Efficient degradation of amoxicillin using Bi$_2$O$_3$ /Fe synthesized by microwave-assisted precipitation method

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Abstract: Bi$_2$O$_3$/Fe material has been successfully synthesized using the microwave-assisted precipitation method. This study aims to analyze the effect of Fe on the characteristics of Bi$_2$O$_3$ and its ability to photodegrade amoxicillin. XRD characterization showed that all samples (Bi$_2$O$_3$/Fe 0–9%) formed an α-Bi$_2$O$_3$ phase. The addition of Fe concentration did not significantly change the crystal structure of α-Bi$_2$O$_3$. The morphology of Bi$_2$O$_3$/Fe is mostly rod and spherical porous which is indicated as Bi$_2$O$_3$ and Fe particles. EDX characterization informed that all samples contained Bi, O, and Fe elements which were evenly distributed. The addition of Fe up to 3% will increase the crystallite size and specific surface area of Bi$_2$O$_3$ but decrease the energy gap. Meanwhile, the addition of more than 3% Fe causes an increase in the energy gap of the Bi$_2$O$_3$ but will decrease the crystallite size and specific surface area. Bi$_2$O$_3$/Fe 3% is the best sample because it has the largest crystallite size (29.1 nm), the lowest energy gap (2.02 eV), the largest specific surface area (6.864 m$^2$/g), and can degrade amoxicillin to 76.34% with a degradation rate of 0.0079 min$^{-1}$.

Subjects: Physical Chemistry; Environmental Chemistry; Composites

Keywords: Bi$_2$O$_3$/Fe; microwave irradiation; photodegradation; amoxicillin

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PUBLIC INTEREST STATEMENT

Amoxicillin is one of the most used antibiotics. The use of antibiotics of amoxicillin which is quite a lot in daily life in addition to providing health benefits, also make one source of pollution of the water environment through medical waste. The existence of amoxicillin in the water environment can damage the environment and threaten health. Photocatalyst material currently has an important role in the degradation of medical waste. In this study, we found effective and efficient material for the degradation of amoxicillin medical waste, namely Bi$_2$O$_3$/Fe which was synthesized using the precipitation method assisted by microwave radiation. It is hoped that this discovery is useful for overcoming water environmental problems by Amoxicillin medical waste.
1. Introduction

In recent years, environmental pollution from liquid medical waste has become increasingly widespread. It is a challenge for both researchers and the pharmaceutical industry because drugs produce medical waste that can threaten ecosystems and human health (Wang et al., 2019). One of the medical waste that is a source of environmental pollution is amoxicillin. Amoxicillin (AMX) is the most widely used type of antibiotic because of its extraordinary antibacterial properties (Jung et al., 2012). However, AMX has low biodegradability and remarkable stability with many complex aromatics in its molecule, making it difficult to destroy by conventional methods (Zhang et al., 2019). Therefore, we need the proper technique to degrade AMX efficiently.

Several alternatives have been carried out to remove these compounds, including reverse osmosis, adsorption, and advanced oxidation technologies such as fenton reaction, ozonation, and photocatalytic technology (Benitez et al., 2011). Photocatalytic shows promising prospects among these methods due to its sustainability and environmental friendliness (Wang et al., 2018). Bismuth oxide (Bi$_2$O$_3$) is a photocatalyst material that is of interest to researchers because of its high redox inversion, environmental friendliness, thermal stability, and energy bandgap between 2.58 and 2.85 eV, which shows a response to visible light (Basith et al., 2018). The phase (monoclinic) Bi$_2$O$_3$ has semiconductor properties, is stable at low temperatures, and is more energy-efficient in the synthesis process (Gadhi et al., 2016). However, photon-induced electron–hole pairs have poor light utilization and fast recombination rates limiting photocatalytic activity (Zhou et al., 2019).

