

## Enhanced Photocatalytic Activity of Co Doped SnO<sub>2</sub> Nanoparticles for the Degradation of Rhodamine B

Nanda Pertiwi<sup>1</sup>, Hary Sanjaya<sup>2\*</sup>, Miftah Patriela<sup>3</sup>

<sup>1-3</sup>Departement of Chemistry, Universitas Negeri Padang

\*Corresponding author.

\*Email: [hary.s@fmipa.unp.ac.id](mailto:hary.s@fmipa.unp.ac.id)

### Abstract

*The increasing growth of the textile industry in Indonesia also contributes to environmental pollution due to textile dye pollutants. This research aims to synthesize tin dioxide (SnO<sub>2</sub>) semiconductor doped with cobalt (Co) using the sol-gel method to improve its photocatalytic performance in degrading Rhodamine B dye. The synthesis involves varying Co doping concentrations (0.4 mmol, 0.6 mmol, and 0.8 mmol) with the addition of 1 mL of diethanolamine (DEA) as an additive. Characterization using UV-DRS spectroscopy shows a decrease in the band gap energy of SnO<sub>2</sub> from 3.455 eV to 1.910 eV after being doped with Co<sup>2+</sup> ions at an optimum doping concentration of 0.8 mmol. SEM analysis confirmed the spherical morphology and uniform distribution of the synthesized nanoparticles. Photocatalytic tests showed that Co-doped SnO<sub>2</sub> (0.8 mmol) achieved 65.43% degradation of Rhodamine B in 90 minutes under UV light, compared to 24% for undoped SnO<sub>2</sub> in 120 minutes. These findings demonstrate that Co doping significantly improves the photocatalytic efficiency of SnO<sub>2</sub>, offering a potential semiconductor-based solution to reduce textile dye pollutants and reduce environmental pollution.*

**Keywords :** SnO<sub>2</sub>, Co<sup>2+</sup> ions, semiconductors, sol-gel method, photocatalyst

### Introduction

The growth of the textile industry in Indonesia has made textile factories one of the sectors that contribute greatly to improving the national economy (Hisbiyah & Komala, 2019). However, this rapid development also causes an increase in textile dye waste which has a serious impact on water and environmental pollution (Herlambang, 2006). Based on data from the Ministry of Environment and Forestry, textile waste contributed 2.4% of total waste in 2019, increasing to 6.99% in 2021, 8.2% in 2022 (Nationalgeographic.co.id), and reaching 12% in 2023 (Kumparan.com). This increase shows the need for effective methods to reduce the environmental impact of textile dye waste (Asiah, et al., 2017).

Various methods have been used to treat textile waste, such as adsorption and activated sludge methods. However, both of these methods have weaknesses, namely that adsorption can cause a buildup of organic waste in the adsorbent (Utubira et al., 2010), while activated sludge takes a long time and consumes large amounts of energy

(Jannah & Muhimmatin, 2019). To overcome these limitations, semiconductor photocatalysis with the help of UV light has been proven to be an efficient method for decomposing dyes into compounds that are safer for the environment (Sanjaya et al., 2023), The photocatalyst process was chosen as an effective method for processing dye waste because this process is environmentally friendly. Photocatalysts do not produce dangerous deposits and are able to convert organic pollutants into CO<sub>2</sub> and H<sub>2</sub>O (Rahman & Rita Sulistyowati, 2023).

Semiconductors are materials that can conduct electricity within a certain range. The electrical and optical properties of semiconductors have a major influence on the performance of devices such as solar cells, photo electrocatalysts and photocatalysts (Wang et al., 2021). The advantages of semiconductors include their ability to be processed by deposition at low temperatures, produce smooth layers, and allow the creation of large areas on glass, as well as the flexibility of plastic substrates which are affected by the lack of long-range order (Kim et al., 2018). Several semiconductor materials, such as TiO<sub>2</sub>, ZnO, and SnO<sub>2</sub>, are widely used in the photodegradation of organic pollutants (Yang et al., 2012). Among oxide semiconductors, tin dioxide (SnO<sub>2</sub>) is one of the materials frequently used for photocatalytic applications (Mounkachi et al., 2016).

