



# SYNTHESIS OF AN AMINOSILANE-MODIFIED IRON OXIDE–SILICA COMPOSITE FOR AMPICILLIN REMOVAL FROM AQUEOUS SOLUTION

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## ABSTRACT

Antibiotic residues in aquatic environments contribute to antimicrobial-resistance risks and require effective removal technologies. In this study, an aminosilane-modified iron oxide–silica composite (FNS) was synthesized and evaluated for ampicillin (AMP) removal from aqueous solution. The iron-oxide component was prepared by alkaline precipitation of Fe(III), while amine-functionalized silica was obtained by a sol–gel route using tetraethyl orthosilicate (TEOS) and (3-aminopropyl)trimethoxysilane (APTMS). The two components were combined at iron oxide:NH<sub>2</sub>/SiO<sub>2</sub> mass ratios from 1:1 to 1:7. The 1:3 composite exhibited the highest AMP removal, approximately 82% under the investigated conditions, although BET surface area continued to increase at larger silica fractions. AMP removal was strongly pH-dependent, with the best performance at pH 4, and the removal profile approached a plateau after about 120 min. The pH response, together with the point of zero charge (pH<sub>pzc</sub> ≈ 3.46), supports a mechanism governed by the combined effects of surface charge, AMP speciation, hydrogen bonding, and specific interactions between AMP functional groups and silanol, amine, and oxide surface sites. These results show that the adsorption performance of FNS is controlled by a balance between accessible surface area and interfacial chemistry rather than by BET area alone.

**KEYWORDS:** Antibiotic; Adsorption; Wastewater treatment; Silica; Iron.

## 1. INTRODUCTION

Antibiotic contamination in aquatic environments has become an increasingly important environmental concern because the continuous release of pharmaceutical residues can contribute to ecological toxicity and the development of antimicrobial resistance. Ampicillin (AMP), a widely used  $\beta$ -lactam antibiotic in human and veterinary medicine, is frequently introduced into water bodies through domestic wastewater, livestock effluents, and pharmaceutical discharges. Conventional biological treatment processes are often insufficient for complete AMP removal because of its chemical stability and persistence at low concentrations. Therefore, developing an efficient, recoverable, and practically applicable adsorbent is necessary for advanced water and wastewater treatment.

Iron oxide nanoparticles are attractive adsorbent components because of their surface reactivity and potential magnetic recoverability, while silica provides a stable, porous framework that can be readily functionalized. Aminosilane modification introduces surface –NH<sub>2</sub> groups that may enhance AMP uptake through electrostatic attraction, hydrogen bonding, and acid–base interactions. However, adsorption performance does not depend solely on surface area; it is also controlled by the balance between iron oxide content, amine-functionalized silica, surface charge, and solution pH. This creates a need to identify an appropriate composite composition and clarify the adsorption behavior of AMP under relevant operating conditions.

In this study, an aminosilane-modified iron oxide–silica composite (FNS) was synthesized and evaluated for AMP removal from aqueous solution. The effects of composite ratio,

solution pH, and contact time were systematically examined, and the adsorption mechanism was interpreted using surface-charge behavior and AMP speciation. The material is intended as a reusable, easily separable adsorbent for polishing antibiotic-contaminated wastewater, particularly livestock and decentralized treatment streams where simple operation and rapid solid recovery are essential. Such a system could also reduce downstream treatment demand and secondary contamination risks.

## 2. LITERATURE REVIEW

### 2.1. The real situation of antibiotic abuse in livestock

Antibiotic resistance is regarded as a serious global crisis [1, 2]. The world is facing a post-antibiotic era, when very normal diseases can also be fatal to humans. This is the inevitable consequence of indiscriminate use of antibiotics, doctors prescribing drugs for patients is not really reasonable. In addition, the use of antibiotics in livestock, poultry and aquaculture is not fully controlled. This led to Japan and the EU to warn about antibiotic residues, and required 19 businesses and processing establishments to export seafood and seafood from Vietnam to have shipments to the EU and Japan ensure food safety, seriously investigate, determine causes and overcome consequences [3]. The two main products warned were shrimp and catfish. The main reason is that these products contain antibiotic residues exceeding the allowable limit or the detection of banned chemical residues. Unnecessary use or misuse of the antibiotic can lead to antibiotic resistance, reducing the effectiveness of the drug.

