THE PERFORMANCE OF DIFFERENT TYPES OF FLOWER-LIKE ZINC OXIDE FOR PHOTOCATALYTIC DESULFURIZATION OF SYNTHETIC THIOPHENE

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For my beloved mother and father

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ABSTRACT

Zinc oxide (ZnO) nanoparticles have received great attention due to their advantages. Several improvements on the morphology of ZnO have been widely studied to solve the problem of agglomeration and surface-active sites. To date, there are limited studies involving the effect of flower-like ZnO in the application of thiophene desulfurization via photocatalysis process. Thus, this study focuses on the performance of different flower-like ZnO for synthetic thiophene desulfurization. Eight ZnO photocatalyst species were synthesised and categorized into two groups, namely flower-like ZnO and non-flower-like ZnO. The physical properties of all the ZnO morphologies were analysed. Moreover, their performances for desulfurization of synthetic thiophene were evaluated. From the findings, flower-like ZnO flakes showed the highest performance in synthetic thiophene desulfurization (30%). Higher pH (pH 11) and turbidity reduction (32%) of the permeate indicated the higher generation of hydroxyl radicals causing higher desulfurization of thiophene. From the kinetic study, all ZnO morphologies were applicable with pseudo-second-order models due to higher linear regression (R^2) values. The highest concentration equilibrium, C_e value for flower-like ZnO flakes (909.09 mg/g) confirmed greater desulfurization of thiophene. Moreover, it was found that pH 7 in the presence of 0.05 g/L flower-like ZnO flakes for 90 minutes of irradiation were the best conditions and yield the highest desulfurization of 300 ppm synthetic thiophene (30%) due to the highest generation of hydroxyl radical. It is expected that this integrated approach could bring forward other initiative methods in overcoming the problems in petroleum industry related to desulfurization of sulphur-containing compounds.

ABSTRAK

Nanozarah zink oksida (ZnO) telah mendapat perhatian tinggi di kalangan penyelidik disebabkan kelebihannya. Beberapa penambahbaikan terhadap morfologi ZnO telah banyak dikaji untuk menyelesaikan masalah penggumpalan dan pertingkatkan tapak aktif permukaan. Sehingga kini, kajian adalah terhad dalam melibatkan keberkesanan ZnO berbentuk bunga dalam penyahsulfuran tiofen melalui pelantar reaktor foto-pemangkin. Maka, kajian ini memfokuskan kepada prestasi pelbagai jenis ZnO berbentuk bunga dalam penyahsulfuran tiofen sintetik. Lapan spesis foto-pemangkin ZnO telah dibentuk dan dikategorikan kepada dua kumpulan, iaitu ZnO berbentuk bunga dan ZnO tidak berbentuk bunga. Sifat fizikal kesemua spesis ZnO telah dianalisis. Tambahan, prestasi ZnO ini telah dinilai dalam penyahsulfuran tiofen sintetik. Daripada penemuan, kepingan ZnO berbunga telah menunjukkan prestasi tertinggi dalam penyahsulfuran tiofen sintetik (30%). pH yang tertinggi (pH 11) dan pengurangan kekeruhan yang tinggi (32%) menunjukkan penjanaan radikal hidroksil yang sangat besar menyebabkan penyahsulfuran dan menguraikan sebilangan besar sebatian tiofen. Daripada kajian kinetik kesemua morfologi ZnO bersesuaian dengan model pseudo-kedua kerana nilai garisan regresi (R^2) yang tertinggi. Ketinggian nilai keseimbangan kepekatan, C_e untuk kepingan ZnO berbunga (909.09 mg/g) mengesahkan penyahsulfuran tiofen sintetik yang lebih besar. Tambahan, didapati bahawa pH 7 dengan kehadiran serpihan ZnO berbunga sebanyak 0.05 g/L selama 90 minit masa penyinaran adalah kondisi terbaik untuk penyahsulfuran 300 ppm tiofen sintetik dan menghasilkan penyahsulfuran tertinggi (30%) disebabkan penjanaan radikal hidroksil yang banyak semasa penyinaran. Pendekatan bersepadu ini diharapkan dapat membawa kemajuan terhadap kaedah inisiatif lain dalam mengatasi masalah dalam industri petroleum berkaitan penyahsulfuran sebatian mengandungi sulfur (SCC).