In this study, the Bi$_2$O$_3$ semiconductor will be inserted with Fe material with the microwave-assisted precipitation method. This experiment is believed to increase the rate of electron–hole pair separation by acting as a shallow trap where the permissible energy states are close to the conduction band and valence band and reduce the rate of electron–hole pair recombination in Bi$_2$O$_3$ materials (Zhu et al., 2011). Finally, the authors hope to be able to produce innovative materials that are effective in degrading AMX.

2. Experiment method

2.1. Synthesis of Bi$_2$O$_3$/Fe

Bi$_2$O$_3$/Fe was synthesized using a microwave-assisted precipitation method. The synthesis process of Bi$_2$O$_3$/Fe is shown in Figure 1. Bi(NO$_3$)$_3$·5H$_2$O 0.5 g and Fe(NO$_3$)$_3$·9H$_2$O with different mass...
(1/100, 3/100, 5/100, 7/100, 9/100) (%wt) were dissolved in 50 ml of 5% HNO₃ solution (1 mol/l) stirred for 10 minutes using a magnetic stirrer on a hot plate at room temperature. A total of 250 ml of NaOH (1 mol/l) was added to the solution and stirred for 2 hours, then allowed to stand to produce a precipitate. The precipitate was separated and heated on a hotplate for 2 hours at 120°C to produce a still moist Bi₂O₃/Fe powder. Furthermore, the resulting Bi₂O₃/Fe powder was then dried by exposing it to 100 Watt microwave power for 3 hours.

### 2.2. Characterization

Structural analysis of Bi₂O₃/Fe powder was carried out using X-Ray Diffraction (XRD Shimadzu 6100/7000 type). The X-ray wavelength used is 1.5406 Å. Data retrieval is carried out every 0.02° angle range. The crystallite size of Bi₂O₃/Fe was calculated using the Debye-Scherrer equation (Equation 1; Xie et al., 2019).

\[ D_s = \frac{k \lambda}{\beta \cos \theta} \]  

(1)

Ds is the crystallite size (nm), \( \lambda = 1.5406 \) Å is the wavelength of X-rays, k = 0.9 is the Scherrer constant, is the Full Width and Half Maximum or FWHM (in radians), and is the Bragg angle of diffraction or peak position (in degree).

The surface morphology of Bi₂O₃ powder was obtained from the Scanning Electron Microscopy and Energy Dispersive X-Ray (SEM-EDX) characterization data. The SEM-EDX image is used to determine the element, shape, and particle size. The specific surface area was obtained from the Surface Area Analyzer (SAA) characterization. UV-Vis transmittance data of Bi₂O₃/Fe powder was used to determine the energy band gap value.

### 2.3. Amoxicillin degradation

The degradation was carried out by adding 0.02 g of Bi₂O₃/Fe powder into 50 ml of 10 ppm AMX solution obtained by dissolving 10 mg of AMX powder (Amoxicillin Trihydrate 500 mg generic) into 1 liter of distilled water. The solution was irradiated with UV light for 180 minutes, and the degradation products were taken every 30 minutes. The degradation results were analyzed using a UV-Vis Spectrophotometer UHS5300 (Hitachi, Japan). Photocatalyst efficiency (EF) is calculated using Equation 2. (Sudrajat et al., 2018).

\[ EF(\%) = \left(1 - \frac{C_f}{C_0}\right) \times 100\% \]  

(2)

where \( C_0 \) and \( C_f \) are the initial and final concentrations of the solution.

### 3. Results and discussions

Bi₂O₃/Fe has been synthesized using a microwave-assisted precipitation method. This method is very advantageous because it is energy-intensive, homogeneous, efficient, can reach high temperatures, and start reactions quickly. Microwaves simplify and speed up the synthesis process by generating heat in a short time due to the activity of compounds that oscillate and collide with each other. Simultaneously, microwaves help the growth (nucleation) of the material due to the slight gradient or heat difference that occurs (Fatimah et al., 2015). The high-frequency motion of molecules from microwaves causes the magnetic dipoles of the molecules to change direction very quickly and cause friction. As a result, friction will generate thermal energy used in the sintering process to form a photocatalyst Bi₂O₃/Fe. In addition, molecular vibrations due to microwaves cause chemical bonds in the precursor to be rearranged (Rahmayanti et al., 2015).

