67 h	(Chen *et al*., 2014)
Ball-milled Al/C	Al-23wt%C-2%wt NaCl, 65°C, 1atm	86%, ~ 5.83 h	(Huang *et al.*, 2012)
SMAP	30wt% Al: 70wt% γ-Al_2O_3, 25°C, 1atm	27.6%, ~ 22 h	(Deng *et al.*, 2005)

Table 2. Hydrogen generation from water using Al powder activated with different methods.

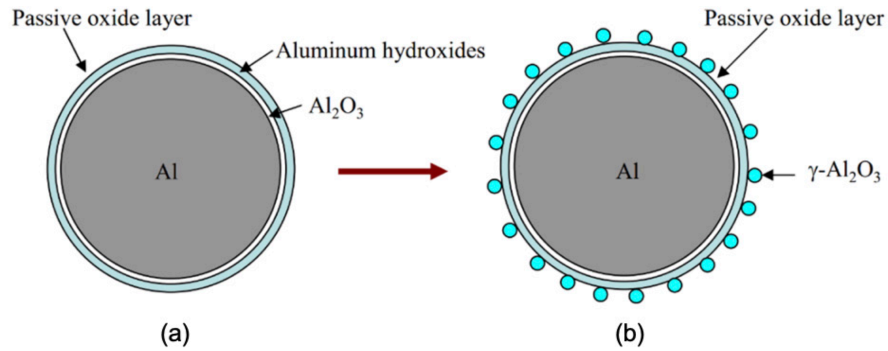

Figure 6. The surface structures of Al particles (a) before and (b) after heat treatment (Gai *et al.*, 2015).

lated to the structural characteristics of these oxides or hydroxides.

Compared to the common Al surface treatment method, the Al surface modification process possesses advantages such as mild fabrication conditions, no corrosion to reaction facilities, and a lower cost. However, the slow reaction kinetics limit its large-scale application to a certain degree; this could be overcome through lowering the initial reaction gas pressure and elevating the reaction temperature.

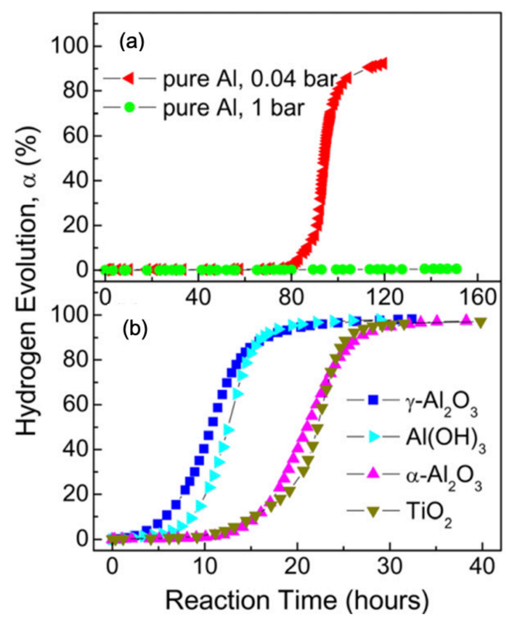

Figure 7. The effect of (a) initial gas pressure and (b) different oxides or hydroxides on Al-water reaction for hydrogen generation (Gai *et al.*, 2015).

3. Application of SMAP in Water Treatment

Apart from the Al-water reaction for hydrogen generation, another successful application of SMAP is in the field of water treatment. SMAP presents excellent effects in reduction removal of aqueous contaminants such as heavy-metal ions, inorganic salts and organic dyes. Although the destination contaminants are different, their removal mechanisms by SMAP share some similarities, which are all fundamentally based on the mechanism of electron transfer, as illustrated in *Figure 8.*

3.1. SMAP Used for Cr(VI) Removal

Chromium (Cr)—a byproduct of industrial processes such as powder metallurgy, product manufacturing, metal surface treatment, forging and leather tanning—is one of the most concerning heavy metals in wastewater due to its high toxicity, carcinogenicity and mutagenicity. The United States Environmental Protection Agency lists chromium as one of the most poisonous of seventeen elements and set 0.1 mg L^{-1} of chromium as the upper limit in drinking water (Zhang *et al*., 2018). Chromium has

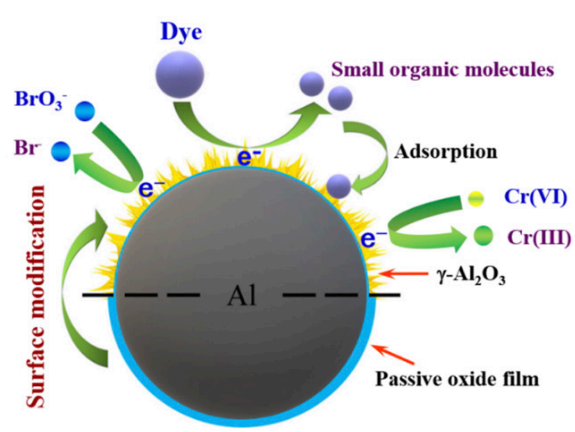

Figure 8. Schematic representation of aqueous contaminant removal by SMAP.

diverse oxidation states, among which Cr(III) and Cr(VI) states are the most widespread and stable in the natural environment. Because Cr(VI) has a much higher toxicity and solubility than Cr(III), a common and effective way to eliminate the toxicity of chromium-containing water is the reduction from highly soluble Cr(VI) ions into Cr(III) ions with low solubility. Up to now, various methods used for reductive removal of aqueous Cr(VI) ions have been exploited, as shown in *Table 3*.