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LIST OF SYMBOLS AND ABBREVIATIONS

BOD	-	Biochemical oxygen demand
CB	-	Conduction band
CBD	-	Chemical bath deposition
CC	-	Cymbopogon citrus
COD	-	Chemical oxygen demand
CP	-	Cholrophenol
CTAB	-	Cetyltrim ethyl ammonium bromide
Eg	-	Band gap energy
EQA	-	Environmental quality act
FESEM	-	Field emission scanning electron microscope
FTIR	-	Fourier transform infrared spectrometer
GFD	-	Gallons per square foot per day
HCl	-	Hydrochloric acid
HDS	-	Hydrodesulfurization
HMTA	-	Hexamethylenetetramine
hv	-	Photon energy
KOH	-	Potassium hydroxide
MF	-	Microfiltration
NaOH	-	Sodium hydroxide
NF	-	Nanofiltration
NTU	-	Nephelometric turbidity units
PA	-	Polypiperazine-amide
PEG	-	Polyethylene glycol
PES	-	Polyether sulfone
PL	-	Photoluminescence
PMR	-	Photocatalytic membrane reactor
POMSE	-	Palm oil mill secondary effluent

ppm	-	Parts per million
PVDF	-	Polyvinylidene fluoride
PVP-St	-	Polyvinylpyrrolidone
RhB	-	Rhodamine B
SCCs	-	Sulphur containing compounds
UF	-	Ultrafiltration
UV-Vis	-	Ultra violet - visible
VB	-	Valence band
W	-	Watt
XRD	-	X-ray diffractometer
ZnAc	-	Zinc acetate
ZnNit	-	Zinc nitrate
ZnO	-	Zinc oxide

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Petroleum industry is one of the largest industries in Malaysia and is a vital part of the national economy. Nevertheless, this largest industry also contributes to major sources of environmental pollutions. Sulphur is the third most abundant element after carbon and hydrogen in petroleum and contributes to air pollutions due to the production of SO_2 species known as toxic gas during combustion (Mousavi-Kamazani, 2020). Thiophene is one of the sulphur pollutants in petroleum and this compound is known as sulphur-containing compounds (SCCs) in petroleum. Previous findings in the literature have defined that thiophene has a simple aromatic compound containing sulphur atom (C_4H_4S). It belongs to heterocyclic compounds as it is structured as five-member rings consisting of one heteroatom, which is Sulphur (Hamdan et al., 2021). Moreover, thiophene is a toxic and flammable aromatic compound where the production of toxic oxides during combustion could lead to negative impact especially on human health such as respiratory problems, wheezing, phlegm and asthma attack meanwhile negative impact on environment such as acid rain (Sadare et al., 2017). Conventional technology, which is hydrodesulfurization, seems not very effective which increases the demand for desulfurization in petroleum. Other observations have indicated that this process requires higher temperatures (>300^oC), higher hydrogen pressures (>30 atm) and more active catalysts to achieve deep desulfurization. However, the removal of thiophene through this process is difficult due to its stable aromatic ring structure. Thus, this conventional method is still far from complying with the standard regulations (Rudreshwar et al., 2016).

To date, photocatalysis process has attracted much attention for environmental purification and treatment especially in thiophene desulfurization as it is more environmentally friendly. Previous studies have reported that thiophene was successfully desulfurized more than 95% via photocatalysis process using semiconductor photocatalysts, such as copper-decorated zirconia-silica (ZrO_2-SiO_2), Mn_3O_4-coupled Ag_2WO_4, flower-like BiOI/$BiPO_4$, CdSe/rGO and others. However, the preparation of these photocatalysts was very complicated, inducing high level of heavy metal and high cost of chemical reagents when utilized in industrial scale. In addition, the air/oxygen supply to the system over a longer period could affect the capital cost for industrial scale (Sadare et al., 2017). Therefore, the preparation of flower-like zinc oxide (ZnO) via simple route and less hazardous was performed in this study for photo-desulfurization of thiophene.