The synthesized powder shows a yellow physical color that shifts brownish with increasing Fe concentration, as shown in Figure Figure 2. The color change occurs because Fe(NO₃)₃·9H₂O when
dissolved, forms a brownish to dark-colored solution due to hydrolysis. As the concentration of Fe increases, the reaction shifts in the opposite direction of the substance. Bi₂O₃ added with Fe will shift its color from yellow to brown. It follows Le Chatelier’s Principle, which studies changing conditions on an equilibrium system. If colored ions are added to a reaction, the compound formed will be darker (Prakoso et al., 2012).

To confirm the success of Bi₂O₃/Fe synthesis, the first thing to do is test the crystallinity. Based on the XRD Bi₂O₃/Fe pattern as shown in Figure 3, the resulting diffraction peaks correspond to JCPDS No. 27–0053 with space group P2₁/c, monoclinic crystal system, unit cell parameters; a = 5.83 Å b = 8.14 Å c = 7.48 Å β = 67.07°, and density 9.467 g/cm³ (Devi et al., 2019). The main diffraction peak is at 2θ = 24.54°; 25.75°; 26.91°; 27.38°; 27.99°; 32.30°; 33.08°; 35.04°; 37.60°; 46.31°; and 48.54° with miller index (102), (002), (112), (121), (012), (211), (202), (212), (113), (223), and (104). The synthesized Bi₂O₃ material is in the α-Bi₂O₃ phase. These results indicate that the Bi₂O₃ material has been completely formed and has an excellent level of stability at low temperatures (Chen et al., 2011). There is a difference in intensity in the XRD pattern, but it does not significantly change the lattice structure. Based on the Debye-Scherrer equation, the crystallite size of Bi₂O₃ with the addition of Fe from 0–9%, respectively, was 25.7 nm, 27.1 nm, 29.1 nm, 23.7 nm, 24.0 nm, and 21.7 nm. The addition of Fe resulted in differences in the size of the resulting crystals. The smaller the FWHM, the crystallinity is better.

The resulting crystallite size is inversely proportional to the FWHM value (Table 1), while the intensity of each crystal plane influences the FWHM value, the higher the intensity, the smaller the FWHM value. The smaller the FWHM value, the better crystal quality because it shows that adjacent atoms are easier to adjust the direction and length of their bonds (Suryanarayana, 1998).

Increasing the concentration of Fe from 5% to 9% causes the emergence of a new phase at 2θ = 41.79°; 43.77°; 45.62°; 52.62°; 54.26°; 55.88°; and 62.05° with miller index (323), (422), (341), (343), (424), (352), and (613) indicated to be the bismuth iron oxide (Bi₂FeO₄) phase.

Figure 2. Physical appearance of the sample Bi₂O₃/Fe: (a) 0% (b) 1% (c) 3% (d) 5% (e) 7% (f) 9%.
according to JCPDS No. 46–0416 (Basith et al., 2018). The phase percentage between \(\alpha\)-Bi\(_2\)O\(_3\) and Bi\(_{25}\)FeO\(_{40}\) was 82.6\%: 17.4\%. It indicates that the 5–9\% Fe doped still has a main phase of \(\alpha\)-Bi\(_2\)O\(_3\), but there is a secondary phase of Bi\(_{25}\)FeO\(_{40}\). The secondary phase is formed due to the addition of a larger Fe dopant concentration in Bi\(_2\)O\(_3\), which causes the Bi and Fe atoms to undergo a reaction so that Fe should partially replace the position of the Bi atom, but due to the high concentration of Fe atom, the position of the Bi atom is completely replaced by Fe atom (Yuwita et al., 2019). The appropriate Fe dopant can increase the crystallite size. However, more than 3\% Fe dopant causes the crystallite size to decrease due to the reaction between Fe and Bi atoms. The difference influences the reaction in the ionic radius of Fe\(^{3+}\) (0.69 Å) smaller than the ionic radius of Bi\(^{3+}\) (1.17 Å). The difference in atomic radius inhibits the Bi nucleation process because the increasing presence of Fe restrains it.