Yang *et al*. (2020) developed a simple Al surface modification method, where commercial Al powder was soaked in water for a length of time and then the Al containing suspension was centrifuged to obtain wet Al mud. Subsequently, the wet Al mud was dried at 60° and then heat-treated at 400° for a length of time to obtain the final SMAP. Compared to the common Al surface modification methods, including tableting and sintering processes (Deng *et al*., 2001a), Yang's manufacturing process has a more effective enhancement on Al reactivity. That is because the Al particle surface hydrated oxide layer could be transformed into fine γ-Al_2O_3 grains in the heat-treatment process and these fine γ-Al_2O_3 grains cover the Al particle surface more uniformly and result in a more excellent Al surface modification effect.

Yang *et al*. (2020) further used the above SMAP in the reduction removal of Cr(VI) ions in aqueous solution, which is the first study that reported the application of SMAP in the field of water treatment. The results confirmed that the surface treatment methods through soaking and then heat treatment processes could effectively improve Al reactivity. The obtained SMAP powder exhibited high reduction ability for transformation from high-toxic Cr(VI) ions into low-toxic Cr(III) ions [as Eq. (15) and *Figure 9(a)*], which provided a promising water-purification material

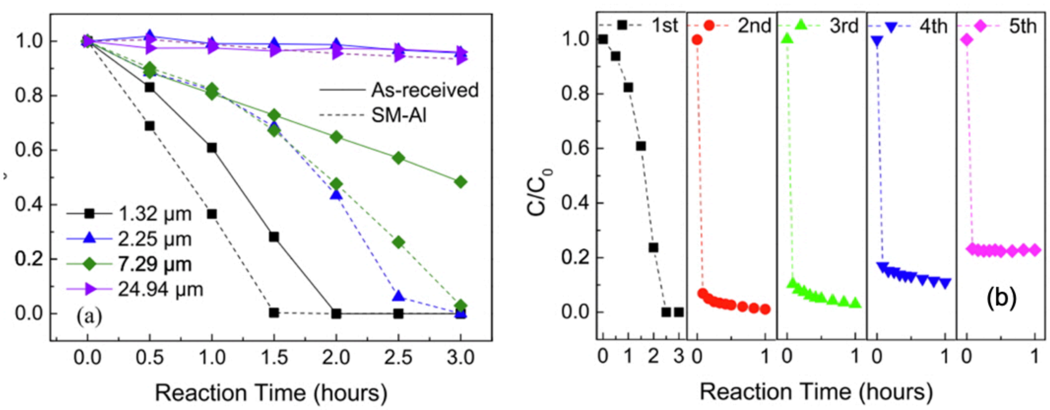

Figure 9. (a) Cr(VI) removal by SMAP and (b) the reusability of SMAP (Yang *et al.*, 2020).

Processing methods	Reaction condition	Removal ratio and time	Ref.
Acid washing	$[Cr(VI)]_0$ = 20.0mg L^{-1}, $[Al]_0$ = 0.4 g L^{-1}, pH_0 = 1.5	100%, 150 min	(Fu *et al*., 2016)
Al deposited with Fe	$[Cr(VI)]_0$ = 20.0mg L^{-1}, $[Fe/Al]_0$ = 6.0 g L^{-1}, Fe/Al mass ratio: 0.75g Fe/g Al, pH_0 = 3.0	100%, 10 min	(Fu *et al.*, 2015)
SMAP	$[Cr(VI)]_0$ = 8mg L^{-1}, $[Al]_0$ = 4 g L^{-1}, near neutral pH,	100%, 60 min	(Yang *et al.*, 2020)
Ball milling	5.0 wt% NaCl (grinding aid), 300rpm, 1.0h, N_2, $[Cr(VI)]_0$ = 0.2mM, $[Al]_0$ = 4 g L^{-1}, pH_0 = 7.00	100%, 380 min	(Zhang *et al*., 2018)
Ball milling	Ethanol (grinding aid), 3.00h, $[Cr(VI)]_0$ = 20mg L^{-1}, $[Al]_0$ = 4 g L^{-1}, near neutral pH	100%, 25 min	(Ren *et al*., 2020)

Table 3. Activated Al using different methods for aqueous Cr(VI) removal.

fabrication technology. Besides, the study demonstrated that as the pre-soaked time length was prolonged, the Cr(VI) removal kinetics by SMAP would be increased. This is because increasing the soaking time length would lead to the generation of a thicker Al surface hydrated layer that would be transformed into finer γ-Al_2O_3 grains and a uniformly surrounded Al particle surface, as shown in *Figure 8*. Moreover, this SMAP exhibited excellent reusability in aqueous Cr(VI) removal, since ~ 80% of aqueous Cr(VI) ions could be removed even after SMAP were reused for five cycles [*Figure 9(b)*]. Interestingly, the recycled SMAP exhibited a higher reactivity in the reduction from Cr(VI) ions into Cr(III) ions, as compared to the unused ones. The higher reactivity of recycled SMAP in Cr(VI) removal can be attributed to the byproducts AlOOH or $Al(OH)_3$ generated in the Al-water reaction. The byproducts AlOOH or $Al(OH)_3$ covered the surface of the recycled Al particles, which would further promote the hydration process in the Al surface oxide layer and greatly decrease the induction time in the Cr(VI) reduction reaction using SMAP.

