Synthesis, Antimicrobial Activity, and Photocatalytic Performance of Ce Doped SnO$_2$ Nanoparticles

Bhawna$^{1,2}$, Ashish Kumar Choudhary$^3$, Akanksha Gupta$^{*4}$, Sanjeev Kumar$^{1,2}$, Pramod Kumar$^4$, R. P. Singh$^4$, Prashant Singh$^6$ and Vinod Kumar$^{1,7}$*$

$^1$Department of Chemistry, Kirori Mal College, University of Delhi, New Delhi, India, $^2$Department of Chemistry, University of Delhi, New Delhi, India, $^3$Department of Botany, University of Delhi, New Delhi, India, $^4$Department of Chemistry, Sri Venkateswara College, University of Delhi, New Delhi, India, $^5$Department of Chemistry, Sri Aurobindo College, Delhi University, New Delhi, India, $^6$Department of Chemistry, Atma Ram Sanatan Dharma College, Delhi University, New Delhi, India, $^7$Special Centre for Nano Sciences, Jawaharlal Nehru University, New Delhi, India

This work represented the synthesis of Ce doped SnO$_2$ nanoparticles by a wet chemical method and was characterized by various characterization techniques. PXRD confirmed the presence of the rutile phase for Ce doped SnO$_2$ nanoparticles. SEM image and elemental mapping showed agglomerated irregular shaped particles and uniform distribution of 5% Ce ions within the SnO$_2$ lattice, respectively. Ce doped SnO$_2$ nanoparticles showed antimicrobial activity against E. coli and prevented the growth of bacteria. The nanoparticles were found photocatalytically active and photocatalytic behavior was elucidated by the degradation of Malachite Green dye under UV light irradiation.

Keywords: cerium, E. coli, malachite green, photocatalyst, doping

INTRODUCTION

There has been a continuous threat to health, food packaging, cosmetics, and many more industries due to microbes and these industries highly depend on various antimicrobial agents (Ananpattarachai et al., 2009). Contaminated surfaces, colonization, subsequent biofilm formation, improper cleaning of equipments are found to be the primary carriers of microorganisms leading to several foodborne and other outbreaks (Swaminathan and Smidt, 2007; Yemmireddy and Hung, 2017). Nanotechnology has its impacts on all fields of science related to nanomedicine, biomedical, biosensor, development of smart cities, energy, environment, etc. (Kumar et al., 2019a; Bhawna et al., 2020; Gupta et al., 2020a, b).

Nanoparticles have been long known for their antimicrobial behavior against gram-positive and gram-negative bacteria, pathogens, and other microbes (Azam et al., 2012; Vargas-Reus et al., 2012). Metal oxide nanoparticles serve as antimicrobial agents owing to their large surface area (Raghunath and Perumal, 2017). Out of several metal oxide nanomaterials, scientists have more interest in SnO$_2$ nanoparticles because of their novel properties such as high chemical stability, high transparency, and low electrical sheet resistance, etc. (Jarzbski and Marton, 1976a, b; Jarzbski and Morton, 1976). The modified SnO$_2$ also has great technical and scientific interests because of its diverse applications, e.g., transparent conducting electrodes, gas sensors, as electrodes in lithium-ion batteries, electronic devices, dye-based solar cells, H$_2$ generation, etc. (Jiang et al., 2017, 2018; Park et al., 2017; Xie et al., 2017; Wang et al., 2018; Bhawna et al., 2020). Other than these applications, SnO$_2$ has been seeking attention as an antimicrobial agent and has played an essential role against the growth of various bacterial strains like Staphylococcus aureus, E. coli...
Green synthesis of SnO₂ nanoparticles using *Aloe barbadensis miller* showed antibacterial and antifungal activities (Ayesharam et al., 2013). Apart from antimicrobial activities, other important biological properties like anticancer, antitumor, and antioxidant activities have also been reported using green synthesized SnO₂ nanoparticles (Kamaraj et al., 2014; Khan et al., 2018). However, when doped with transition metal ions, SnO₂ disinfects microbes with good efficiency, i.e., Co-doped SnO₂ and Ag-doped SnO₂ nanoparticles have shown potent antibacterial activities (Chandran et al., 2015; Nasir et al., 2017; Qamar et al., 2017; Ali et al., 2018). Only a few reports are available on antimicrobial activities of Ce doped metal oxide NPs. Ce-doped ZnO NPs showed antimicrobial activity against both gram-negative and gram-positive bacteria (Rooshde et al., 2020). Similarly, Ce doped CuO NPs completely eradicated the *E. coli* and *S. aureus* bacteria (Jan et al., 2014) and Ce-doped ZrO₂ NPs showed high antibacterial property against gram-positive bacteria than gram-negative bacteria (Mekala et al., 2018).