SEM characterization was carried out to determine the surface morphology of the sample. The characterization image can be seen in Figure 4(a–f). Pure Bi\(_2\)O\(_3\) particles are indicated to have like a rod structure (Mukholit et al., 2019), but due to the high agglomeration rate, the rod particles accumulate in one area and form spheres (Figure 4(a)). The addition of 1\% Fe causes the particle surface to become porous (Figure 4(b)). The addition of 3–9\% Fe displayed a porous sphere and rod (Figures 4(c–f)). Particles with a porous spherical shape are indicated as Fe particles (McRae et al.,

**Table 1. 2θ, FWHM, and crystallite size of Bi\(_2\)O\(_3\)/Fe**

| Sample | 2θ (°) | FWHM (rad) | \(D_s\) (nm) |
|--------|--------|------------|-------------|
| 0%     | 27.40  | 0.172      | 25.7        |
| 1%     | 27.38  | 0.168      | 27.1        |
| 3%     | 27.42  | 0.142      | 29.1        |
| 5%     | 27.77  | 0.232      | 23.7        |
| 7%     | 27.83  | 0.234      | 24.0        |
| 9%     | 27.78  | 0.273      | 21.7        |
The number of particles resembling a porous sphere increases with increasing Fe doping concentration. This is consistent with the results of the SEM-EDX mapping (Table 2). The addition of Fe concentration from 1% to 9% increased the %mass and %atoms Fe in the sample. The mapping results also show that the resulting sample contains Bi, O, and Fe elements. However, increasing the concentration of Fe doping resulted in a decrease in the particle size of Bi$_2$O$_3$ because the crystal Bi$^{3+}$ ions were retained during the sintering process. When Fe$^{3+}$ ions are inserted into the Bi$_2$O$_3$ crystal lattice, a certain degree of deformation will be introduced into the lattice due to the difference in ionic radius between Fe$^{3+}$ ions (0.69 Å) and Bi$^{3+}$ ions (1.17 Å), this is similar to the description of previous studies (Liang et al., 2014). Particle size was measured using Image J software. The average particle sizes of Bi$_2$O$_3$ 0–9% were 1.5 $\mu$m, 1.2 $\mu$m, 4.6 $\mu$m, 3.6 $\mu$m, 2.1 $\mu$m, and 1.6 $\mu$m. While the average particle sizes of Fe doped 1–9% were 1.5 $\mu$m, 2.4 $\mu$m, 2.8 $\mu$m, 2.2 $\mu$m, and 1.8 $\mu$m. Particle size measurement through SEM image has a larger size than XRD pattern crystal size measurement because the particles group together which causes agglomeration during synthesis (Hernowo & Nurhasanah, 2019). The structure of Fe, which resembles a porous sphere, can increase the photocatalytic activity of Bi$_2$O$_3$. One of the requirements for
a good photocatalyst material is to have a porous surface to increase the surface area for photon absorption during photocatalysis. The large surface area results in more vacancies, thereby increasing the diffusion between AMX pollutant molecules and the photocatalyst material (Rissa et al., 2012; Sistesya & Sutanto, 2013).

Table 2. Result of SEM-EDX

| Component | Element | 0%  | 1%  | 3%  | 5%  | 7%  | 9%  |
|-----------|---------|-----|-----|-----|-----|-----|-----|
| Mass (%)  | Bi      | 94.66 | 91.04 | 85.23 | 87.19 | 91.35 | 87.52 |
|           | O       | 5.34 | 8.65 | 13.99 | 11.85 | 7.57 | 11.08 |
|           | Fe      | 0    | 0.31 | 0.78  | 0.96  | 1.08 | 1.40 |
| Atomic (%)| Bi      | 57.56 | 44.36 | 31.46 | 35.50 | 47.03 | 36.85 |
|           | O       | 42.44 | 55.08 | 67.46 | 62.03 | 50.89 | 60.94 |
|           | Fe      | 0    | 0.56 | 1.08  | 1.47  | 2.08 | 2.21 |