$$Al + CrO_4^{2-} + 4H_2O \rightarrow Al(OH)_3\downarrow + Cr(OH)_3\downarrow + 2OH^- \quad (15)$$

3.2. SMAP Used for Removal of Methyl Orange/ Methyl Blue

Large amounts of organic dyes are consumed every year in textile, printing, and some other industries (Ahmad *et al*., 2019; Ahmad *et al*., 2020). Some of them enter the natural water system, becoming one of the sources of water contamination (Hao *et al*., 2012; Shabbir *et al*., 2017).

Xie *et al*. (2021) adopted Yang's manufacturing processes in section 3.1 to obtain the SMAP and then studied the effect of SMAP used in the removal of aqueous methyl orange and methyl blue [*Figures 10(a)* and *10(b)*]. It was found that the surface modification process sharply reduced the organic dye removal time length to just one third of that using the untreated Al powder. It was also found that the dye removal performance using SMAP was superior to that of the ultrasound splitting effect. Meanwhile, the SMAP demonstrated an excellent reusability in the removal of aqueous organic dyes, where more than 80% of methyl orange or methyl blue could be removed efficiently even after SMAP was used for three

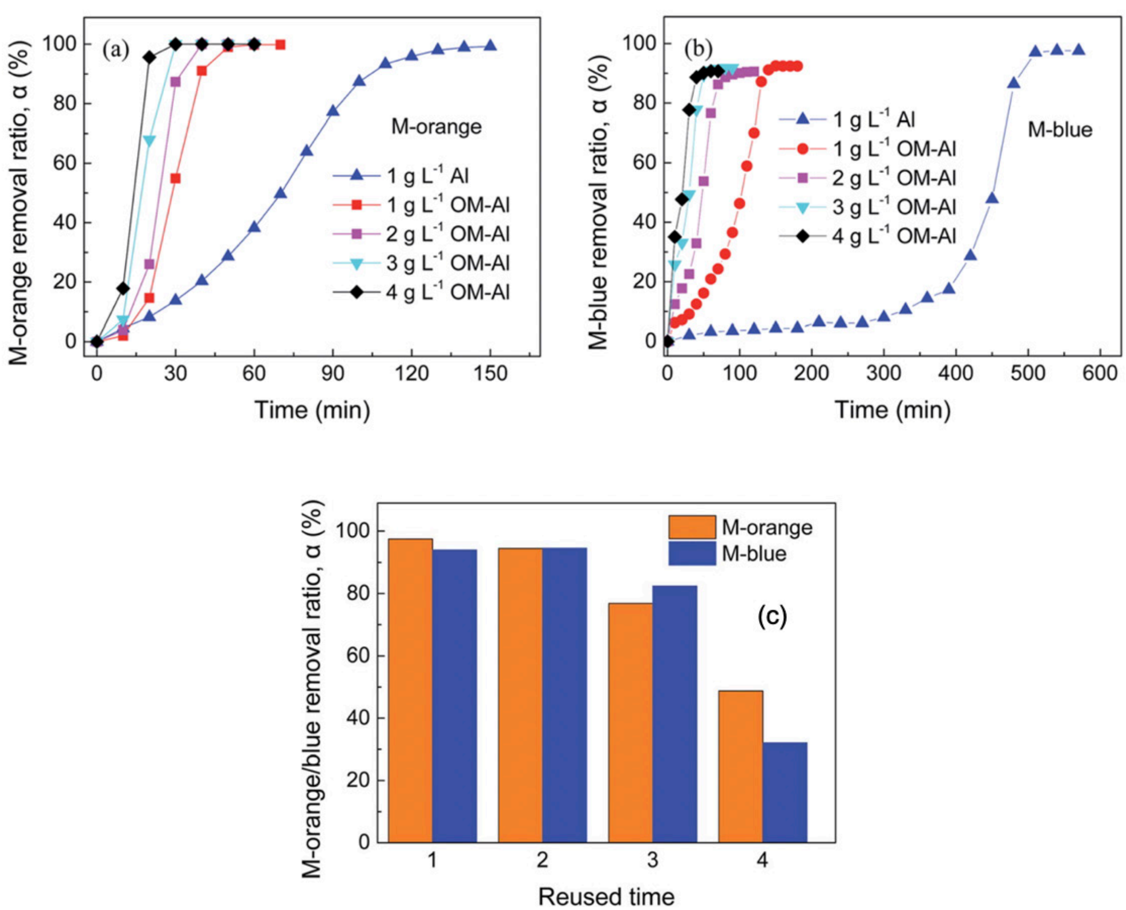

Figure 10. SMAP used for removal of (a) methyl orange, (b) methyl blue and (c) reusability test (Xie *et al.*, 2021).