Khan et al. (2015) stated that photocatalyst should have the desired band gap, suitable morphology, higher surface area, reusability and stability to increase the efficiency of photocatalytic activity. Metal oxides are the best photocatalysts commonly used for photocatalysis process due to their ability to absorpt light and generate oxidation of organic pollutants (Kang et al., 2019). ZnO is one of the semiconductor metal oxides that has a direct wide band gap of 3.37 eV and a large excitation binding energy of 60 meV that is widely applied in piezoelectric nano-generators, dye-sensitized solar cells, biodevices, optoelectronic nano-devices and photocatalyst for the degradation and removal of environmental pollutants. Compared to titanium dioxide (TiO_2), ZnO is more stable, economically photosensitive and has higher H_2O_2 generation (Desa et al., 2019). The wurtzite structure of ZnO allows for large excitation binding energy that generates ultraviolet (UV) light efficiency at standard temperature. However, previous studies have emphasized less on improving the morphological structure of ZnO. By improving the morphology and surface area, the efficiency of photocatalytic activity could be increased (Khan et al., 2015).

To date, the control of the shape of ZnO nanostructures has received much attention due to improved morphology, surface area and stability. There are three types of dimensional ZnO structures that have been synthesized: 1-dimensional structure (rod, wires, tubes), 2-dimensional structure (ribbons, sheets) and 3-dimensional structure (flower). Among them, flower-like ZnO structures have shown the best photocatalytic activity due to the improved morphological structure (Fan et al., 2016). Various studies have revealed that the highest degradation of organic compound was

successfully achieved due to greater amount of oxygen vacancies existed on the surface of flower-like ZnO. During the photodegradation, oxygen vacancies act as active centres to inhibit recombination of photoelectrons and photo-holes, thus exhibiting higher photocatalytic activity (Li et al., 2013; Fan et al., 2016). However, studies on photodegradation of thiophene in the presence of flower-like ZnO are still limited. Therefore, this study attempts to discover the performance of different types of flower-like ZnO for desulfurization of thiophene.

The structure of flower-like ZnO composed of 2-dimensional structure of ZnO nanorods. These nanorods are assembled and intersect with each other to form a flower-like structure. To date, there are many techniques for preparing flower-like ZnO including thermal evaporation, chemical vapor deposition, hydrothermal and electro-deposition (Liang et al., 2019). However, most of the reported techniques require special conditions, high temperatures, longer preparation time, and difficulty in tailing ZnO microstructure. Therefore, this study synthesized flower-like ZnO using a simpler and low-temperature preparation method. Recently, hydrothermal method has been used to prepare flower-like ZnO structure as it offers many advantages to produce products that are homogenous in composition, and control morphology, purity, composition, size and crystallinity of nanomaterial. Previously, Rayerfrancis et al. (2015) synthesized flower-like ZnO using hydrothermal method under basic conditions. They claimed that the synthesized flower-like ZnO has pure composition and greater wurtzite structure.

Another simpler method is the chemical bath deposition (CBD) method which promises a great commercial value, better replicability, large area scaling, simplicity and convenience (Dubal et al., 2014). On another note, Zhang et al. (2015) synthesized branch-like ZnO nanorods which were similar to that of flower-like via CBD technique at low temperatures and times without the surfactant addition and pH modification. They have found that the branch-like ZnO nanorods combined with copper oxide/copper sulphate (CuO/CuS) core–shell structures exhibited good performance under visible light for photocatalytic degradation of RhB solution (Cao et al., 2019). However, there is little discussion on the preparation of flower-like ZnO via CBD and hydrothermal method including its application in desulfurization of thiophene. Therefore, this study has been conducted through hydrothermal and CBD method due to its promising replicability, simple route and less harmful, which is proven the improvement of morphology, surface area, stability, less poisonous and band gap of

flower-like ZnO photocatalyst. Besides, their performances in desulfurization of thiophene via photocatalytic reactor were evaluated.

1.2 Problem statement

Petroleum is the largest industry that contributes to major hazardous air and water pollutants which could adversely affect the environment and human. Thiophene is one of the sulphur-containing compounds (SCCs) in petroleum known as an aromatic compound with toxic and flammable behaviour. This compound could cause air pollutions due to toxic gases produced during combusting and also cause severe corrosion of reactors and equipment during oil processing. In conventional technology, hydrodesulfurization (HDS) is still ineffective for removing thiophene due to stable aromatic compound. This technology also requires high cost to implement due to its high demand. Therefore, advanced desulfurization technology is required to reduce problems such as photocatalytic desulfurization.