Water is a crucial factor for the existence of life on earth and clean water is the necessity of the hour. Consumption of water by a rapid increasing population is leading to the depletion of major aquifers. On the other hand, organic manufacturing industries have been the target for disposing of their chemical wastes into water bodies. According to research, the world’s dye production of about 0.7 million tons (>11%) is annually released as industrial wastewater (Samadi et al., 2019). Among various known dyes, Malachite green dye has its extensive uses worldwide. Besides its use as a dye in silk, jute, leather, wool and paper industries; it is also used as a food additive, coloring agent and as a disinfectant. However, due to its carcinogenic effects on human health and aquatic life, it has now become a controversial compound and has been banned in many countries. Continuous efforts are being made to recycle contaminated water containing bacteria, toxic chemicals, dyes, heavy metals, etc. to make it safe for drinking and other purposes. Some conventional methods are: photocatalysis, ozonation, Fenton’s reagent, electrochemical routes, membrane filtration, coagulation, adsorption, ion-exchange, irradiation, anaerobic and aerobic degradation, etc. (Gusain et al., 2019). Though, metal oxides such as TiO₂, SnO₂, ZnO have been found as better photocatalysts for the degradation of organic dyes in aqueous solution. SnO₂ as an n-type semiconductor has also been reported for the degradation of various azo dyes. Besides antimicrobial activities, doped SnO₂ finds improved results in photocatalytic activities. Ce doping has been known for bandgap tailoring as well as lattice distortion in SnO₂. There are various methods reported in literature for the synthesis of Ce doped SnO₂ such as: sol-gel (Shide et al., 2010; Ahmed et al., 2019), hydrothermal (Lian et al., 2017), co-precipitation (Bharath et al., 2017; Kumar et al., 2018), wet-chemical (Kumar et al., 2019b), flame spray method (Kotchak et al., 2018), etc. Kumar et al. showed degradation of dyes such as methylene blue and methyl orange using Ce doped SnO₂ nanoparticles (Kumar et al., 2019b) whereas Wu et al. degraded methyl orange dye using Ce doped SnO₂ (Shide et al., 2010).

To the best of our knowledge, until now, no work has been reported on antimicrobial behavior using Ce doped SnO₂.

This work involves the facile synthesis of Ce doped SnO₂ nanoparticles and reports its antimicrobial behavior against microbes. It also represents photocatalytic degradation of malachite green dye using Ce doped SnO₂.

**EXPERIMENTAL SECTION**

Ce doped SnO₂ nanoparticles were synthesized by a wet-chemical method using hydrogen peroxide, as mentioned in our previous report (Kumar et al., 2019b). Solutions of SnCl₂₂H₂O (Merck, 18 ml of 0.5 M) and CeCl₃ (Merck, 6 mL of 40 mM) were mixed and 30 mL hydrogen peroxide was added into the mixture. Then, the mixture was refluxed at 100°C for 14 h. The white suspension was cooled to room temperature, centrifuged, and was dried after washing several times to remove dissolved impurities.

**Characterization Details**

The powder X-ray diffraction (PXRD) pattern was recorded using Rigaku, Miniflex 600 X-ray diffractometer employing monochromatized Cu K Radiation. The Field Emission Scanning Electron Microscope (FESEM) image of the SnO₂ NPs was recorded on a ZEISS Gemini SEM 500.