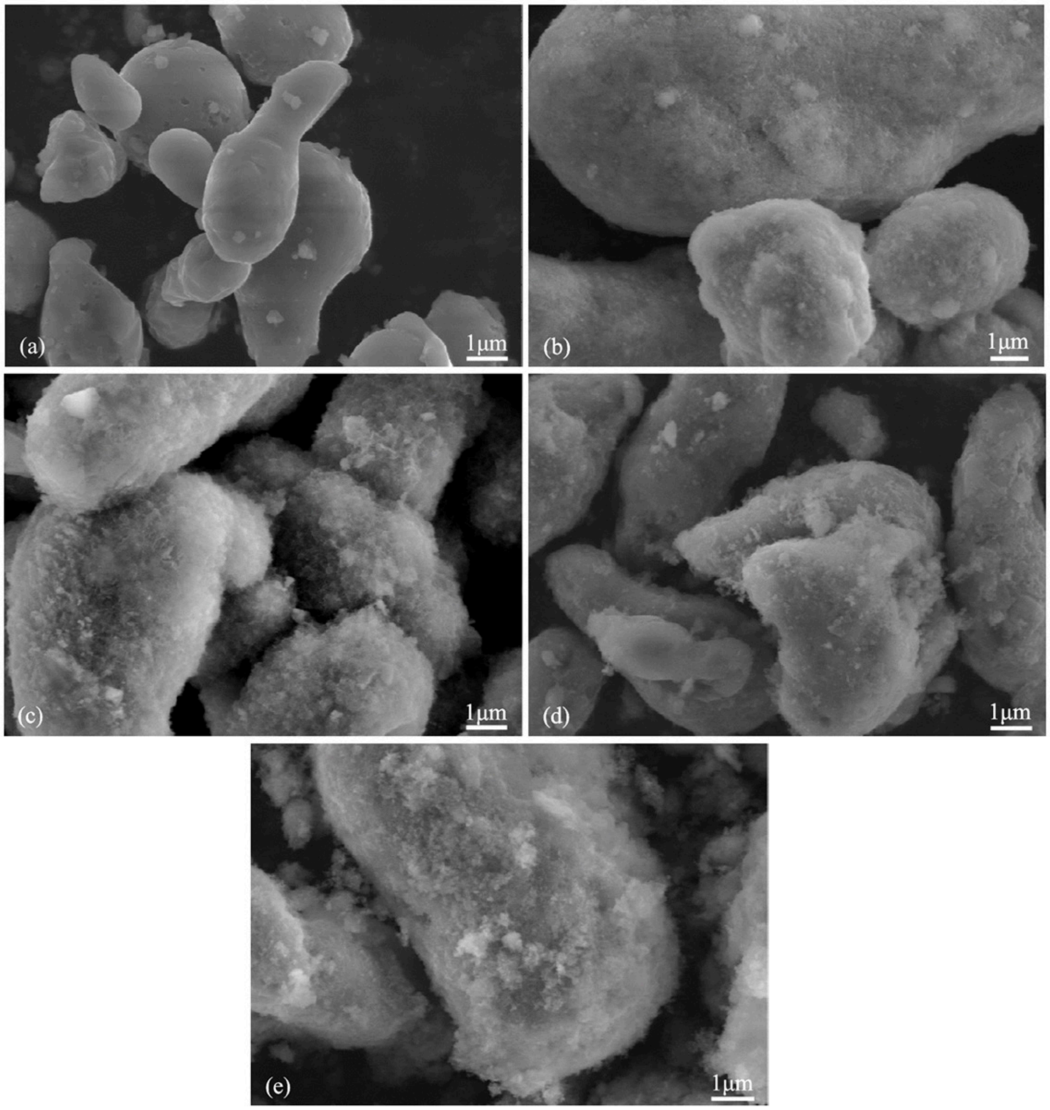

Figure 11. SEM micrographs of (a) as-received Al powder, (b) Al powder that is soaked and then freeze-dried, (c) Al powder that is soaked and then heat-treated, SMAP with a composition of (d) 10 vol% γ-Al2O3 + 90 vol% Al and (e) 30 vol% γ-Al2O3 + 70 vol% Al (Zhou *et al.*, 2021)

Processing methods	Reaction condition	Degradation ratio and time	Ref.
Periphyton	Dosage: 4g L^{-1}, pH: 7.0, C_0: 50mg L^{-1}, T: 30 °C	70%, 168 h (M-orange)	(Shabbir *et al.*, 2017)
SMAP	Dosage: 1g L^{-1}, pH: 5.9, C_0: 20mg L^{-1}, T: 45 °C	100%, 1 h (M-orange)	(Xie *et al.*, 2021)
SMAP	Dosage: 1g L^{-1}, pH: 5.7, C_0: 20mg L^{-1}, T: 45 °C	96%, 2.5 h (M-blue)	(Xie *et al.*, 2021)
Aluminum foam	pH: 7.2, C_0: 20mg L^{-1}, with ultrasound and direct electric current	100%, 8 h (M-orange)	(Liu *et al.*, 2018)

Table 4. Methyl orange/methyl blue removal by different materials.