The results of the Surface Area Analyzer (SAA) to the Bi$_2$O$_3$/Fe samples showed the specific surface area of the Brunauer-Emmet-Teller (BET). The specific surface area is calculated with N$_2$ adsorption-desorption analysis that obtained successive results for Bi$_2$O$_3$/Fe 0–9% were 3.975 m$^2$/g, 3.354 m$^2$/g, 6.864 m$^2$/g, 2.258 m$^2$/g, 3.634 m$^2$/g, and 3.069 m$^2$/g. Bi$_2$O$_3$/Fe 3% has an optimal specific surface area so that it has the best potential in the AMX degradation process. The specific surface area of a large catalyst powder can increase the amount of AMX adsorbed on the surface of the Bi$_2$O$_3$/Fe powder (Nurhasni et al., 2018).

The energy gap value (Figure 5) is obtained by plotting $ahv^2$ and $hv$ of the transmittance spectrum using the Tauc Plot method. Calculation of Energy gap ($E_g$) using Equation 3 (Raizada et al., 2017).

\[
ahv = A(hv - E_g)^{2/3}
\]

The index ($k$) is determined from the Bi$_2$O$_3$ semiconductor optical transition type, namely 4 for indirect transition (Liang et al., 2014) $hv$ is the photon energy, $A$ is the proportionality constant, and indicates the photon energy the absorption coefficient. The synthesized Bi$_2$O$_3$/Fe has an $E_g$ of about 2.02–2.81 eV, presented in Table 2. The addition of a suitable Fe dopant can reduce the energy bandgap of the semiconductor. The minimum energy gap is obtained at the addition of 3% Fe, which is 2.02 eV. A small energy gap indicates that the energy band gap is getting narrower between the valence band and the conduction band. So that when excitation occurs due to the influence of photon energy from UV light irradiation, it will facilitate the production of electrons and holes because the energy needed for electrons to move from the valence band to the conduction band is getting smaller. The higher the production of electrons and holes can increase the photocatalytic activity.

The degradation of AMX determined the photocatalytic activity of Bi$_2$O$_3$/Fe. This photocatalytic activity shows a decrease in absorbance, efficiency, and degradation rate constant. Figure 6(a) showed that the absorbance value of AMX decreased with the length of irradiation time. The longer duration of irradiation resulted in more degrading species from the active Bi$_2$O$_3$/Fe photocatalyst so the greater the concentration of degraded AMX. The efficiency of the Bi$_2$O$_3$/Fe photocatalyst in degrading AMX is shown in Figure 6(b). The highest efficiency was obtained at 3% Fe doping, which was 76.00%.

The rate degradation of Bi$_2$O$_3$/Fe concerning AMX according to the Langmuir–Hinshelwood (L–H) kinetic model, determined by the pseudo-first-order kinetic equation (Equation 4)
Figure 5. The energy gap of Bi₂O₃/Fe: (a) 0%, (b) 1%, (c) 3%, (d) 5%, (e) 7%, (f) 9%.

\[
\ln \frac{C_0}{C} = k_{app} t
\]

(4)

\(C_0\) is the initial AMX concentration (mg/l), \(C\) is the AMX concentration at a certain time \(t\) (mg/l), \(k_{app}\) is the pseudo-first-order rate constant (min\(^{-1}\)) (Qin et al., 2014). The results can be seen in Figure 6(c) and in Table 3. The calculation results of the degradation rate explain that the 3% Bi₂O₃/Fe sample has the highest degradation rate constant of 0.0079 min\(^{-1}\), while 9% Bi₂O₃/Fe has the lowest degradation rate constant of 0.0048 min\(^{-1}\). The rate of degradation describes the speed of the material in degrading waste, the higher the value of the rate of degradation, the faster the material in degrading waste, so that the waste contained in the material is less.