To stimulate animal growth, reduce feed consumption, to increase profits, many farms use large amounts of antibiotics

[4, 5]. Mixing antibiotics directly into food without regard to the health of consumers, however, this has caused very dangerous harm to human health. Currently, farms often use antibiotics to supplement food and water for livestock to prevent common diseases such as intestinal and respiratory diseases. Even the use of banned antibiotics, antibiotics limited to use in livestock. For the purpose of disease prevention, people often use low doses, not enough to kill bacteria, so it is easy to create antibiotic resistant strains. This is quite dangerous because if the animals and animals get sick, when they are resistant to the drug, these diseases will not go away but are at risk of getting worse. Currently, there are pharmacies that easily sell antibiotics to patients without a prescription from a doctor [1, 2, 6-11]. This makes antibiotics not only incurable, but also causes the human body to produce resistant bacteria that are dangerous for the patient. Only infectious diseases should be indicated for the use of antibiotics, for the majority of bacterial infections, antibiotics should be used [12-15].

## 2.2. Abuse of Ampicillin in medicine

In particular, Ampicillin (AMP) is an oral antibiotic of the penicillin group used to treat some common infections such as urinary tract infections, pharyngitis, respiratory infections, sinusitis treatment, otitis media, chronic bronchitis, epiglottitis caused by susceptible strains of bacteria, treatment of gonorrhea, treatment of sepsis in infants and young children, treatment of meningitis, bacterial infections in lung [16-19]. It works by killing bacteria by interfering with bacterial cell formation while the cell is growing. That causes the cells to weaken and rupture, causing bacterial death. AMP is not effective against influenza, colds or other viral illnesses. AMP is produced into an antibiotic with a variety of dosage forms. For example, hard capsules are taken by mouth; powder for injection. AMP is sometimes combined with another active ingredient to increase its antibacterial effect such as AMP-sulbactam. The detail formation of AMP was listed in the Table 1 below [18, 19].

**Table 1. AMP molecular structure and physical-chemical properties**

| Physical description                           |                                                                                     |
|------------------------------------------------|-------------------------------------------------------------------------------------|
| Synonym                                        | D-(-)- $\alpha$ -Aminobenzylpenicillin                                              |
| Chemical structure                             |  |
| Group                                          | Beta - lactam, penicillin A group                                                   |
| Empirical formula                              | C <sub>16</sub> H <sub>19</sub> N <sub>3</sub> O <sub>4</sub> S                     |
| Molecular weight                               | 349.40                                                                              |
| Impurity                                       | ≤ 1%                                                                                |
| Appearance                                     | White powder                                                                        |
| Melting point                                  | 200 °C                                                                              |
| Acid dissociation constant (pKa)<br>(at 25 °C) | pK <sub>a1</sub> = 2.6 (carboxyl)<br>pK <sub>a2</sub> = 7.4 (amine)                 |
| Solubility                                     | 50 mg/mL in 1 M HCl and 10 mg/mL in water                                           |
| Technical grade                                | Analytical standard                                                                 |

AMP is a broad spectrum antibiotic that is active against both Gram-positive and Gram-negative cocci. AMP has good effects on some intestinal Gram-negative bacteria such as *E. coli*, *Proteus mirabilis*, *Shigella*, *Salmonella*. With its antibacterial spectrum and pharmacokinetic properties, AMP is often chosen by doctors to treat urinary tract infections, cholecystitis and cholangitis.