cycles [*Figure 10(c)*]. The removal of methyl orange by SMAP can be attributed to the released electrons from Al attacking -N=N- bonds in methyl orange molecules [Eqs. (16)-(19)] (Shabbir *et al*., 2017), which then directly decomposed into small organic fragments, achieving the purpose of decolorization or lowering wastewater toxicity. In contrast, methyl blue removal using SMAP proceeds based on the synergistic effects of the reduction mechanism and Al surface adsorption: Initially, the methyl blue molecules gained the electrons released from Al and decomposed into small organic fragments; then these fragments would be adsorbed by the surface of the Al particles. *Table 4* compares the methyl orange or methyl blue removal performances using various materials.

$$Al \rightarrow Al^{3+} + 3e^- \quad (16)$$

$$2H_2O + 2e^- \rightarrow H_2\uparrow + 2OH^- \quad (17)$$

$$Ar_1\text{-}N{=}N\text{-}Ar_2 + e^- + H_2 \rightarrow Ar'_1\text{-}NH{=}NH\text{-}Ar'_2 \quad (18)$$

$$Ar'_1\text{-}NH\text{-}NH\text{-}Ar'_2 \rightarrow Ar'_1\text{-}NH_2 + HN_2\text{-}Ar'_2 \quad (19)$$

3.3. SMAP Used for Bromate Ion Removal

Bromate belongs to Group 2B carcinogens to humans according to the classification of the International Agency for Research on Cancer (IARC) because even a low dosage of bromate can lead to oxidative deoxyribonucleic acid (DNA) damage (WHO, 2011). WHO has set 0.01 mg L^{-1} of bromate as the upper limit in drinking water (WHO, 2011).

Zhou *et al*. (2021) adopted four methods—soaking, soaking and then cold drying, soaking and then heat treatment, and γ-Al_2O_3 modification—to treat the Al particle surface oxide layer. The structure of the Al surface oxide layer became loose after using different surface treatment processes, in contrast to that of the raw Al powder (*Figure 11*). The researchers found that the surface treatment processes remarkably increased the bromate removal efficiency by Al under neutral aqueous conditions. The bromate ion removal kinetics by Al with different surface treatment processes ranked as γ-Al_2O_3 modification > soaking > soaking and then cold drying > soaking and then heat treatment > raw Al powder [*Figure 12(a)*]. Like the Al-water reaction for hydrogen generation, the enhanced effect of surface modification on bromate ion removal by Al powder is attributed to the fact that the surface treatment would increase the hydration process in the Al surface oxide layer and consequently increase the breakage of the Al surface hydrated oxide layer. This leads to quick contact between the aqueous bromate ions and the inner fresh Al. Consequently, the bromate removal kinetics by Al would be remarkably increased, as illustrated in *Figure 8*. Interestingly, the Al encountered different surface treatment processes that exhibited good reusability in bromate removal. Thus, 90% of aqueous bromate could be removed even when the SMAP was reused for four recycles [*Figure 12(b)*]. *Table 5* summarizes the aqueous bromate ion removal performances using different metals.

4. Conclusion and Prospects

Surface modification processes could promote the hydration process in the Al surface oxide layer and increase the breakage of the surface hydrated oxide layer, which is a promising technology used for recovering Al reactivity. In contrast to the usual Al surface treatment methods, such as acid or alkali corrosion, alloying and ball milling, the surface modification method has unique advantages: a simple fabrication process, no corrosion to reaction facilities and low cost. These merits endow SMAP with a

Materials	Dosage ($g\ L^{-1}$)	pH	$C_0(BrO_3^-)$ ($mg\ L^{-1}$)	T (°C)	Removal ratio and time	Ref.
SMAP	2.0	5.7	16	35	100%, 30min	(Zhou *et al*., 2021)
Acid-washed Fe	25	6.0-6.5	5.0	20	100%, 30min	(Xie and Chang, 2006)
Acid-washed Zn	5.0	3.0	10	20	100%, 60min	(Lin *et al*., 2017)
Acid-washed Al	3.5	3.0	10	60	100%, 30min	(Lin *et al*., 2017)
Acid-washed Al + oxalic acid	3.5	7.0	10	60	100%, 20min	(Lin *et al*., 2017)

Table 5. Bromate removal by different materials.

strong application potential in the fields of clean energy generation and water treatment. The mechanisms of Al-water reactions for hydrogen generation and Al-pollutant reactions for water treatment are both essentially based on the reduction effect because Al is naturally an excellent electron donor.

Although Al surface modification has been widely studied in the fields of Al-water reaction for hydrogen generation and water treatment, several emergent problems for SMAP in the practical applications still exist:

(1) The SMAP-water reaction has slow kinetics under ordinary conditions. The question of how to further elevate Al reactivity under mild reaction conditions through improving the SMAP materials manufacturing process has guiding significance for Al practical application in the Al-water reaction for clean energy generation and water treatment;

(2) Al^{3+} leakage into the aqueous solution accompanying the Al-pollutant reaction process would possibly lead to secondary pollution to water bodies. The Al^{3+} content is a crucial standard of drinking water, with the allowed upper limit of 0.2 mg L^{-1} (Wu *et al*., 2020; US EPA, 2014). Ways to develop a method for aqueous Al^{3+} removal by physical adsorption using activated charcoal, zeolite, bacteria, fungi and algae, etc. should be investigated in detail in future studies;

(3) Present studies about SMAP application in water treatment are mainly based on direct electrons attaching to the chemical bonds, which is hard for mineralization of the organic contaminants. The advanced oxidation processes based on SMAP for Al application in water treatment are worth investigating because the free radicals with high oxidation ability generated in advanced oxidation processes could sufficiently mineralize the aqueous organic contaminants into CO_2 and H_2O;

(4) Reactivity deterioration of SMAP in the Al-water reaction for hydrogen generation or water treatment is an obstacle restricting Al reusability. As the reaction proceeds, the Al surface hydrated oxide layer would become thicker and thicker. So, studies are needed to explore a surface treatment process that can make the Al surface oxide layer more prone to be broken and prevent the Al surface from secondary passivation, both of which are helpful for enhancing Al reusability in practical applications.