Recently, ZnO nanoparticles have showed great performance for desulfurization of thiophene and produced high quality of permeate. However, previous studies have focused less on the improvement of the morphological and surface structure of ZnO. By improving ZnO morphology, the efficiency of the photocatalytic activity could be increased. Previously, precipitation method of ZnO nanoparticles has a major problem in controlling the morphologic, size distribution and surface area of ZnO nanoparticles.

Morphology of flower-like ZnO have shown the best photocatalytic activity due to improved morphology, surface area and light absorption thus, increase the degradation efficiency of organic compound. However, the challenging is most of the reported preparation methods require special conditions, high temperatures, longer preparation time, and difficulty in tailing ZnO microstructure. Besides, studies on photo-desulfurization of thiophene in the presence of flower-like ZnO are still limited. Therefore, this study evaluated the performance of different types of flower-like ZnO for desulfurization of thiophene via photocatalytic reactor rig.

1.3 Objectives of study

The objectives of this study are:

(i) To synthesis flower-like ZnO via hydrothermal and chemical bath deposition (CBD) methods.

(ii) To characterize the physicochemical properties of flower-like ZnO.

(iii) To elucidate the performance of flower-like ZnO for synthetic thiophene desulfurization in terms of desulfurization efficiency, kinetic study and optimum condition.

1.4 Scopes of study

The scopes of this study are:

(i) Synthesis of flower-like ZnO via hydrothermal and chemical bath deposition (CBD) method under different chemical precursors (ZnAc-NaOH, ZnAc-HMTA and ZnNit-HMTA), pH (6-12), temperature (90-150^{o}C), operating time (1-10 hours) to study and differentiate the effects of different conditions on ZnO morphology.

(ii) Characterization of flower-like ZnO using X-ray diffractometer (XRD), field emission scanning electron microscope (FESEM) and Fourier transform infrared (FTIR) spectrometer to investigate crystallinity, purity, morphology, particle size and functional group, respectively.

(iii) Elucidation of flower-like ZnO performance in desulfurization of synthetic thiophene via photocatalysis process under different initial pH (6, 7, 8) and types of flower-like ZnO photocatalyst to determine the best and higher performance among the synthesized photocatalyst.

(iv) Analysis of permeate quality in terms of concentration, pH and turbidity to study the effectiveness of synthesized ZnO photocatalysts in desulfurization of synthetic thiophene.

(v) Elucidation of kinetic studies on photocatalytic desulfurization of synthetic thiophene through pseudo-first-order and second-order kinetic reaction to evaluate the efficiency of synthesized ZnO photocatalysts in synthetic thiophene desulfurization

(vi) Determination of the optimum conditions for flower-like ZnO photocatalyst in

desulfurization of synthetic thiophene in terms of photocatalyst loading (0.04, 0.05, 0.06 g/L) and time contact (5 hours).

1.5 Significance of the study

This study focuses on the long-term benefits of photocatalytic degradation for treating crude petroleum oil from sulphur-containing compounds (SCCs) by increasing the desulfurization efficiency of thiophene to enhance petroleum refining plant technology. Higher demand in the petroleum industry confirms that more effective sulphur-treatment approach is necessary. Thus, this study applied the recommended treatment approach that is technically and economically significance to the industry to produce less harmful and environmentally friendly petroleum oils. It is important to save energy as well as to reduce capital cost and installation size due to higher temperature, higher hydrogen pressure and greater amount of active catalyst are not required for this photocatalytic system. Moreover, this preliminary study is important and could serve as a reference for future applications in the pilot scale of treatment plant. Therefore, this study provides an elucidation of the performance of different types of flower-like ZnO in desulfurization of synthetic thiophene to develop advanced sulphur treatment systems that have the potential to comply with the permissible limit of sulphur-containing compounds worldwide.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Currently, the petroleum industry is one of the largest industries in Malaysia and is a vital part of the national economy. Towards achieving developing country status, the industry is growing day by day to support the development of advanced technology. Apart from the positive impacts on the industry, adverse impacts also need to be considered. It is known that this largest industry is also major sources of hazardous, toxic, air and water pollutants which can adversely affect the environment and human (Kan et al., 2010). Therefore, petroleum refining is the most importance sector to separate and treat crude oil into safe and environmentally friendly petroleum products (petroleum gas, diesel fuel, motor oil and others) through a series of physical and chemical separation and treatment techniques. There are five major processes involved in crude oil refining, namely conversion, treatment, blending or combination and auxiliary processes. Among these processes, petroleum refining needs to be emphasized more to separate and reduce impurities, undesired and potentially harmful components from the products.