## 2.3. Applications of iron oxide and polymer

At present, adsorbents prepared with nanometer-sized metal oxides are receiving the attention of many publications because of their great adsorption efficiency, as compared with other materials such as rice husk, biochar, clay minerals, and soil minerals. One of the metal oxides that are commonly used to remove pollutants is iron oxide, especially Fe<sub>2</sub>O<sub>3</sub>. Iron oxide Fe<sub>2</sub>O<sub>3</sub> has been synthesized by some other recent authors, however, the use of Fe<sub>2</sub>O<sub>3</sub> for adsorption of antibiotic residues in solution is less mentioned. Depending on the preparation method, Fe<sub>2</sub>O<sub>3</sub> obtained has its own morphological and physical

and chemical characteristics. With the aim of preparing Fe<sub>2</sub>O<sub>3</sub> as an adsorbent, we synthesize Fe<sub>2</sub>O<sub>3</sub> with lattice fringes, porous structure and large specific surface area by iron salt (III) precipitation method.

Furthermore, (3-Aminopropyl) trimethoxysilane (APTMS) is an aminosilane which is used in silanization processes as a silane coupling agent for modification of silica surfaces. APTMS provides chemical crosslinking, immobilized composite, improved polymer, particle dispersion and enhances adhesive bonding. Many authors have shown that this polymer has good surface stability with metal oxide nanoparticles and binds effectively together. .

## 3. METHODOLOGY

### 3.1. Reagents and dissolutions

All solutions were prepared in deionized water (DI water) with specific resistivity. AMP solutions were prepared daily by dilution of a 1.0 g/L standard solution. All chemicals were



analytical grade and used without further purification, Cemaco Co., Ltd, Merck-German, Vietnam.

### 3.2. Determination of AMP removal efficiency and adsorption capacity

Removal of AMP concentration was measured by UV/VIS spectrophotometer. Percentage removal of AMP was calculated as:  $R(\%) = (C_0 - C_t)/C_0 \times 100\%$ . There, R is removal efficiency,  $C_0$  is the initial AMP concentration, and  $C_t$  is the final AMP concentration. The AMP adsorption capacity is described by mass balance as following:  $q_t = [(C_0 - C_t) \times V]/m$ . There,  $q_t$  is the quantity of AMP retained per gram of adsorbent at a certain time t (mg/g),  $C_0$  is the initial concentration of AMP,  $C_t$  is the concentration of AMP at time t (mg/L), V is the volume (L) of AMP, and m is the mass of adsorbent (g).

The concentration of AMP in the aqueous phase was detected by UV-Vis absorption method at the wavelength of 204 nm (Genesis 10S UV-VS, Thermo Scientific). The magnetic properties of samples were investigated using a LakeShore-7305 vibrating sample magnetometer (VSM) at room temperature (RT).

### 3.3. AMP adsorption tests

The process of AMP adsorption by adsorbent is investigated under static conditions, using a variable method to determine the optimal conditions for the adsorption process. The pH factor was changed from 2.0 to 13.0 using NaOH and HCl solutions, the adsorption time was changed from 0-300 min. The concentration of AMP before and after the adsorption process is determined by UV-Vis method at 204 nm, after the product is repeatedly centrifuged to remove the adsorbent.

### 3.4. Preparation of adsorbents

#### Preparation of $Fe^{3+}$ nanoparticles

$Fe_2O_3$  was generated by facile precipitation pathway, using the certain amount of iron III chloride salt ( $FeCl_3 \cdot 6H_2O$ ) and ammonia solution. 10 g of  $FeCl_3 \cdot 6H_2O$  salt was added to DI water to reach a homogeneous solution, and 150 mL of  $NH_4OH$  (27%) solution was gradually added to the system under constant stirring, and pH = 11. The precipitated solid was separated, washed, and heated in a furnace for 12 h at 250 °C, with a heating rate is 10 °C/min. The final powder was washed by liquid ethanol (EtOH) to remove the impurities, then grinded into tiny pieces by ball milling grinder to form iron oxide nanoparticles  $Fe_2O_3$  in fine size.