**EVALUATION OF ANTIMICROBIAL ACTIVITY**

The Antimicrobial activity of Ce doped SnO₂ nanoparticles was carried out using Diffusion Susceptibility Test method (Bauer et al., 1966). The bacterial strain, *E. coli* was inoculated in 5 ml LB Media (Luria-Bertani; HiMedia Laboratories) and was kept at 37°C and 180 rpm for overnight incubation. The overnight incubated bacterial culture was diluted in 1:100 ratios with fresh LB media. A zone of inhibition experiment was analyzed using an LB Agar plate well-diffusion method. The sterilized...
well cutter was used for boring the LB Agar plate. The diluted overnight bacterial culture of *E. coli* was spread on LB agar plate. Thereafter, seven concentrations of Ce: SnO$_2$ NPs, namely, 0.25, 0.50, 1, 2, 3, 4, and 5 mg were poured into LB Agar wells. The well in the center of LB agar plate did not contain Ce doped SnO$_2$ NPs and was used as a control. Thereafter, the LB agar plate with Ce doped SnO$_2$ NP was incubated at 37°C for 16 h.

**Photocatalytic Degradation of Pollutants**

Photocatalytic degradation of dye was performed in an in-house fabricated solar reactor under UV (λ < 400 nm) light by high vapor pressure mercury lamp 125 W (Osram, India) (Kumar et al., 2011). In the photocatalytic activity, 0.1 g of Ce: SnO$_2$ NPs were suspended into an aqueous solution of 100 mL of 15 μM MG dye, which was taken in the photoreactor. The dye solution suspended with the catalyst was stirred for 30 min in the dark to attain the equilibrium and then the light was irradiated over the solution. Each time, five mL volume were pipetted out timely, centrifuged and the absorbance was noted using the UV-visible spectrometer.

**RESULT AND DISCUSSION**

The Powder X-ray diffraction pattern of the synthesized Ce doped SnO$_2$ nanoparticles has been shown in the Figure 1. It shows a rutile structure with tetragonal symmetry space group P4$_2$/mnm \([a = 4.680 \text{ Å} \text{ and } c = 3.167 \text{ Å}]\) and shows clear reflection at (110), (101), (200), and (211) crystallographic planes corresponding to JCPDS file no. 41-1445 (Kumar et al., 2019). The absence of any other characteristic peaks rule out possibilities of impurities or other species within the lattice represents high phase purity. The broadness of the diffracted peaks depicts a small size of crystals and the average crystallite size determined using the Scherrer formula was found to be \(\sim 6\) nm (Scherrer, 1912).

The morphology and elemental mapping of Ce doped SnO$_2$ nanoparticles was investigated through FESEM (Figure 2). Irregularly shaped particles distributed unevenly over the lattice surface has been shown through SEM imaging. Elemental mapping shows the spatial distribution of elements within the lattice and provides the evidence that Ce (yellow), Sn (purple), and O (green) were homogeneously distributed within the crystal lattice.
After elucidation of the phase formation and morphology of the formed nanoparticles, the concentration of Ce ions was found to be 5% as determined through X-ray photoelectron spectroscopy in our previous report (Kumar et al., 2019b). Also, the presence of Ce$^{3+}$ and Ce$^{4+}$ ions was confirmed into SnO$_2$ lattice, which caused charge imbalance and hence disorder in the lattice (Kumar et al., 2019b).

**Analysis of Antimicrobial Activity**

Antibacterial activity of Ce doped SnO$_2$ NPs was observed on LB Agar well-diffusion method (Dil and Sadeghi, 2018). Antibacterial activity of the NPs was compared with the control well (without NPs). The antibacterial activity of Ce doped SnO$_2$ NPs was not observed at concentration 0.25–3 mg (Figure 3). Figure 3 suggested that the zones of inhibition were prominent at two concentrations namely, 4 and 5 mg, respectively and was highest at 5 mg concentration. The antibacterial activities have been assessed through the diameter of the zone of inhibition. At a concentration of 4 mg or above, Ce doped SnO$_2$ NPs showed potent antibacterial activities (Table 1).

Previously, other metal ions doped with SnO$_2$ like Co-doped SnO$_2$, Cu-doped SnO$_2$, Fe-doped SnO$_2$, and Ag-doped SnO$_2$ nanoparticles have also been reported for their antibacterial activities (Chandran et al., 2015; Nasir et al., 2017; Ali et al., 2018; Baig et al., 2020; Sathishkumar and Geethalakshmi, 2020). Generally, nanoparticles kill the bacteria through cell membrane disruption, free radical formation causing reactive oxygen species responsible for antibacterial action (Sirelkhatim et al., 2015).