SnO<sub>2</sub> is an n-type oxide semiconductor with a band gap of 3.6 eV which has good electrical conductivity (Köse et al., 2015). This material has several advantages, including excellent optical properties, non-toxicity, wide band gap, and efficiency in photocatalytic activity (Sudha & Sivakumar, 2015). With its wide optical band gap and transparency to visible wavelengths, SnO<sub>2</sub> is well suited for various applications such as solar cells, gas sensors, batteries, transistors, transparent electrodes, and catalysts (Patel et al., 2021).

The synthesis of SnO<sub>2</sub> materials uses several methods, including magnetron sputtering (Ning et al., 2009), chemical coprecipitation (Liu et al., 2012), hydrothermal (Akhir et al., 2019), and sol-gel (Patel et al., 2021). Among various synthesis methods, the sol-gel method has the advantage namely good product homogeneity, easy to control composition, using relatively low temperatures, large coating area, low equipment costs, and having good optical properties (Ilican et al., 2008), simple, and low levels of energy and material consumption (Saini et al., 2007). Based on research by Patel et al. (2021),

optical analysis shows that SnO<sub>2</sub> nanoparticles have a band gap of 3.64 eV (Patel et al., 2021). A smaller band gap can increase effectiveness in the photodegradation process because it is easier for electrons to move from the valence band to the conduction band. To reduce the band gap value, SnO<sub>2</sub> is modified with metal doping, one of which is the addition of cobalt to SnO<sub>2</sub> nanoparticles (Taringan et al., 2017).

Cobalt (Co) is an effective doping because Co ions can donate electrons to the conduction band of SnO<sub>2</sub>, which causes a decrease in the band gap value of SnO<sub>2</sub> nanoparticles (Lu et al., 2024). Research by Pirmoradi et al. (2011) showed that Co doping on SnO<sub>2</sub> synthesized using the sol-gel method could reduce the band gap value from 3.19 eV to 2.97 eV (Pirmoradi et al., 2011). Meanwhile, research by Mariammal et al. (2011) showed that SnO<sub>2</sub> which was not doped with Co had a band gap of 3.6 eV, while SnO<sub>2</sub> which was doped with Co had a band gap of 3.04 eV (Mariammal et al., 2011). These results indicate that Co-doped SnO<sub>2</sub> is effective for photocatalyst applications (Vindhya & Kavitha 2023). In this research, the photocatalyst application uses rhodamine B dye degradation, which is one of the dyes often used in the textile industry.

Based on this, this research was carried out by synthesizing Co<sup>2+</sup> doped SnO<sub>2</sub> nanoparticles using the sol-gel method to optimize their use as a photocatalyst in the degradation process of Rhodamine B dye.

## **Method**

### **Tools and Materials**

The tools used in this research include chemical glasses, measuring cups, measuring flasks, volumetric pipettes, evaporating cups, watch glasses, measuring pipettes, desiccators, mortar and pestle, analytical balance, magnetic stirrer, stirrer bar, furnace, UV spectrophotometry -Diffuse Reflectance (UV-DRS), Scanning Electron Microscope (SEM), as well as tools for testing SnO<sub>2</sub> photocatalysts doped Co used a UV-Vis Spectrophotometer (Thermo Scientific Genesys 30) and two 15 Watt UV lamps. The materials used in this research include SnCl<sub>2</sub>·2H<sub>2</sub>O(Merck), CoCl<sub>2</sub>·6H<sub>2</sub>O(Merck), methanol (p.a), Diethanolamine (DEA) (p.a), rhodamine B, and distilled water.

### **Synthesis of SnO<sub>2</sub> Material**

SnCl<sub>2</sub>·H<sub>2</sub>O (1 mmol) was dissolved in 50 mL methanol (p.a.), then covered with plastic wrap and homogenized using a magnetic stirrer for around 1 hour 30 minutes. The solution was then sonicated for 30 minutes at 45 W to obtain a homogeneous solution and left for 24 hours to stabilize the sol. The samples were dried in an oven at 110°C for about 1 hour. The gel obtained was calcined in a furnace at 600°C for around 3 hours to produce SnO<sub>2</sub>. The samples were stored in a desiccator, after cooling, the samples were crushed using a mortar and pestle for characterization (Ningsih et al., 2020).