Preparation of aminosilane silica ( $NH_2/SiO_2$ ) by sol-gel method

A nanopowder of  $NH_2/SiO_2$  was prepared by the sol-gel method as the previously reported papers with a modification [20]. 10 mL of tetraethyl orthosilicate (TEOS ~ 99.9%) and 2.5 mL of (3-Aminopropyl)trimethoxysilane (APTMS 97%) was dissolved in 60 mL EtOH and sonicated in an ultrasonic bath for 2 h at room temperature (RT). The volume ratio of TEOS/APTMS/EtOH was fixed at 1:0.25:6, respectively. The sol-gel products were centrifuged at 4000 rpm in 1 h, and then repeatedly washed with EtOH and DI water, freeze dried in 24 h. The sample was designated as APTMS/ $SiO_2$  (or  $NH_2/SiO_2$ ).

#### Grafting iron nanoparticle with $NH_2/SiO_2$

The synthesis of aminosilane crosslinked silica incorporated iron nanoparticles was conducted according to synthesized 1; 2; 3; 4; 5; 6; and 7 adsorbent composite, which the weight ratios between  $Fe_2O_3$  and  $NH_2/SiO_2$  were 1; 2; 3; 4; 5; 6; and 7 wt %, respectively. The mixture was dispersed in 100 mL EtOH and sonicated under an ultrasonic bath for 6 h at RT, led to the  $Fe^{3+}$  particles were grafted  $NH_2/SiO_2$  (denoted as FNS material). The final black gelation was collected by a magnet and washed several times with DI water and EtOH to remove impurities. The powder was freeze-dried at 105 °C for 24 h.

#### Material characterization

The specific surface area and pore volume were determined by gas adsorption (BET method). Surface charge was evaluated by zeta-potential measurements as a function of pH, and the point of zero charge was estimated from the sign change in zeta potential. The original experimental section also identifies a LakeShore-7305 vibrating sample magnetometer (VSM) for room-temperature magnetic measurements.

#### Batch adsorption experiments and analytical determination

Batch adsorption experiments were conducted under static conditions while varying one operating factor at a time. The investigated pH range was 2–13, adjusted using HCl or NaOH. Contact time was varied from 0 to 300 min. AMP concentration in the aqueous phase was determined by UV-Vis spectrophotometry at 204 nm (GENESYS 10S UV-Vis, Thermo Scientific). Suspended adsorbent was removed before analysis by centrifugation. Removal efficiency, R, and adsorption capacity at time t,  $q_t$ , were calculated as:

$$R(\%) = [(C_0 - C_t)/C_0] \times 100 \quad (1)$$

$$q_t = [(C_0 - C_t)V]/m \quad (2)$$

where  $C_0$  and  $C_t$  (mg  $L^{-1}$ ) are the initial and time-t AMP concentrations, V (L) is solution volume, and m (g) is adsorbent mass. Equilibrium capacity  $q_e$  is calculated analogously using  $C_e$ .

## 4. RESULTS

### 4.1. Characterizations of adsorbent

Table 2. BET surface area and pore volumes of synthesized FNS

| Compositions                 | BET Surface area ( $m^2/g$ ) | Pore volume ( $cm^3/g$ ) |
|------------------------------|------------------------------|--------------------------|
| 1 $Fe_2O_3$ : $NH_2-SiO_2$   | 43.7                         | 0.29                     |
| 1 $Fe_2O_3$ : 2 $NH_2-SiO_2$ | 52.9                         | 0.29                     |
| 1 $Fe_2O_3$ : 3 $NH_2-SiO_2$ | 65.4                         | 0.30                     |
| 1 $Fe_2O_3$ : 4 $NH_2-SiO_2$ | 73.2                         | 0.31                     |
| 1 $Fe_2O_3$ : 5 $NH_2-SiO_2$ | 85.2                         | 0.34                     |
| 1 $Fe_2O_3$ : 6 $NH_2-SiO_2$ | 93.3                         | 0.34                     |
| 1 $Fe_2O_3$ : 7 $NH_2-SiO_2$ | 101.5                        | 0.33                     |



In the Table 2 shows the variable values of BET surface area and pore volume of synthesized FNS. As can be seen that while the amount (by weight percent) of  $\text{NH}_2\text{-SiO}_2$  increased, led to BET value of final product also increased, and reached at the highest BET value of  $101 \text{ m}^2/\text{g}$ . It was suggested that after the modification, the value of BET surface area (textural structure) of FNS might be enhanced and improved to some extent, and only a slight changes in pore volume values from 0.29 to  $0.34 \text{ cm}^3/\text{g}$ .