**Photocatalytic Dye Degradation**

The degradation of malachite green was performed photocatalytically using Ce: SnO$_2$ nanoparticles (Figure 4) under UV light irradiation. It degrades malachite green dye $\sim$50% in 120 min of light irradiation. When compared with other metal oxides, it is found that undoped TiO$_2$ NPs and F doped TiO$_2$ NPs photocatalytically degraded 99.9 and 54.26% MG dye in 240 min and 120 min, respectively (Chen et al., 2007; Panahian and Arsalani, 2017). Sn doped TiO$_2$ has been reported degrading 85% MG in 340 min under light irradiation (Sayilkan et al., 2007), while SnO$_2$ NPs degraded 27% MG in 180 min under UV light irradiation (Kumar et al., 2016).

The probable mechanism for the degradation of malachite green dye using Ce doped SnO$_2$ NPs has been revealed in Figure 5. Electrons were excited into the conduction band of Ce doped SnO$_2$ nanoparticles from its valence band on light irradiation [bandgap = 3.80 eV (Kumar et al., 2019b)]. Electrons were also injected into the conduction band of photocatalyst after transfer from HOMO to LUMO of malachite green dye (Helaïli et al., 2017). These electrons from two different sites then move to the surface for surface reactions. The electrons at the surface react with adsorbed/dissolved oxygen to produce O$_2^-$ radical. The concentration of the O$_2$ molecule is responsible for the efficiency.

**Table 1** Concentration and observation of zone of inhibition of Ce doped SnO$_2$.

| Concentration of Ce doped SnO$_2$ (mg) | 0.25 | 0.50 | 1 | 2 | 3 | 4 | 5 |
|---------------------------------------|-----|-----|---|---|---|---|---|
| Zone of inhibition                     | No  | No  | No| No| Least| Moderate| Strong activity |

![FIGURE 3](image1.png) | Antibacterial activity of Ce-doped-SnO$_2$ NPs.

![FIGURE 4](image2.png) | Adsorption of MG in dark and photocatalytic degradation of MG in the presence of Ce doped SnO$_2$ under UV irradiation.

![TABLE 1](table1.png) | Concentration and observation of zone of inhibition of Ce doped SnO$_2$. |
of degradation as these molecules scavenge the electrons in the conduction band, preventing electron-hole recombination. Moreover, holes in the valence band react with water molecules or hydroxide ions to produce hydroxyl radicals (OH•) (Kumar et al., 2016; Ma et al., 2018). The generated oxidizing agents (superoxide radical anions and hydroxyl radicals) contributed to the oxidative degradation of malachite green, which was then converted into simple and less harmful products. The high stability of Ce doped SnO2 NPs mentioned in the previous report and hence, these nanoparticles can be reused without undergoing any change in structure (Kumar et al., 2019b).

CONCLUSION

Facile and economical synthesis of Ce doped SnO2 NPs showed potent antimicrobial properties so far. Also, nanomaterials were able to degrade toxic organic pollutants like malachite green. These nanomaterials could be used against bacterial infection as well as for multidrug-resistant bacteria along with wastewater treatment purposes.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

ACKNOWLEDGMENTS

Bhawna and SK thanks UGC and CSIR for Junior Research Fellowship, respectively. The authors also thanks USIC, Department of Chemistry, University of Delhi and SCNS, JNU for various characterizations. The authors also thank Dr. V. K. Singh for valuable discussion and suggestions.

REFERENCES

Ahmed, A., Siddique, M. N., Ali, T., and Tripathi, P. (2019). Defect assisted improved room temperature ferromagnetism in Ce doped SnO2 nanoparticles. Appl. Surf. Sci. 483: p. 463–471. doi: 10.1016/j.apsusc.2019.03.209

Ali, T., Ahmed, A., Alam, U., Uddin, I., Tripathi, P., and Muneer, M. (2018). Enhanced photocatalytic and antibacterial activities of Ag-doped TiO2 nanoparticles under visible light. Mater. Chem. Phys. 212, 325–335. doi: 10.1016/j.matchemphys.2018.03.052

Ananpattarachai, J., Kajitvichyanukul, P., and Seraphin, S. (2009). Visible light absorption ability and photocatalytic oxidation activity of various interstitial N-doped TiO2 prepared from different nitrogen dopants. J. Hazard. Mater. 168, 253–261. doi: 10.1016/j.jhazmat.2009.02.036

Ayeshamariam, A., Meera, T., Jayachandran, M., Kumar, P., and Bououdina, M. (2013). Green synthesis of nanostructured materials for antibacterial and antifungal activities. Int. J. Bioassays 2, 304–311.