### **Synthesis of Co-Doped SnO<sub>2</sub> with DEA Additive**

SnCl<sub>2</sub>·H<sub>2</sub>O (1 mmol) and CoCl<sub>2</sub>·6H<sub>2</sub>O with varying concentrations of 0.4 mmol, 0.6 mmol, and 0.8 mmol were dissolved in 50 mL of methanol (p.a.). The solution was covered with plastic wrap and homogenized using a magnetic stirrer for 40 minutes. Then 1 mL of Diethanolamine (DEA) (p.a.) was added to each solution and stirred for about 1 hour 30 minutes. The solution was sonicated for 30 minutes at 45 W to ensure homogeneity and left for 24 hours to stabilize the sol. The samples were then dried in an oven at 110°C for about 1 hour. The gel obtained was calcined in a furnace at a temperature of 600°C for about 3 hours to produce Co-doped SnO<sub>2</sub>. The samples were stored in a desiccator, after cooling, the samples were crushed using a mortar and pestle for characterization (Kasuma et al., 2020).

### **Photocatalyst Effectiveness Test on Co-Doped SnO<sub>2</sub> Nanoparticles**

0.1 gram of rhodamine B was dissolved in 100 mL of distilled water in a 100 mL volumetric flask, then 10 mL of the rhodamine B stock solution was transferred into a 1000 mL volumetric flask. 0.1 gram of photocatalyst (at optimum doping and additive conditions) was added to 100 mL of rhodamine B solution. Before being exposed to ultraviolet light, the solution was stirred in a dark room for 30 minutes to achieve adsorption and desorption balance. The photolysis irradiation time was set at 0 minutes, 30 minutes, 60 minutes, 90 minutes, 120 minutes, and 150 minutes. 5 mL of solution was taken at each interval and centrifuged for 10 minutes to remove particles. The absorbance of the supernatant solution was measured using a UV-Vis spectrophotometer at a wavelength of 554 nm (Toloman et al., 2020).

### **Results and Analysis**

### UV-DRS Spectrophotometer Characterization of SnO<sub>2</sub> and Co-Doped SnO<sub>2</sub>

In this research, modification of Co-doped SnO<sub>2</sub> was carried out. The bandgap value was determined using UV-DRS spectroscopy in the wavelength range 185-1100 nm. The aim of this research is to reduce the bandgap value by varying the cobalt (Co) doping concentration, thereby increasing the potential of the material for photocatalytic applications (Mariammal et al., 2011). Co-doped SnO<sub>2</sub> nanoparticles were synthesized using various Co doping concentrations, namely 0.4 mmol, 0.6 mmol, and 0.8 mmol, with the addition of 1 mL of diethanolamine as an additive. The bandgap value is calculated using the Kubelka-Munk equation (Sanjaya, 2018).

$$E_g = hc/\lambda$$

Where  $E_g$  is the gap energy (eV)

The results of band gap measurements with variations in Co doping concentrations can be seen in Table 1.

Table 1. Band gap Energy with Effect of Co Doping Concentration

Sample	Band gap Value ( $E_g$ )
SnO <sub>2</sub>	3,455 eV
1 mmol SnO <sub>2</sub> + 0,4 mmol Co + DEA 1 mL	2,134 eV
1 mmol SnO <sub>2</sub> + 0,6 mmol Co + DEA 1mL	2,006 eV
1 mmol SnO <sub>2</sub> + 0,8 mmol Co + DEA 1 mL	1,910 eV