#### 4.2. Effect of solution pH

Due to the protonation/neutral/deprotonation of AMP and the change of the surface charge of FNS correlated to the solution pH. Therefore, the pH value played a critical role for the AMP adsorption. The AMP adsorption onto FNS was demonstrated in pH range from 2.0 to 13.0, and the results were determined in Fig. 2a. The adsorption efficiencies were stable and desired at acidic pH ranged from 3.0 to 6.0, and reached

optimum condition at pH 4. However, the adsorption removal decreased dramatically while increasing pH value above 6.0. It suggested that in the alkaline environment, the removal efficiency of AMP by FNS was unfavorable. The main reason for the optimum pH range will be evaluated in the next part in this study, and the fixed pH 4 will be remained for further tests.

#### 4.3. AMP removal on the view of phase contact time

To choose the optimum ratio of material in FNS for the AMP adsorption, the time-dependent adsorption of AMP on FNS was examined for the comparison. The results adsorption tests were found at an ideal weight ratio of  $1\text{Fe}_2\text{O}_3 + 3\text{NH}_2\text{-SiO}_2$ , provided much larger AMP adsorption efficiencies, as compared with other products (Fig. 1). Thus the equilibrium time for the AMP adsorption was around 120 min, a slight improvement from 150 to 200 min, and did not changed after 200 min. The fixed pH 4, and time = 130 min will be fixed for further tests.

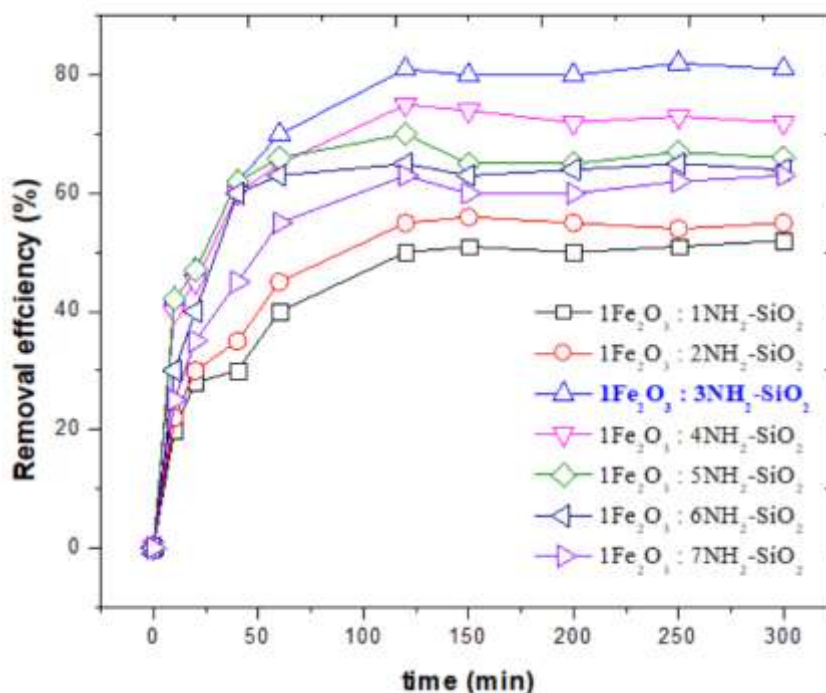


Fig. 1. Removal percentages of AMP on various ratio (w/w %) of synthesized FNS (conditions:  $C_0$ : 20 ppm,  $m_{\text{FNS}}$ : 20 mg, time: 0-300 min, pH = 4, and V: 20 mL)

#### 4.4. Rational adsorption mechanism

Several proposed mechanisms had been employed to interpret the phase adsorption mechanism of antibiotic, such as

chemical bonds, electrostatic forces, stronger bonding of surface functional groups, and surface complexation.