Azam, A., Ahmed, A. S., Oves, M., Khan, M. S., Habib, S. S., and Memic, A. (2012). Antimicrobial activity of metal oxide nanoparticles against Gram-positive and Gram-negative bacteria: a comparative study. Int. J. Nanomed. 7:6003. doi: 10.2147/IJNN.S35347

Baig, A. B. A., Rathinam, V., and Ramya, V. (2020). Synthesis and investigation of Fe doped SnO2 nanoparticles for improved photocatalytic activity under visible light and antibacterial performances. Mater. Technol. 2020, 1–13. doi: 10.1080/10667857.2020.1786781

Bauer, A., Kirby, W. M., Sherris, J. C., and Turck, M. (1966). Antibiotic susceptibility testing by a standardized single disk method. Am. J. Clin. Pathol. 45, 493–496. doi: 10.1093/ajcp/45.4.493

Bharathi, P. M. R. M., Amutha, T., Rameshbabu, M., and Prabha, K. (2017). Synthesis and Investigation of Ce doped Tinoxide (SnO2) nanoparticles. Int. Res. J. Eng. Technol. 4:334–337.

Bhawna, Gupta, A., Kumar, P., Tyagi, A., Kumar, R., Kumar, A., Singh, P., et al. (2020). Facile synthesis of N-Doped SnO2 nanoparticles: a cocatalyst-free promising photocatalyst for hydrogen generation. ChemistrySelect 5, 7775–7782. doi: 10.1002/slct.202001301

Chandran, D., Nair, L. S., Balachandran, S., Babu, K. R., and Deepa, M. (2015). Structural, optical, photocatalytic, and antimicrobial activities of cobalt-doped tin oxide nanoparticles. J. Sol Gel Sci. Technol. 76, 582–591. doi: 10.1007/s10971-015-3808-z

Chen, C., Lu, C. S., Chung, Y. C., and Jan, J. L. (2007). UV light induced photodegradation of malachite green on TiO2 nanoparticles. J. Hazard. Mater. 141, 520–528. doi: 10.1016/j.jhazmat.2006.07.011

Dil, N. N., and Sadeghi, M. (2018). Free radical synthesis of nanosilver/gelatin-poly (acrylic acid) nanocomposite hydrogels employed for antibacterial activity and removal of Cu (II) metal ions. J. Hazard. Mater. 351, 38–53. doi: 10.1016/j.jhazmat.2018.02.017

Gupta, A., Kumar, S., Kumar, R., Choudhary, A. K., Kumar, K., Singh, P., et al. (2020a). COVID-19: emergence of infectious diseases, nanotechnology aspects, challenges, and future perspectives. ChemistrySelect 5:7521. doi: 10.1002/slct.202001709

Gupta, A., Kumar, V., Ahmed, S., and Gautam, S. (2020b). "Impact of nanotechnology in the development of smart cities,” in Smart Cities-Opportunities and Challenges, Smart Cities-Opportunities and Challenges. Lecture Notes in Civil Engineering, eds S. Ahmed, S. Abbas, and H. Zia (Singapore: Springer), 845–857. doi: 10.1007/978-981-15-2545-2_68
Gusain, R., Gupta, K., Joshi, P., and Khatri, O. P. (2019). Adsorptive removal and photocatalytic degradation of organic pollutants using metal oxides and their composites: a comprehensive review. Adv. Colloid Interface Sci. 272:102009. doi: 10.1016/j.cis.2019.102009

Helali, N., Boudjamaa, A., Kebir, M., and Bachari, K. (2017). Efficient photo-catalytic degradation of malachite green using nickel tungstate material as photo-catalyst. Environ. Sci. Pollut. Res. 24, 6481–6491. doi: 10.1007/s11356-016-8296-3