Speight (1980) reported that in petroleum, sulphur is the third most abundant element after carbon and hydrogen. About 0.05 to 5% present in crude oils. The sulphur content in petroleum could contribute to air pollution as it produces SO_2 species known as toxic gas during combustion (Alhaddad & Shawky, 2020). Severe corrosion of reactors and equipment could also occur during oil processing steps due the presence of sulphur compound (Rudreshwar et al., 2016). Due to this serious environmental issue, new regulation has been gazette to lower the sulphur content

(S-content) in fuel oils. Hence, the permissible limit of sulphur-containing compounds in fuels is 10-15 ppm worldwide (Amiri et al., 2020). Refining plays an important role especially during the petroleum refining process as this process could reduce sulphur content from the petroleum products. Hydrodesulfurization (HDS) is a conventional desulfurization technology applied during petroleum refining. This technology promotes the removal of sulphur compounds such as thiols, sulphides and disulphides by converting them into hydrogen sulphide (Shafi et al., 2000). However, HDS could lead to high capital cost as this process requires high temperatures (>300^{o}C), high hydrogen pressures (>30 atm) and more active catalysts to achieve deep desulfurization (Shawky et al., 2020). Moreover, some sulphur compounds in fuels, such as thiophene, are difficult to remove by typical HDS due to its stable aromatic ring structure (Di-shun et al., 2008). HDS technology can be burdensome to the petroleum industry owing to high capital cost and the sulphur content in fuels is still far from complying with standard regulations.

Thiophene is found as a contaminant in benzene as it has the simplest aromatic compound but contains sulphur atom and it has similar chemical properties similar to benzene (Mishra et al., 2011). In addition, thiophene is known as a sulphur pollutant as it is categorized as sulphur-containing compounds (SCCs) in petroleum. The sulphur content could lead to negative impact on the environment due to its toxic behaviour (Sadare et al., 2017). This compound is also difficult to oxidise and degrade as it has stable aromatic ring structure (Otsuki et al., 2000). Since conventional HDS is not effective, other alternative to deep desulfurization of petroleum oil was examined in this study to improve the cost-effectiveness of the process.

2.2 Thiophene

Before implementing the thiophene desulfurization technique, the properties and behaviour of thiophene need to be studied. Thiophene is defined as the simplest aromatic compound containing sulphur atom with the formula C_4H_4S and belongs to heterocyclic compounds as it is structured as five-member ring consisting of one heteroatom, which is sulphur (Shah & Verma, 2018). Thiophene and its derivatives are usually present in petroleum oil or coal. Previous literature has described the physical behaviour of thiophene as a colourless liquid which has a mild pleasant odour reminiscent of benzene as it shares some chemical properties similar to benzene.

Thiophene also has high reactivity to sulphonation which is difficult to separate from benzene by distillation due to its similar boiling points (4^{o}C at ambient pressure) (Mishra et al., 2011).

Table 2.1: Toxicological data for thiophene and its derivatives (Canada National Energy Board, 2006)

	Thiophene	*2-Methylthiophene*	*2-Acetylthiophene*	*2-Bromothiophene*
Acute Toxicity				
Oral LD_{50}	1400 mg/kg (rat)	3200 mg/kg (mouse)	50 mg/kg (mouse)	200-250 mg/kg (rat)
Dermal LD_{50}	830 mg/kg (rabbit)	No data	370 mg/kg (rat)	134 mg/kg (rat)
Inhalation LC_{50}	9500 mg/kg (mouse)	No data	1460 mg/m^3, 1h (rat)	1.04 mg/L, 4h (rat)
Irritation				
Skin	Yes	Expected	Not reported	Yes
Eye	Yes	Expected	Predicted	Yes
Eco toxicity	- Caused acid rain that harm aquatic organism -Inflammation and irritation to respiratory system - Contribute to air pollution	- Caused acid rain that harm aquatic organism -Inflammation and irritation to respiratory system - Contribute to air pollution	- Caused acid rain that harm aquatic organism -Inflammation and irritation to respiratory system - Contribute to air pollution	- Caused acid rain that harm aquatic organism -Inflammation and irritation to respiratory system - Contribute to air pollution
Occupational exposure limits	None specified	None specified	2ppm (provisional)	1 ppm (provisional)
Persistence	Expect ultimate biodegradability	Expect ultimate biodegradability	Expect ultimate biodegradability	Expect very slow biodegradability
Materials to avoid	Strong oxidizers	Strong oxidizers	Strong oxidizers	Strong oxidizers
Conditions	Stable under normal conditions	stable under normal conditions	stable under normal conditions	slow decomposition unless cool/dark
Combustion products	Toxic oxides of S+CO, CO_2	Toxic oxides of S+CO, CO_2	Toxic oxides of S+CO, CO_2	HBr during storage, CO, CO_2