The data shows a decrease in the bandgap energy in SnO<sub>2</sub>, the lowest bandgap value is achieved at a concentration of 0.8 mmol Co (1.910 eV), which is the maximum bandgap obtained from variations in doping concentration. The doping concentration is lower than that of the SnO<sub>2</sub> precursor, aiming to increase conductivity without altering the material properties of SnO<sub>2</sub> nanoparticles. This decrease is caused by the interaction between DEA as an additive and the semiconductor matrix, which results in a smaller particle size and a decrease in the energy band gap value (Ningsih, 2013). Apart from that, according to Ningsih, et al., 2021, impairment *bandgap* caused by the interaction between the electron band and the delocalization of electrons in the transition ion

resulting in metal ion substitution (Ningsih et al., 2021), in this case is by adding  $\text{Co}^{2+}$  ions as doping of  $\text{SnO}_2$  nanoparticles. Reduced value bandgap causes the distance between the valence band and the conduction band to get closer and the excitation of electrons becomes faster so that less photon energy is needed to excite electrons from the valence band to the conduction band (Ningsih et al., 2021). This shows that value *bandgap* The lower one has the potential for photocatalytic applications in the degradation of rhodamine B dye.

### Scanning Electron Microscope (SEM) Characterization of $\text{SnO}_2$ and Co-Doped $\text{SnO}_2$

Scanning Electron Microscope (SEM) was used to observe differences in morphology, particle distribution and particle size in  $\text{SnO}_2$  and Co- $\text{SnO}_2$ . In this research, characterization using SEM was carried out on  $\text{SnO}_2$  with the addition of 0,8 mmol Co doping and compared with  $\text{SnO}_2$  without additional doping. SEM observations were carried out with a magnification of 20,000x. Results of characterization analysis using SEM for  $\text{SnO}_2$  and Co- $\text{SnO}_2$  can be seen in Figure 1.

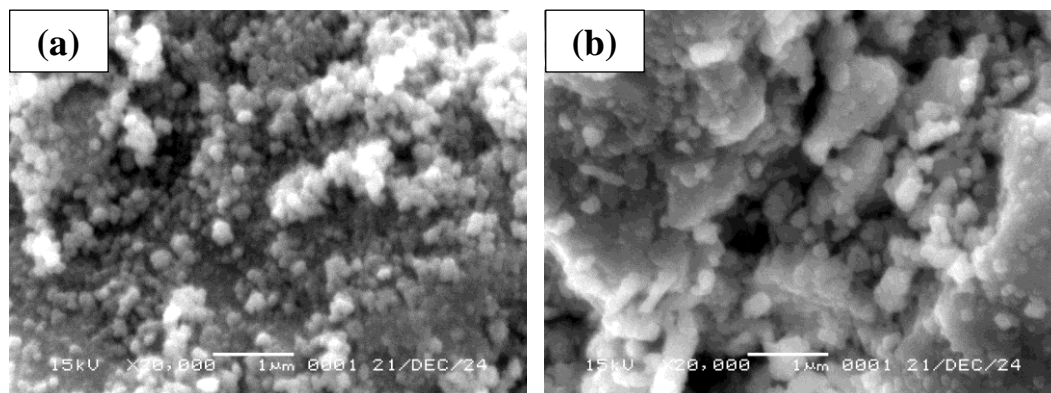


Figure 1. (a) SEM image of  $\text{SnO}_2$  (b) SEM image of Co (0,8 mmol)- $\text{SnO}_2$

The characterization results in Figure 1 show SEM photos of  $\text{SnO}_2$  nanoparticles and Co (0,8 mmol)- $\text{SnO}_2$ . Surface morphology of  $\text{SnO}_2$  nanoparticles and Co- $\text{SnO}_2$  visible in SEM 20,000x magnification shaped spherical. This is in accordance with previous research conducted by Mariammal, et al, in 2011, which obtained similar morphological results for  $\text{SnO}_2$  nanoparticles and Co doped  $\text{SnO}_2$  that is, shape sperichal (Mariammal et al., 2011).