Jan, T., Iqbal, J., Mansoor, Q., Ismail, M., Naqvi, M. S. H., Gul, A., et al. (2014). Synthesis, physical properties and antibacterial activity of Ce doped CuO: a novel nanomaterial. J. Phys. D Appl. Phys. 47,355301. doi:10.1088/0022-3727/47/35/355301

Jarzebski, Z., and Marton, J. (1976a). Physical properties of SnO2 materials: I. preparation and defect structure. J. Electrochem. Soc. 123:199C. doi:10.1149/1.2133010

Jarzebski, Z., and Marton, J. (1976b). Physical properties of SnO2 materials: III. Optical properties. J. Electrochem. Soc. 123, 333C. doi:10.1149/1.2133264

Jiang, B., He, Y., Li, B., Zhao, S., Wang, S., He, Y. B., et al. (2017). Polymer-templated formation of polydopamine-coated SnO2 nanocrystals: anodes for cyclable lithium-ion batteries. Angew. Chem. Int. Ed. 56, 1869–1872. doi:10.1002/anie.201611160

Jiang, Q., Zhang, X., and You, J. (2018). SnO2: a wonderful electron transport layer for perovskite solar cells. Small 14:1801154. doi:10.1002/smll.201801154

Kamaraj, P., Vennila, R., Arthanareeswari, M., and Devikala, S. (2014). Biological activities of tin oxide nanoparticles synthesized using plant extract. World J. Pharm Pharm Sci. 3, 382–388.

Khan, S. A., Kanwal, S., Rizwan, K., and Shahid, S. (2018). Enhanced antimicrobial, antioxidant, in vivo antitumor and in vitro anticancer effects against breast cancer cell line by green synthesized un-doped SnO2 and Ce-doped SnO2 nanoparticles from clerodendrum inerme. World J. Pharm Pharm Sci. 4:428.

Kumar, V., Govind, A., and Nagarajan, R., Optical and photocatalytic properties of SnO2 nanoparticles and their acetone gas sensing properties. Appl. Surf. Sci. 407:474–455. doi:10.1016/j.apsusc.2017.02.228

Ma, Y., Ni, M., and Li, S. (2018). Optimization of malachite green removal from water by TiO2 nanoparticles under UV irradiation. Nanomaterials 8:428. doi:10.3390/nano8060428

Mekala, R., Rajendran, V., and Deepa, B. (2018). Effect of cerium doped Bardeleleyte on their antibacterial activity co by precipitation method. Mater. Sci. Eng. 366:012104. doi: 10.1088/1757-899X/360/1/012104

Nasir, Z., Shakir, M., Wahab, R., Shoob, M., Alam, P., Khan R. H., et al. (2017). Co-prefivation synthesis and characterization of Co doped SnO2 NPs, HSA interaction via various spectroscopic techniques and their antimicrobial and photocatalytic activities. Int. J. Biol. Macromol. 94, 554–565. doi:10.1016/j.ijbiomac.2016.10.057

Panahian, Y., and Arsalani, N. (2017). Synthesis of hedgehoglike F-TIO2 (B)CNT nanocomposites for sonophotocatalytic and photocatalytic degradation of malachite green (MG) under visible light: kinetic study. J. Phys. Chem. A 121, 5614–5624. doi:10.1021/acs.jpca.7b02580

Park, G. D., Lee, J. K., and Kang, Y. C. (2017). Synthesis of uniquely structured SnO2 hollow nanoparticles and their electrochemical properties for Li-ion storage. Adv. Funct. Mater. 27:1603399. doi:10.1002/adfm.201603399

Phukan, A., Bhattacharjee, R. P., and Dutta, D. K. (2017). Stabilization of SnO2 nanoparticles into the nanopores of modified montmorillonite and their antibacterial activity. Adv. Powder Technol. 28, 139–145. doi:10.1016/j.apt.2016.09.005

Qamar, M., Shahid, S., Khan, S. A., Zaman, S., and Sarwar, M. N. (2017). Synthesis characterization, optical and antibacterial studies of Co-doped SnO2 nanoparticles. Dig. J. Nanomater. Biostruct. 12, 1127–1135. doi:10.13140/RG.2.2.292842.22720