REFERENCES

Alahabadi, A., Rezai, Z., Rahmani-Sani, A., Rastegar, A., Hosseini-Bandegharaei, A., & Gholizadeh, A. (2016). Efficacy evaluation of NH_4Cl-induced activated carbon in removal of aniline from aqueous solutions and comparing its performance with commercial activated carbon. Desalination and Water Treatment, 57(50), 23779–23789. Retrieved from https://doi.org/10.1080/19443994.2015.1134356

Alhaddad, M., & Shawky, A. (2020). Superior photooxidative desulfurization of thiophene by reduced graphene oxide-supported MoS_2 nanoflakes under visible light. Fuel Processing Technology, 205(March), 106453. https://doi.org/10.1016/j.fuproc.2020.106453

Aljeboree, A. M., Alshirifi, A. N., & Alkaim, A. F. (2017). Kinetics and equilibrium study for the adsorption of textile dyes on coconut shell activated carbon. Arabian Journal of Chemistry, 10, S3381–S3393. https://doi.org/10.1016/j.arabjc.2014.01.020

Amin, G., Asif, M. H., Zainelabdin, A., Zaman, S., Nur, O., & Willander, M. (2011). Influence of pH, Precursor Concentration, Growth Time, and Temperature on the Morphology of ZnO Nanostructures Grown by the Hydrothermal Method. 2011. https://doi.org/10.1155/2011/269692

Amiri, O., Beshkar, F., Ahmed, S. S., Mahmood, P. H., & Dezaye, A. A. (2020). Hierarchical p-BiOI/n-BiPO4 heterojunction nanocomposite with enhanced visible-light photocatalytic desulfurization of thiophene under mild conditions. International Journal of Hydrogen Energy, xxxx. https://doi.org/10.1016/j.ijhydene.2020.11.181

Aneesh, P. M., Vanaja, K. A., & Jayaraj, M. K. (2007). Synthesis of ZnO nanoparticles by hydrothermal method. 6639, 1–9. https://doi.org/10.1117/12.730364

Atitar, M. F., Bouziani, A., Dillert, R., El Azzouzi, M., & Bahnemann, D. W. (2018). Photocatalytic degradation of the herbicide imazapyr: Do the initial degradation rates correlate with the adsorption kinetics and isotherms. Catalysis Science and Technology, 8(4), 985–995. https://doi.org/10.1039/c7cy01903c

B.Q. Cao, W.P. Cai, G.T. Duan, Y. Li, Q. Zhao, D.P. Yu. (2005). A template-free electrochemical deposition route to ZnO nanoneedle arrays and their optical and field emission properties, Nanotechnology 16, 2567–2574.

Batool, F., Akbar, J., Iqbal, S., Noreen, S., & Bukhari, S. N. A. (2018). Study of Isothermal, Kinetic, and Thermodynamic Parameters for Adsorption of Cadmium: An Overview of Linear and Nonlinear Approach and Error Analysis. Bioinorganic Chemistry and Applications, 2018. https://doi.org/10.1155/2018/3463724

Bucci, R., Balestrieri, F., Magr, A. D., Magr, A. L., & Marini, F. (2006). UV – Vis spectrophotometric method for the quantitation of all the components of Italian general denaturant and its application to check the conformity of alcohol samples. 68, 781–790. https://doi.org/10.1016/j.talanta.2005.06.002

Cao, F., Pan, Z., & Ji, X. (2019). Enhanced photocatalytic activity of a pine-branch-like ternary CuO/CuS/ZnO heterostructure under visible light irradiation. New Journal of Chemistry, 43(28), 11342–11347. https://doi.org/10.1039/c9nj01785b