References

Ahmad ZU, Yao LG, Lian QY, Islam F, Zappi ME, Gang DD (2020). The use of artificial neural network (ANN) for modeling adsorption of sunset yellow onto neodymium modified ordered mesoporous carbon. Chemosphere 256: 127081-127093.

Ahmad ZU, Yao LG, Wang J, Gang DD, Islam F, Lian QY, Zappi ME (2019). Neodymium embedded ordered mesoporous carbon (OMC) for enhanced adsorption of sunset yellow: Characterizations, adsorption study and adsorption mechanism. Chem Eng J 359: 814-826.

Amberchan G, Lopez I, Ehlke B, Barnett J, Bao NY, Allen A, Singaram B, Oliver SRJ (2022). Aluminum Nanoparticles from a Ga-Al Composite for Water Splitting and Hydrogen Generation. ACS Appl Nano Mater 5: 2636-2643.

Belitskus D (1970). Reaction of aluminum with sodium hydroxide solution as a source of hydrogen. J Electrochem Soc 117: 1097-1099.

Bokare AD, Choi W (2009a). Zero-valent aluminum for oxidative degradation of aqueous organic pollutants. Environ Sci Technol 43: 7130-7135.

Bokare AD, Choi WY (2014). Review of iron-free Fenton-like systems for activating H2O2 in advanced oxidation processes. J Hazard Mater 275: 121-135.

Chen X, Zhao Z, Hao M, Wang D (2013). Research of hydrogen generation by the reaction of Al-based materials with water. J Power Sources 222: 188-195.

Chen XY, Zhao ZW, Liu XH (2014). Hydrogen generation by the hydrolysis reaction of ball-milled aluminium-lithium alloys. J Power Sources 254: 345-352.

Chen YT, Huang LY, Wang HW (2024). Optimization of aluminum hydroxide catalyst for efficient hydrogen generation from aluminum-water reaction. Int J Hydrogen Energ 91: 303-309.

Cheng ZH, Fu FL, Pang YS, Tang B, Lu J (2015). Removal of phenol by acid-washed zero-valent aluminum in the presence of H2O2. Chem Eng J 260: 284-290.

Cheng ZH, Tang B, Dionysiou DD, Fu FL (2016). Adsorption, oxidation, and reduction behavior of arsenic in the removal of aqueous As(III) by mesoporous Fe/Al bimetallic particles. Water Res 96: 22-31.

Deng ZY, Fukasawa T, Ando M, Zhang GJ, Ohji T (2001a). High-surface-area alumina ceramics fabricated by the decomposition of Al(OH)3, J Am Ceram Soc 84: 485-491.

Deng ZY, Fukasawa T, Ando M, Zhang GJ, Ohji T (2001b). Bulk alumina support with high tolerant strain and its reinforcing mechanisms. Acta Mater 49: 1939-1946.

Deng ZY, Fukasawa T, Ando M, Zhang GJ, Ohji T (2001c). Microstructure and mechanical properties of porous alumina ceramics fabricated by the decomposition of aluminum hydroxide. J Am Ceram Soc 84: 2638-2644.

Deng ZY, Liu YF, Tanaka Y, Ye JH, Sakka Y (2005a). Modification of Al particle surfaces by γ-Al2O3 and its effect on the corrosion behavior of Al. J Am Ceram Soc 88: 977-979.

Deng ZY, Liu YF, Tanaka Y, Zhang HW, Ye JH, Kagawa Y (2005b). Temperature effect on hydrogen generation by the reaction of γ-Al2O3-modified Al powder with distilled water. J Am Ceram Soc 88: 2975-2977.

Deng ZY, Ferreira MF, Tanaka Y, Ye JH (2007). Physicochemical mechanism for the continuous reaction of γ-Al2O3 modified aluminum powder with water. J Am Ceram Soc 90: 1521-1526.

Deng ZY, Liu WH, Gai WZ, Sakka Y, Ye JH (2010). Role of modification agent coverage in hydrogen generation by the reaction of Al with water. J Am Ceram Soc 93: 2534-2536.

Fan MQ, Sun LX, Xu F (2010). Feasibility study of hydrogen production for micro fuel cell from activated Al-In mixture in water. Energy 35: 1333-1337.

Fan MQ, Xu F, Sun LX, Zhao JN, Jiang T, Li WX (2008). Hydrolysis of ball milling Al-Bi-hydride and Al-Bi-salt mixture for hydrogen generation. J Alloy Compd 460: 125-129.

Fu FL, Cheng ZH, Dionysiou DD, Tang B (2015). Fe/Al bimetallic particles for the fast and highly efficient removal of Cr(VI) over a wide pH range: Performance and mechanism. J Hazard Mater 298: 261-269.