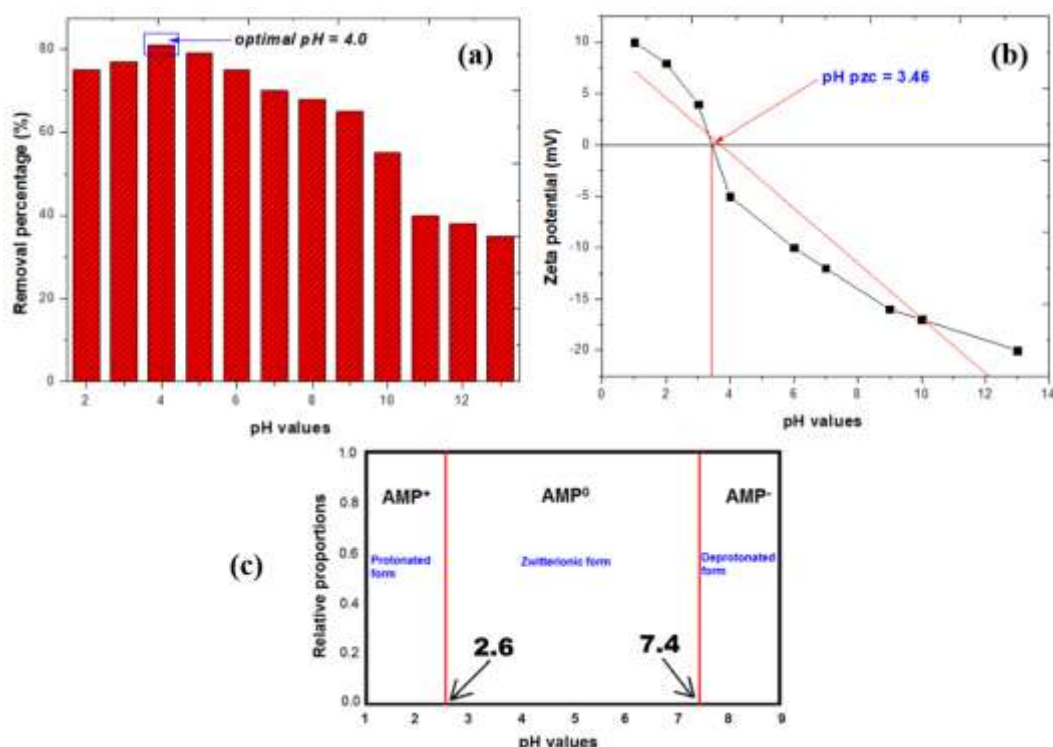


Fig. 2. (a) Influence of pH on the AMP removal (conditions:  $C_0$ : 100 ppm,  $m_{FNS}$ : 50 mg, time: 140 min, pH = 4, and V: 200 mL), (b)  $pH_{pzc}$  value of FNS, and (c) AMP forms with protonation/deprotonation sites

#### 4.5. Electrostatic force

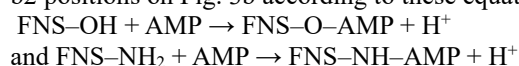
The zeta potential data ( $pH_{pzc}$  value) of FNS shown in Fig. 2b revealed that the surface charge of FNS is positive at pH below 3.46, and negative at a pH above 3.46. The existence of AMP charge molecules suitable for the presence of acid-base functional groups in its structure such as amine, and carboxylic acid. AMP can play a role as both weak base and weak acid because of the lone pair electrons on the nitrogen atom (amine group), and hydrogen atom on carboxylic group ( $COOH$ ). On the other hand, AMP can display anions, cationic and zwitterionic forms when amino group, phenol and carboxylic were presented [21]. Fig. 2c shows the AMP forms in three types of protonation, zwitterionic and deprotonation, and the  $pK_a$  values of AMP are  $pK_{a1}=2.6$ ,  $pK_{a2}=7.4$ . Therefore, protonated AMP, neutral AMP, and deprotonated AMP existed while the solution pH is below 2.6, from 2.6 to 7.4, and above 7.4, respectively. Considering the impact of pH shown in Fig. 2a, electrostatic force can be regarded for the proposed

mechanism. However, it is really difficult to explain the significant removal percentage (R%) of pH 2. At pH 2, R% is around 75 %, the surface charge of FNS is positive, and the positive  $AMP^+$  (deprotonated form), thus the electrostatic force was impossible to explain this case. There might be another mechanism affected to the AMP removal.