Chen, C., Mei, W., Wang, C., Yang, Z., Chen, X., Chen, X., & Liu, T. (2020). Synthesis of a flower-like SnO/ZnO nanostructure with high catalytic activity and stability under natural sunlight. Journal of Alloys and Compounds, 826, 154122. https://doi.org/10.1016/j.jallcom.2020.154122

Chen, X., Wu, Z., Liu, D., & Gao, Z. (2017). Preparation of ZnO Photocatalyst for the Efficient and Rapid Photocatalytic Degradation of Azo Dyes. Nanoscale Research Letters, 12(1), 4–13. https://doi.org/10.1186/s11671-017-1904-4

Chen, Y., Xiang, Z., Wang, D., Kang, J., & Qi, H. (2020). Effective photocatalytic degradation and physical adsorption of methylene blue using cellulose/GO/TiO_2 hydrogels. RSC Advances, 10(40), 23936–23943. https://doi.org/10.1039/d0ra04509h

Cuccureddu, F., Murphy, S., Shvets, I. V, Porcu, M., Zandbergen, H. W., Sidorov, N. S., & Bozhko, S. I. (2010). Surface Science Surface morphology of c -plane

sapphire (α -alumina) produced by high temperature anneal. SUSC, 604(15–16), 1294–1299. https://doi.org/10.1016/j.susc.2010.04.017

Desa, A. L., Hairom, N. H. H., Sidik, D. A. B., Zainuri, N. Z., Ng, L. Y., Mohammad, A. W., Jalil, A. A. (2020). Performance of tight ultrafiltration membrane in textile wastewater treatment via MPR system: Effect of pressure on membrane fouling. IOP Conference Series: Materials Science and Engineering, 736(2). https://doi.org/10.1088/1757-899X/736/2/022033

Dhasmana, H., Dutta, V., Kumar, A., Kumar, A., Verma, A., & Jain, V. K. (2020). Materials Today: Proceedings Hydrothermally synthesized zinc oxide nanoparticles for reflectance study onto Si surface. Materials Today: Proceedings, 1–7. https://doi.org/10.1016/j.matpr.2020.01.374

Doke, K. M., & Khan, E. M. (2017). Equilibrium, kinetic and diffusion mechanism of Cr(VI) adsorption onto activated carbon derived from wood apple shell. Arabian Journal of Chemistry, 10, S252–S260. https://doi.org/10.1016/j.arabjc.2012.07.031

Dubal, D., Holze, R. & Gomez-Romero, P. Development of hybrid materials based on sponge supported reduced graphene oxide and transition metal hydroxides for hybrid energy storage devices. Sci Rep 4, 7349 (2015). https://doi.org/10.1038/srep07349

Fan, J., Li, T., & Heng, H. (2016). Hydrothermal growth of ZnO nanoflowers and their photocatalyst application, 39(1), 19–26.

Gao, X., Fu, F., Zhang, L., & Li, W. (2013). The preparation of Ag – BiVO 4 metal composite oxides and its application in ef fi cient photocatalytic oxidative thiophene, 419, 80–85. https://doi.org/10.1016/j.physb.2013.03.024

Guo, J., Yuan, S., Jiang, W., Yue, H., Cui, Z., & Liang, B. (2016). Adsorption and photocatalytic degradation behaviors of rhodamine dyes on surface-fluorinated TiO2 under visible irradiation. RSC Advances, 6(5), 4090–4100. https://doi.org/10.1039/c5ra14379a

Haddad, K., Gheid, A., Haddad, D., & Oulmi, K. (2019). Experimental and numerical study on the leaching of pesticides into the groundwater through a porous medium: Effects of transport parameters. Environmental Technology and Innovation, 13, 244–256. https://doi.org/10.1016/j.eti.2018.12.009

Hairom, N. H. H., Mohammad, A. W., & Kadhum, A. A. H. (2014a). Effect of various zinc oxide nanoparticles in membrane photocatalytic reactor for Congo red

dye treatment. Separation and Purification Technology, 137, 74–81. https://doi.org/10.1016/J.SEPPUR.2014.09.027

Hairom, N. H. H., Mohammad, A. W., & Kadhum, A. A. H. (2014b). Nanofiltration of hazardous Congo red dye: Performance and flux decline analysis. Journal of Water Process Engineering, 4(C), 99–106. https://doi.org/10.1016/j.jwpe.2014.09.008