Fu FL, Han WJ, Cheng ZH, Tang B (2016). Removal of hexavalent chromium from wastewater by acid-washed zero-valent aluminum. Desalin Water Treat 57: 5592-5600.

Fu PY, Yang SY, Bao XJ, Wang HC (2024). Reductive decomplexation of Cu(II)-complexes from copper wastewater by zero-valent aluminum material. Chem Eng J 479: 147705-147716.

Gai WZ, Liu WH, Deng ZY, Zhou JG (2012). Reaction of Al powder with water for hydrogen generation under ambient condition. Int J Hydrogen Energy 37: 13132-13140.

Gai WZ, Fang CS, Deng ZY (2014). Hydrogen generation by the reaction of Al with water using oxides as catalysts. Int J Energ Res 38: 918-925.

Gai WZ, Shi Y, Deng ZY, Zhou JG (2015). Clarification of activation mechanism in oxide-modified aluminum. Int J Hydrogen Energy 40: 12057-12062.

Gao Z, Ji F, Cheng DF, Yin CX, Niu JT, Brnic J (2021). Hydrolysis-Based Hydrogen Generation Investigation of Aluminum System Adding Low-Melting Metals. Energies 14: 1433-1444.

Hao XL, Liu H, Zhang GS, Zou H, Zhang YB, Zhou MM, Gu YC (2012). Magnetic field assisted adsorption of methyl blue onto organo-bentonite. Appl Clay Sci 55: 177-180.

Huang XN, Lv CJ, Wang Y, Shen HY, Chen D, Huang YX (2012). Hydrogen generation from hydrolysis of aluminum/graphite composites with a core-shell structure. Int J Hydrogen Energy 37: 7457-7463.

Kanakasabai P, Rajasekaran R, Sivamani S, Banerjee S (2023). Catalytic Hydrogen Production using Aluminium Water Reaction in the Presence of Alkali. Theor Found Chem Eng 57: S57-S70.

Kumar D, Liu YQ, Yang EH (2023). Simplified kinetics model for hydrogen gas generation from metallic aluminum in municipal solid waste incineration bottom ash. J Environ Chem Eng 11: 111129.

Li QF, Wang HC, Yang SY (2023). Solid regulating the electron transfer of ZVAl by ball milling for enhanced para-nitrophenol reduction: Necessity of iron sources. Sep Purif Technol 327: 124872-124886.

Li X, Li Y, Yang SY (2024). Enhanced mineralization of nitrophenols by a novel C@ZVAl-PS based sequential reduction-oxidation process. Sci Total Environ 950: 175288-175302.

Lin KYA, Lin CH (2016). Simultaneous reductive and adsorptive removal of bromate from water using acid-washed zero-valent aluminum (ZVAl). Chem Eng J 297: 19-25.

Lin KYA, Lin CH, Yang HT (2017a). Enhanced bromate reduction using zero-valent aluminum mediated by oxalic acid. J Environ Chem Eng 5: 5085-5090.

Lin KYA, Lin CH, Lin JY (2017b). Efficient reductive elimination of bromate in water using zero-valent zinc prepared by acid-washing treatments. J Colloid Interf Sci. 504: 397-403.

Liu CM, Huang XY, Zhang HY, Dai JD, Ning CC (2018). The decolouration of methyl orange using aluminum foam, ultrasound and direct electric current. Mate Res Express 5: 015501-015507.

Liu WH, Gai WZ, Deng ZY, Tang JW (2012). Enhancing hydrogen-generation performance of γ-Al2O3 modified Al powder by ultrasonic dispersion. J Am Ceram Soc 95: 1193-1196.

Liu W, Zhang H, Cao B, Lin K, Gan J (2011). Oxidative removal of bisphenol A using zero valent aluminum-acid system. Water Res 45: 1872-1878.

Liu Y, Wang X, Liu H, Dong Z, Li S, Ge H, Yan M (2015). Effect of salts addition on the hydrogen generation of Al-LiH composite elaborated by ball milling. Energy 89: 907-903.

Manilevich FD, Pirskyy YK, Kutsyi A, Berezovets VV, Yartys VA (2024). Aluminium as an efficient energy storage substance for the catalysed generation of hydrogen from water. J Energy Storage 96: 112748-112757.

Mercati S, Milani M, Montorsi L, Paltrinieri F (2013). Optimization of the working cycle for a hydrogen production and power generation plant based on aluminum combustion with water. Int J Hydrogen Energy 38: 7209-7217.

Mutlu RN, Kandasamy J, Kiymaz TB, Güleryuz D, Böncü E, Eroglu E, Goeurokalp I (2024). Optimization of aluminum hydrolysis reactions and reactor design for continuous hydrogen production using aluminum wire feeding. Int J Hydrogen Energy 52: 1390-1403.

Pyun SI, Moon SM (2000). Corrosion mechanism of pure aluminium in aqueous alkaline solution. J Solid State Electr 5: 267-272.

Ravavi-tuousi SS, Szpunar JA (2013). Effect of structural evolution of aluminum powder during ball milling on hydrogen generation in aluminum-water reaction. Int J Hydrogen Energy 38: 795-806.