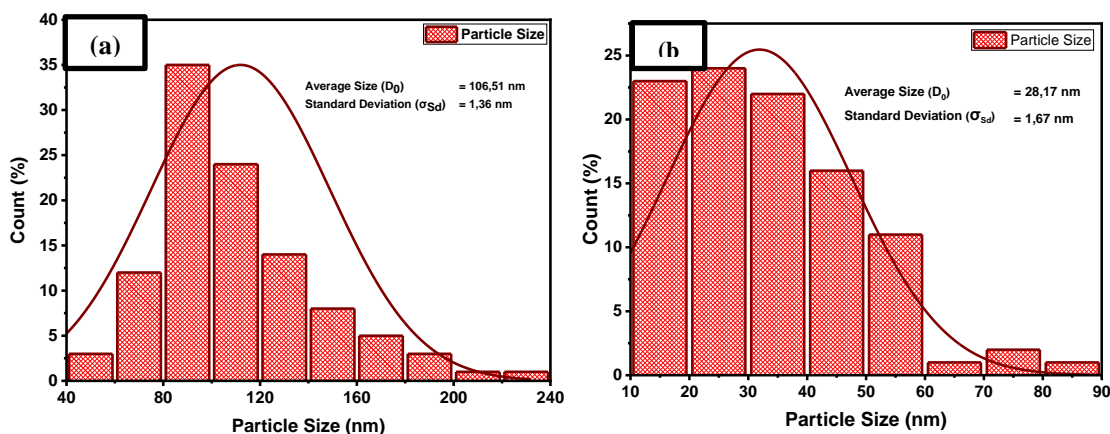


Figure 2. Particle Size distribution histogram of (a) SnO<sub>2</sub> and (b) Co (0,8 mmol)-SnO<sub>2</sub>

SnO<sub>2</sub> particle size and Co (0,8 mmol)-doped SnO<sub>2</sub> can be measured using software *imageJ*. In Figure 2 it can be seen that the size distribution of SnO<sub>2</sub> particles without doping and DEA additives have sizes ranging from 40-240 nm with an average particle size of 106.51 nm. Co (0,8 mmol)-doped SnO<sub>2</sub> with the addition of 1 mL DEA has the particle size of Co-SnO<sub>2</sub> ranges from 10-90 nm with an average particle size of 28.17 nm. This is in accordance with the literature which states that the addition of additives plays a role in controlling the morphology of the product formed, resulting in a product with a high level of homogeneity and a large surface area due to the small particle size (Ningsih, 2016). In Masjedi-Arani's 2017 research, using diethanolamine (DEA) as an additive in the synthesis of SnO<sub>2</sub> nanoparticles<sub>2</sub> which is doped with Co metal produces shaped nanoparticles *spherical* with a small particle size with a wide particle distribution (Masjedi-Arani & Salavati-Niasari, 2017).

### Activity Photocatalysts SnO<sub>2</sub> and Co-SnO<sub>2</sub> with Rhodamine B

In the research This activity test was conducted photocatalyst on SnO<sub>2</sub> and Co-SnO<sub>2</sub> nanoparticles with rhodamine B which is contacted below UV light . Length value wave maximum rhodamine B and absorbance measured with use UV-Vis spectrophotometer in the range long 400-800 nm wave . Measurement results absorption maximum rhodamine B at length 554 nm wave with mark absorbance of 1,325 Abs. This

is in accordance with reference Rhodamine B has a wavelength of maximum at 554 nm (Letifi et al., 2019). In the study This done degradation rhodamine B with SnO<sub>2</sub> without addition of doping Co and DEA, and Co (0,8 mmol) -SnO<sub>2</sub> with addition of 1 mL DEA for compare mark degradation and see effectiveness from second variation catalyst In the research This use variation time degradation 0 minutes , 30 minutes , 60 minutes , 90 minutes , 120 minutes , and 150 minutes . In Figure 3, it can be seen seen results degradation rhodamine B with SnO<sub>2</sub> and Co-SnO<sub>2</sub> catalysts .