The photocatalytic activity of Fe-doped Bi₂O₃ is higher than that of pure Bi₂O₃ due to the synergistic effect of Fe³⁺ ions and Bi₂O₃. The 3% Bi₂O₃/Fe material has the most significant degradation efficiency. These results indicate that adding Fe up to a concentration limit of 3% in Bi₂O₃ will increase the photocatalytic activity, while the addition of more than 3% will decrease photocatalytic activity. These results are consistent with previous research by Liang et al. (2014). Photocatalytic activity and degradation efficiency can be related to the crystallite size of Bi₂O₃/Fe (Nandiyanto et al., 2020), where the larger the crystallite size of a material, the greater the photocatalytic ability (Armaković et al., 2017; Sharma et al., 2014). In addition, the presence of Fe particles resembling a porous sphere on the surface of the Bi₂O₃ semiconductor as shown in the SEM image also affects the photocatalytic activity. The porous surface can increase the photocatalyst material's surface area, and the presence of Fe transition metal can suppress the electron-hole recombination rate. This is also under the results of the BET analysis, a large specific surface area can increase photocatalytic activity. The value of the obtained Bi₂O₃/Fe energy gap also affects the photocatalytic activity. As presented in Table 3. The minimum Eg occurs at 3% Fe doping, following the results of the photocatalytic activity test, where the efficiency and optimal rate also occur at 3% Fe doping.

Chemically, the degradation of AMX by Bi₂O₃/Fe can be explained as shown in Figure 7. When Bi₂O₃ is irradiated by UV light, the electrons in the photocatalyst material Bi₂O₃ which are in the valence band will be excited to the conduction band. This results in more electrons in the
conduction band, while in the valence band there will be many holes formed due to electrons being excited to the conduction band. Electrons that do not recombine will be trapped on the surface of the semiconductor. Photogenerated electrons and holes combine with Fe$^{3+}$ ions to form Fe$^{4+}$ and Fe$^{2+}$ ions (Equation 5–8).

\[ \text{Bi}_2\text{O}_3 + \text{hv} \rightarrow \text{e}^- + \text{h}^+ \]  

(5)

| Sample | Efficiency (%) | Degradation rate (min$^{-1}$) | $E_g$ (eV) |
|--------|----------------|-------------------------------|-----------|
| 0%     | 59.14          | 0.0051                        | 2.43      |
| 1%     | 65.59          | 0.0059                        | 2.37      |
| 3%     | 76.00          | 0.0079                        | 2.02      |
| 5%     | 72.04          | 0.0071                        | 2.30      |
| 7%     | 60.22          | 0.0049                        | 2.71      |
| 9%     | 58.06          | 0.0048                        | 2.81      |
$O_2 + Bi_2O_3(e_{cb}) \rightarrow ^{*}O_2$  \hfill (6)

$Fe^{3+} + e^- \rightarrow Fe^{2+}$  \hfill (7)

$Fe^{3+} + h^+_{vb} \rightarrow Fe^{4+}$  \hfill (8)

Fe$^{2+}$ and Fe$^{4+}$ ions are relatively unstable ions when compared to Fe$^{3+}$ ions. Therefore, the trapped charge can be easily released from the Fe$^{2+}$ ions or Fe$^{4+}$ ions and then migrate to the surface to start the photocatalytic reaction with the following reaction:

$Fe^{2+} + O_2 \rightarrow Fe^{3+} + ^{*}O_2$  \hfill (9)

$Fe^{4+} + OH^- \rightarrow Fe^{3+} + ^{*}OH$  \hfill (10)

Fe$^{2+}$ ions can be oxidized to Fe$^{3+}$ ions by transferring electrons to O$_2$ adsorbed on the surface of Bi$_2$O$_3$. Meanwhile, the adsorbed O$_2$ is reduced to superoxide anion radical ($^*O_2^-$) \hfill \text{Equation 9}, which functions as a reducing agent and further reduces the AMX solution. Likewise, Fe$^{4+}$ ions are reduced to Fe$^{3+}$ ions by losing electrons, while the surface hydroxyl group (OH$^-$) becomes a hydroxyl radical ($^*OH$) \hfill \text{Equation 10}. In addition, the unrecycled holes will be trapped on the surface of the Bi$_2$O$_3$ semiconductor and react with H$_2$O and form hydroxyl radicals ($^*OH$). The resulting hydroxyl radical is a potent reducing agent to reduce AMX solution (Saravanan et al., 2013).