#### 4.6. Surface complexation by functional groups

As shown in Fig. 3a, FNS has several surface functional groups such as hydroxyl, silanol, amine, which are able to exchange proton with AMP molecule.

The proton (hydrogen ion) of hydroxyl group and amine group on the surface of FNS was able to exchange with AMP, led to form the surface complexations as shown in the b1 and b2 positions on Fig. 3b according to these equations:



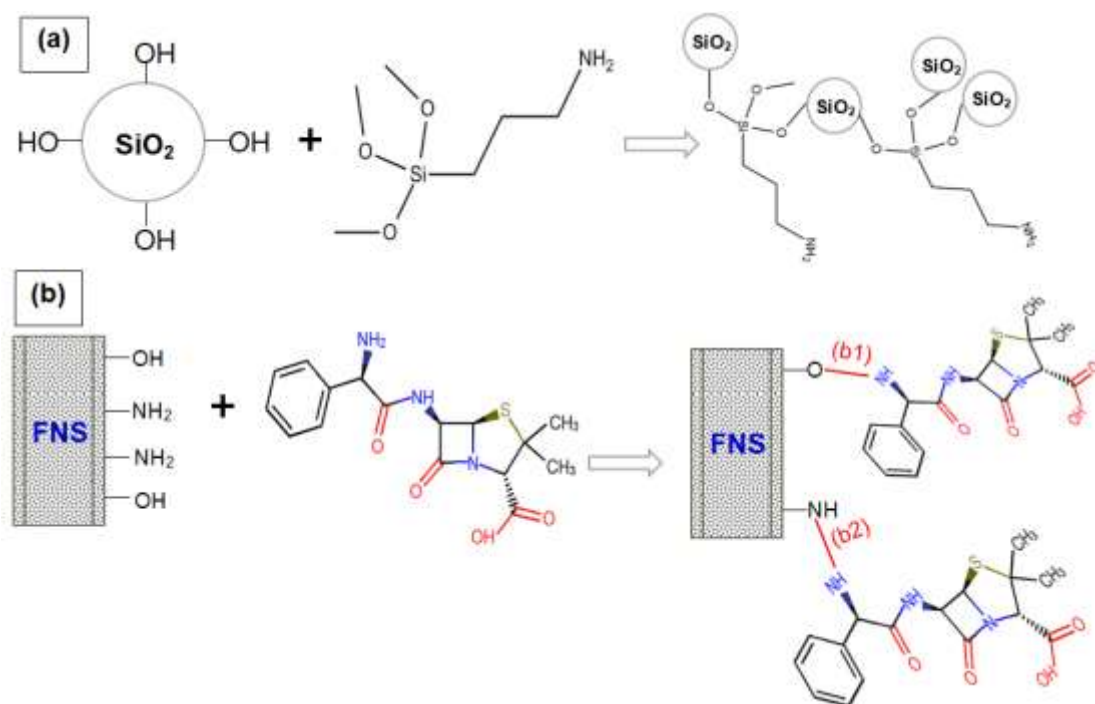


Fig. 3. (a) Existed surface functional groups on FNS, and (b) plausible adsorption mechanisms

## 5. CONCLUSION

In conclusion, FNS was successfully fabricated and demonstrated as a promising material for AMP removal from solution. The AMP adsorption was significantly influenced by solution pH and agitation time. FNS displayed a favorable adsorption under acidic conditions, with the optimum performance observed at pH 4 and 120 min. The ratio of Fe<sub>2</sub>O<sub>3</sub> and NH<sub>2</sub>/SiO<sub>2</sub> at 1:3 investigated the most effective AMP removal. Based on the pH-dependent tests, the pH<sub>pzc</sub> value, and the surface chemistry of the material, AMP adsorption was attributed to a combination of electrostatic interactions, proton exchange, and surface complexation involving hydroxyl, silanol, and amine groups.

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