Ren TF, Zhang YX, Liu JQ, Zhang YQ, Yang SY (2020). Ethanol-assisted mechanical activation of zero-valent aluminum for fast and highly efficient removal of Cr(VI). Appl Surf Sci 533: 147543-147552.

Shabbir S, Faheem M, Ali N, Kerr PG, Wu Y (2017). Periphyton biofilms: A novel and natural biological system for the effective removal of sulphonated azo dye methyl orange by synergistic mechanism. Chemosphere 167: 236-246.

Sohlberg K, Pennycook SJ, Pantelides ST (1999). Hydrogen and the structure of the transition aluminas. J Am Chem Soc 121: 7493-7499.

Soler L, Candela AM, Macanas J, Munoz M, Casado J (2010). Hydrogen generation from water and aluminum promoted by sodium stannate. Int J Hydrogen Energy 35: 1038-1048.

Swamy AKN, Shafirovich E (2014). Conversion of aluminum foil to powders that react and burn with water. Combust Flame 161: 322-331.

US EPA, Drinking water standards and Health Advision Tables [EB/OL]. [2014-04-01]. http://water.epa.gov/drink/standards/hascience.cfm#dw-strandards

Wang CP, Yang T, Liu YH (2014). Hydrogen generation by the hydrolysis of magnesium-aluminum-iron material in aqueous solutions. Int J Hydrogen Energy 39: 10843-10852.

Wang HW, Chung HW, Teng HT, Cao GZ (2011). Generation of hydrogen from aluminum and water-Effect of metal oxide nanocrystals and water quality. Int J Hydrogen Energy 36: 15136-15144.

Wang JQ, Zhang WY, Yang SY (2024). Efficient activation of molecular oxygen across a broad pH range (2.5 to 11) utilizing an aluminum-based solid-phase Fenton reagent. Sep Purif Technol 354: 128780-128790.

Wang W, Chen DM, Yang K (2021). Investigation on microstructure and hydrogen generation performance of Al-rich alloys. Int J Hydrogen Energy 35: 12011-12019.

WHO, Guidelines for drinking-water quality, Fourth edition, (2011) 324. https://www.doc88.com/p-9157319494195.html

Wu S, Yang SY, Liu SJ, Zhang YX, Ren TF, Zhang YQ (2020). Enhanced reactivity of zero-valent aluminum with ball milling for phenol oxidative degradation. J Colloid Interf Sci 560: 260-272.

Xiao F, Liang TX, Liu ZH, Yang RJ, Li JM (2021). Study on the effect of carbon materials with different morphologies on the hydrogen generation performance of aluminum: A strategy to control the hydrogen generation rate of aluminum. J Alloy Compd 879: 160376-160385.

Xie L, Shang C (2006). Effects of copper and palladium on the reduction of bromate by Fe(0). Chemosphere 64: 919-930.

Xie S, Yang Y, Gai WZ, Deng ZY (2021). Oxide modified aluminum for removal of methyl orange and methyl blue in aqueous solution. RSC Adv 11: 867-875.

Yang SY, Yang Z (2023). Mechanism of phase transition on zero-valent aluminum surface and its effect on pollutant removal. Prog Chem 35: 1030-1039.

Yang SY, Zheng D, Chang SY, Shi C (2016). Zero valent aluminum based oxidation/reduction technology applied in water treatment. Prog Chem 28: 754-762.

Yang Y, Gai WZ, Deng ZY, Zhou JG (2014). Hydrogen generation by the reaction of Al with water promoted by an ultrasonically prepared Al(OH)3 suspension. Int J Hydrogen Energy 39: 18734-18742.

Yang Y, Gai WZ, Zhou JG, Deng ZY (2020). Surface modified zero-valent aluminum for Cr(VI) removal at neutral pH. Chem Eng J 395: 125140-125147.

Yavor Y, Goroshin S, Bergthorson JM, Frost DL, Stowe R, Ringuette S (2013). Enhanced hydrogen generation from aluminum-water reactions. Int J Hydrogen Energy 38: 14992-15002.

Zhang JS, Klasky M, Letellier BC (2009). The aluminum chemistry and corrosion in alkaline solutions. J Nucl Mater 384: 175-189.

Zhang SH, Wu MF, Tang TT, Xing QJ, Peng CQ, Li F, Liu H, Luo XB, Zou JP, Min XB, Luo JM (2018). Mechanism investigation of anoxic Cr(VI) removal by nano zero-valent iron based on XPS analysis in time scale. Chem Eng J 335: 945-953.

Zhang YX, Yang SY, Zhang YQ, Wu S, Xin J (2018). Enhancement of Cr(VI) removal by mechanically activated micron-scale zero-valent aluminum (MA-mZVAl): Performance and mechanical especially at near-neutral pH. Chem Eng J 353: 760-768.

Zhou W, Yang Y, Gai WZ, Deng ZY (2021). A comparative study on high-efficient reduction of bromate in neutral solution using zero-valent Al treated by different procedures. Sci Total Environ 795: 148786-148794.

Ziebarth JT, Woodall JM, Kramer RA, Choi G (2011). Liquid phase-enabled reaction of Al-Ga and Al-Ga-In-Sn alloys with water. Int J Hydrogen Energy 36: 5271-5279.