The degradation process occurs through direct charge transfer consisting of photoinduction carriers or reactive oxygen species (ROS; Guo et al., 2011). The ROS that contributes to the photocatalytic reaction of Bi$_2$O$_3$/Fe as a robust oxidizing and reducing species to degrade AMX are superoxide anion radicals ($^*O_2^-$) and hydroxyl radicals ($^*OH$) which will form CO$_2$, H$_2$O, and other inorganic components \hfill \text{Equation 11–15}. These chemical reactions will bind to AMX pollutants around the Bi$_2$O$_3$/Fe material to degrade AMX pollutants. These radicals will be formed continuously as long as the Bi$_2$O$_3$/Fe material is exposed to UV light.

$^*O_2^- + H^+ \rightarrow ^*OOH$  \hfill (11)
\[ \cdot O_2^\cdot + H^+ + \cdot OOH \rightarrow H_2O_2 + O_2 \]  

(12)

\[ H_2O_2 + O_2^- \rightarrow OH + OH^- + O_2 \]  

(13)

\[ \cdot AMX^\cdot + (\cdot OH, \cdot O_2^- + O_2) \rightarrow CO_2 + H_2O + \text{inorganic compounds} \]  

(14)

\[ h^+ + AM \rightarrow CO_2 + H_2O + \text{inorganic compounds} \]  

(15)

In the presence of Fe transition metal doping, Fe\(^{3+}\) ions are responsible for the electron-hole recombination rate and support the increase in photocatalytic activity. Excess Fe\(^{3+}\) ions is entering the cluster formation. This cluster can resist AMX photodegradation by masking the active site from the Bi\(_2\)O\(_3\) surface. Fe\(^{3+}\) ions will act as photo-generated between holes and electron transfer, the rate of electron-hole recombination during irradiation can be suppressed by increasing the number of trapped electrons to increase the lifetime of electrons and holes. This decrease in the recombination rate increases the photocatalytic activity of Bi\(_2\)O\(_3\)/Fe.

The Bi\(_2\)O\(_3\)/Fe material produced is in powder form, so that in its application, it can only be used once to degrade AMX medical waste, the possibility of recycling can be carried out further by coating the material on a glass substrate to produce Bi\(_2\)O\(_3\)/Fe thin-film material. Materials in the form of thin films can be applied repeatedly in the degradation process (Sutanto et al., 2021).

To carry out degradation under solar irradiation, it is necessary to modify the energy bandgap of the Bi\(_2\)O\(_3\)/Fe material which corresponds to the photon energy of visible light, which is smaller than 3.1 eV. In this study, researchers have modified the energy band gap of Bi\(_2\)O\(_3\)/Fe to 2.81–2.02 eV, so that in principle it is possible for electron transfer and photocatalytic reactions to occur even under sunlight.

4 Conclusion
The synthesis of Bi\(_2\)O\(_3\)/Fe has been successfully carried out using the microwave-assisted precipitation method. XRD characterization results showed that the phase formed was α-Bi\(_2\)O\(_3\). The morphology of Bi\(_2\)O\(_3\) is porous rods and spheres indicated as Bi\(_2\)O\(_3\) and Fe particles. Bi\(_2\)O\(_3\)/Fe 3% has the largest crystallite size (29.1 nm), the lowest energy gap (2.02 eV), the most optimal specific surface area (6.864 m\(^2\)/g), the highest degradation rate (0.0079 min\(^{-1}\)), and the most optimal degradation efficiency (76.34%). The addition of Fe with a concentration of up to 3% in Bi\(_2\)O\(_3\) can increase the photocatalytic ability, but a concentration of more than 3% will decrease the photocatalytic ability.

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