Based on figure 3 (a) percent degradation rhodamine B with SnO<sub>2</sub> without the addition of Co and DEA doping has been obtained optimum degradation value rhodamine B, namely by 24% with time degradation for 120 minutes . In figure 3 (b) the optimum value of percent degradation rhodamine B with Co (0,8 mmol)-doped SnO<sub>2</sub> nanoparticles with addition of 1 mL DEA, namely by 65.43% with time degradation for 90 minutes . Increased photocatalytic activity of SnO<sub>2</sub> doped with ions Co<sup>2+</sup> This is because Co doping can increase the crystallinity of SnO<sub>2</sub>, so that the crystal structure becomes more orderly and efficient in supporting the photocatalytic process. Ion Co<sup>2+</sup> creates an additional energy level within the SnO<sub>2</sub> energy band gap, which serves to reduce the recombination of electron-hole pairs formed when exposed to light, thereby allowing these pairs to more effectively participate in photocatalytic reactions (Toloman et al., 2020).

## Conclusion

This research shows the results of the synthesis of Co-doped SnO<sub>2</sub> Nanoparticles using the sol-gel method can improve their photocatalytic performance in degrading Rhodamine B dye. This modification reduces the band gap energy of SnO<sub>2</sub> from 3.455 eV to 1.910 eV at an optimum Co doping concentration of 0.8 mmol with the addition of 1 mL of DEA thereby increasing its photocatalytic properties. Under UV light irradiation, Co (0,8 mmol)-doped SnO<sub>2</sub> showed optimum photocatalytic activity, achieving 65.43% degradation of Rhodamine B at 90 minutes, compared to SnO<sub>2</sub> without doping it only reaches 24% at 120 minutes. These results indicate that the addition of Co doping can increase the photocatalytic efficiency of SnO<sub>2</sub> nanomaterials , thus providing a potential solution in processing textile dye waste and reducing the impact of environmental pollution.

## References

- Akhir, M. A. M., Rezan, S. A., Mohamed, K., Arafat, M. M., Haseeb, A. S. M. A., & Lee, H. L. (2019). Synthesis of SnO<sub>2</sub> nanoparticles via hydrothermal method and their gas sensing applications for ethylene detection. *Materials Today: Proceedings*, 17, 810–819. <https://doi.org/10.1016/j.matpr.2019.06.367>
- Asiah, R. H., Suseno, J. E., & Muhlisin, Z. (2017). Pembuatan sistem ozonizer untuk degradasi pewarna rhodamine B dengan metode peroxone menggunakan mikrokontroler ATMEGA 8535. *Youngster Physics Journal*, 6(4), 323–330.
- Herlambang, A. (2006). Pencemaran Air Dan Strategi. *Jurnal Akuakultur Indonesia*, 2(1), 16–29.
- Hisbiyah, A., & Komala, I. (2019). Komposit Karbon Aktif dari Eceng Gondok dengan TiO<sub>2</sub> untuk Degradasi Fotokatalitik Zat Warna Tekstil Congo Red. *Briliant: Jurnal Riset Dan Konseptual*, 4(1), 5. <https://doi.org/10.28926/briliant.v4i1.256>
- Ilcan, S., Caglar, Y., Caglar, M., & Yakuphanoglu, F. (2008). Structural, optical and electrical properties of F-doped ZnO nanorod semiconductor thin films deposited by sol-gel process. *Applied Surface Science*, 255(5), 2353–2359. <https://doi.org/10.1016/j.apsusc.2008.07.111>
- Jannah, I. N., & Muhimmatin, I. (2019). Pengelolaan Limbah Cair Industri Batik menggunakan Mikroorganisme di Kecamatan Cluring Kabupaten Banyuwangi. *Warta Pengabdian*, 13(3), 106–115. <https://doi.org/10.19184/wrtp.v13i3.12262>
- Kasuma Warda Ningsih, S., Nasra, E., Yanna Rahayu Jurusan Kimia, D., Matematika dan Ilmu Pengetahuan Alam, F., Negeri Padang Jl Hamka, U., & Tawar, A. (2020). Sintesis dan Karakterisasi Nanopartikel Co 2+ doped ZnO dengan Menggunakan Metode Sol-Gel. *Indonesian Journal of Chemical Science*, 9(1), 2–8. <http://journal.unnes.ac.id/sju/index.php/ijcs>
- Kim, B. N., Seo, G. K., Hwang, S. W., Yu, H., Ahn, B., Seo, H., & Cho, I. S. (2018). Photophysical properties and photoelectrochemical performances of sol-gel derived copper stannate (CuSnO<sub>3</sub>) amorphous semiconductor for solar water splitting application. *Ceramics International*, 44(2), 1843–1849. <https://doi.org/10.1016/j.ceramint.2017.10.119>
- Köse, H., Karaal, Ş., Aydin, A. O., & Akbulut, H. (2015). Structural properties of size-controlled SnO<sub>2</sub> nanopowders produced by sol-gel method. *Materials Science in Semiconductor Processing*, 38, 404–412. <https://doi.org/10.1016/j.mssp.2015.03.028>
- Letifi, H., Litaïem, Y., Dridi, D., Ammar, S., & Chtourou, R. (2019). Enhanced Photocatalytic Activity of Vanadium-Doped SnO<sub>2</sub> Nanoparticles in Rhodamine B Degradation. *Advances in Condensed Matter Physics*, 2019. <https://doi.org/10.1155/2019/2157428>
- Liu, T., Du, R. Bin, & Kong, X. J. (2012). Preparation and Electrochemical Properties of