Raghunath, A., and Perumal, E. (2017). Metal oxide nanoparticles as antimicrobial agents: a promise for the future. Int. J. Antimicrob. Agents 49, 137–152. doi:10.1016/j.ijantimicag.2016.11.011

Roohde, M. S., Abdullah, W. R. W., Amran, A. Z., Ibrahim, N. F., Ariffin, F., Sabri, M., et al. (2020). Antimicrobial Activity of Photoactive Cerium Doped Zinc Oxide. In Solid State Phenomena. Trans. Techn. Publ. 307, 217–222. doi:10.4028/www.scientific.net/SSP.307.217

Samadi, M., Zirak, M., Naseri, A., Kheirabadi, M., Ebrahimi, M., and Moslehfegh, A. Z. (2019). Design and tailoring of one-dimensional ZnO nanomaterials for photocatalytic degradation of organic dyes: a review. Res. Chem. Intermid. 45, 2197–2254. doi:10.11614/018.037295

Saiyilkhan, M., and Geethalakshmi, S. (2020). Enhanced photocatalytic and antibacterial activity of Cu:SnO2 nanoparticles synthesized by microwave assisted method. Mater. Today 20, 54–63. doi:10.1016/j.matpr.2019.08.246

Saiyilkhan, F., Asilturk, M., Tatar, P., Kiraz, N., Arpaç, E., and Sayilkhan, H. (2017). Photocatalytic performance of Sn-doped TiO2 nanostructured mono and double layer thin films for malachite green dye degradation under UV and vis-light. J. Hazard. Mater. 144, 140–146. doi:10.1016/j.jhazmat.2016.10.011

Scherrer, P. (1912). “Bestimmung der inneren struktur und der Größe von kolloidchemischen Teilchen,” In kolloidchemie Ein Lehrbuch. (Berlin: Heidelberg: Springer), 387–409. doi:10.1007/978-3-662-33915-2_7

Shahi, W., Chau, L., Wei, W., Huanxin, W., and Youqi, Z. (2010). Synthesis and photocatalytic property of Ce-doped SnO2. J. Rare Earths 28:168–170. doi:10.1016/S1002-0721(10)60312-2

Sirelkhatim, A., Mahmud, S., Seeni, A., Kaus, N. H. M., Ann, L. C., Bakhori, S. K. M., et al. (2015). Review on zinc oxide nanoparticles: antibacterial activity and toxicity mechanism. Nanomicro Lett. 7, 219–242. doi:10.1007/s40820-015-0040-x

Swaminathan, B., and Smidt, P. G. (2007). The epidemiology of human listeriosis. Microb. Infect. 9, 1236–1243. doi:10.1111/j.1469-0691.2007.01893.x

Vargas-Reus, M. A., Memarzadeh, K., Huang, J., Ren, G. G., and Alakar, R. P. (2012). Antimicrobial activity of nanoparticulate metal oxides against peri-implantitis pathogens. Int. J. Antimicrob. Agents 40, 135–139. doi:10.1016/j.ijantimicag.2012.04.012

Vidhu, V., and Philip, D. (2015). Phytosynthesis and applications of bioactive SnO2 nanoparticles. Mater. Charact. 101, 97–105. doi:10.1016/j.matchar.2014.12.027

Wang, Z., Han, T., Fei, T., Liu, S., and Zhang, T. (2018). Investigation of microstructure effect on NO2 sensors based on SnO2 nanoparticles/reduced graphene oxide hybrids. ACS Appl. Mater. Interf. 10, 41773–41783. doi:10.1021/acsami.8b13784

Xie, J., Huang, K., Yu, X., Yang, Z., Xiao, K., Qiang, Y., et al. (2017). Enhanced electronic properties of SnO2 via electron transfer from graphene quantum dots for efficient perovskite solar cells. ACS Nano 11, 9176–9182. doi:10.1021/acsnano.7b04070
Yemmireddy, V. K., and Hung, Y. C. (2017). Using photocatalyst metal oxides as antimicrobial surface coatings to ensure food safety—Opportunities and challenges. Compr. Rev. Food Sci. Food Saf. 16, 617–631. doi: 10.1111/1541-4337.12267

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.