- Amorphous Tin-Copper Composite Oxide CuSnO<sub>3</sub>. *Advanced Materials Research*, 535–537, 31–35. <https://doi.org/10.4028/www.scientific.net/AMR.535-537.31>
- Lu, R., Luo, J., Wang, X., Chen, A., Xie, Y., Xu, Y., Shang, T., Li, R., Jiang, D., & Zhan, Q. (2024). A Co-doped Ag<sub>3</sub>PO<sub>4</sub> photocatalyst: Efficient degradation of organic pollutants and enhancement mechanism. *Molecular Catalysis*, 558(March), 114033. <https://doi.org/10.1016/j.mcat.2024.114033>
- Mariammal, R. N., Rajamanickam, N., & Ramachandran, K. (2011). Synthesis and characterization of undoped and co-doped SnO<sub>2</sub> nanoparticles. *Journal of Nano- and Electronic Physics*, 3(1 PART1), 92–100.
- Masjedi-Arani, M., & Salavati-Niasari, M. (2017). Metal (Mn, Co, Ni and Cu) doped ZnO-Zn<sub>2</sub>SnO<sub>4</sub>-SnO<sub>2</sub> nanocomposites: Green sol-gel synthesis, characterization and photocatalytic activity. *Journal of Molecular Liquids*, 248, 197–204. <https://doi.org/10.1016/j.molliq.2017.10.055>
- Moukachi, O., Salmani, E., Lakhal, M., Ez-Zahraouy, H., Hamedoun, M., Benaissa, M., Kara, A., Ennaoui, A., & Benyoussef, A. (2016). Band-gap engineering of SnO. *Solar Energy Materials and Solar Cells*, 148, 34–38. <https://doi.org/10.1016/j.solmat.2015.09.062>
- Ning, T., Ji, F., Ma, J., Song, Z. G., Pei, X. A., & Tan, Y. L. (2009). Study on Fabrication and Properties of Copper-Tin-Oxide Thin Films. *Advanced Materials Research*, 79–82, 787–790. <https://doi.org/10.4028/www.scientific.net/AMR.79-82.787>
- Ningsih, S. K. W., Sanjaya, H., Bahrizal, Nasra, E., & Yurnas, S. (2021). Synthesis of Cu<sup>2+</sup> doped ZnO by the combination of sol-gel-sonochemical methods with duck egg albumen as additive for photocatalytic degradation of methyl orange. *Indonesian Journal of Chemistry*, 21(3), 564–574. <https://doi.org/10.22146/ijc.57077>
- Patel, G. H., Chaki, S. H., Kannaujiya, R. M., Parekh, Z. R., Hirpara, A. B., Khimani, A. J., & Deshpande, M. P. (2021). Sol-gel synthesis and thermal characterization of SnO<sub>2</sub> nanoparticles. *Physica B: Condensed Matter*, 613(May 2020). <https://doi.org/10.1016/j.physb.2021.412987>
- Pirmoradi, H., Malakootikhah, J., Karimipour, M., Ahmadpour, A., Shahtahmasebi, N., & Koshky, F. E. (2011). Study of Cobalt-Doped SnO<sub>2</sub> Thin Films. *Middle East Journal of Scientific Research*, 8(1), 253–256.
- Rahman, D. Y., & Rita Sulistyowati. (2023). Aplikasi Fotokatalis TiO<sub>2</sub> Dan Alternatifnya Untuk Degradasi Pewarna Sintesis Dalam Limbah Cair. *Environmental Science Journal (Esjo): Jurnal Ilmu Lingkungan*, 1(2), 89–105. <https://doi.org/10.31851/esjo.v1i2.12023>
- Ramadhani, S., Sanjaya, H., & Yohandri, Y. (2023). Degradasi Zat Warna Methyl Orange dengan Katalis TiO<sub>2</sub> Menggunakan Metode Fotosonolisis. *Jurnal Periodic Jurusan Kimia UNP*, 12(1), 17. <https://doi.org/10.24036/p.v12i1.116883>

- Saini, K. K., Sharma, S. D., Chanderkant, Kar, M., Singh, D., & Sharma, C. P. (2007). Structural and optical properties of TiO<sub>2</sub> thin films derived by sol-gel dip coating process. *Journal of Non-Crystalline Solids*, 353(24–25), 2469–2473. <https://doi.org/10.1016/j.jnoncrysol.2006.12.017>
- Sanjaya, H. (2018). DEGRADASI METIL VIOLET MENGGUNAKAN KATALIS ZnO-TiO<sub>2</sub> SECARA FOTOSONOLISIS. *EKSAKTA: Berkala Ilmiah Bidang MIPA*, 19(1), 91–99. <https://doi.org/10.24036/eksakta/vol19-iss1/131>
- Sudha, D., & Sivakumar, P. (2015). Review on the photocatalytic activity of various composite catalysts. *Chemical Engineering and Processing: Process Intensification*, 97, 112–133. <https://doi.org/10.1016/j.cep.2015.08.006>
- Taringan, A. K., Wuntu, A. D., & Aritonang, H. F. (2017). Kinetika Fotodegradasi Remazol Yellow Menggunakan Fotokatalis ZnO dan ZnO-Ag. *Jurnal MIPA*, 6(2), 68. <https://doi.org/10.35799/jm.6.2.2017.17762>
- Toloman, D., Popa, A., Stefan, M., Silipas, T. D., Suciu, R. C., Barbu-Tudoran, L., & Pana, O. (2020). Enhanced photocatalytic activity of Co doped SnO<sub>2</sub> nanoparticles by controlling the oxygen vacancy states. *Optical Materials*, 110, 110472. <https://doi.org/10.1016/j.optmat.2020.110472>
- Utubira, Y., Wijaya, K., Triyono, T., & Sugiharto, E. (2010). PREPARATION AND CHARACTERIZATION OF TiO<sub>2</sub>-ZEOLITE AND ITS APPLICATION TO DEGRADE TEXTILLE WASTEWATER BY PHOTOCATALYTIC METHOD. *Indonesian Journal of Chemistry*, 6(3), 231–237. <https://doi.org/10.22146/ijc.21724>
- Vindhya, P. S., & Kavitha, V. T. (2023). Phyto-mediated synthesis of pure and cobalt-doped SnO<sub>2</sub> nanoparticles for antimicrobial, antioxidant, and photocatalytic activities. *Biomass Conversion and Biorefinery*. <https://doi.org/10.1007/s13399-023-04548-4>
- Wang, M., Guo, Y., Zhu, Z., Liu, Q., Sun, T., Cui, H., & Tang, Y. (2021). Diethanolamine-assisted and morphology controllable synthesis of ZnO with enhanced photocatalytic activities. *Materials Letters*, 299, 130114. <https://doi.org/10.1016/j.matlet.2021.130114>
- Yang, G., Yan, Z., & Xiao, T. (2012). Low-temperature solvothermal synthesis of visible-light-responsive S-doped TiO<sub>2</sub> nanocrystal. *Applied Surface Science*, 258(8), 4016–4022. <https://doi.org/10.1016/j.apsusc.2011.12.092>