Hairom, N. H. H., Mohammad, A. W., Ng, L. Y., & Kadhum, A. A. H. (2015). Utilization of self-synthesized ZnO nanoparticles in MPR for industrial dye wastewater treatment using NF and UF membrane. Desalination and Water Treatment,54(4–5),944–955. https://doi.org/10.1080/19443994.2014.917988

Hamdan, M. A. H., Hairom, N. H. H., Jalil, A. A., Ahmad, M. K., Madon, R. H., Dzinun, H., Hamzah, S., Kamal, A. S. M., & Jusoh, N. W. C. (2020). Catalytic conversion of synthetic sulfur-pollutants in petroleum fractions under different photocatalyst loadings and initial concentration. International Journal of Emerging Trends in Engineering Research, 8(1 1.2 Special Issue), 132–138. https://doi.org/10.30534/ijeter/2020/1881.22020

Hamdan, M. A. H., Hairom, N. H. H., Zaiton, N., Harun, Z., Soon, C. F., Hubadillah, S. K., Jamalludin, M. R., Che Jusoh, N. W., & Abdul Jalil, A. (2021). Photocatalytic Degradation of Synthetic Sulfur Pollutants in Petroleum Fractions under Different pH and Photocatalyst. *Emerging Advances in Integrated Technology*, *2*(1), 30-38. Retrieved from https://publisher.uthm.edu.my/ojs/index.php/emait/article/view/8705

Harish, S., Navaneethan, M., Archana, J., Silambarasan, A., Ponnusamy, S., Muthamizhchelvan, C., & Hayakawa, Y. (2015). Controlled synthesis of organic ligand passivated ZnO nanostructures and their photocatalytic activity under visible light irradiation. Dalton Transactions, 44(22), 10490–10498. doi:10.1039/c5dt01572c

He, D., Wan, J., Liu, G., Suo, H., & Zhao, C. (2020). Design and construction of hierarchical α-$Co(OH)_2$-coated ultra-thin ZnO flower nanostructures on nickel foam for high performance supercapacitors. Journal of Alloys and Compounds, 838, 155556. https://doi.org/10.1016/j.jallcom.2020.155556

Holi, A. M., Zainal, Z., Talib, Z. A., Lim, H., Yap, C., Chang, S., & Ayal, A. K. (2016). Effect of Hydrothermal Growth Time on ZnO Nanorod Arrays Photoelectrode Performance. Optik - International Journal for Light and

Electron Optics. https://doi.org/10.1016/j.ijleo.2016.09.015

Iqbal, S., Bahadur, A., Anwer, S., Ali, S., Irfan, R. M., Li, H., Shoaib, M., Raheel, M., Anjum, T. A., & Zulqarnain, M. (2020). Effect of temperature and reaction time on the morphology of L-cysteine surface capped chalcocite (Cu_2S) snowflakes dendrites nanoleaves and photodegradation Study of Methyl orange dye under visible light. Colloids and Surfaces A: Physicochemical and Engineering Aspects, May, 124984. https://doi.org/10.1016/j.colsurfa.2020.124984

Jang, E. (2017). Review Recent Progress in Synthesis of Plate-like ZnO and its Applications: A Review. 54(3), 167–183.

Jiang, L., Yuan, X., Zeng, G., Wu, Z., Liang, J., Chen, X., Wang, H. (2018). Metal-free efficient photocatalyst for stable visible-light photocatalytic degradation of refractory pollutant. Applied Catalysis B: Environmental, 221(June), 715–725. https://doi.org/10.1016/j.apcatb.2017.09.059

Junejo, R., Memon, S., Memon, F. N., Memon, A. A., Durmaz, F., Bhatti, A. A., & Bhatti, A. A. (2019). Thermodynamic and Kinetic Studies for Adsorption of Reactive Blue (RB-19) Dye Using Calix arene-Based Adsorbent. Journal of Chemical and Engineering Data, 64(8), 3407–3415. https://doi.org/10.1021/acs.jced.9b00223

Kang, X., Liu, S., Dai, Z., He, Y., Song, X., & Tan, Z. (2019). Titanium Dioxide: From Engineering to Applications. Catalysts (Vol. 9). https://doi.org/10.3390/catal9020191

Khan, M. M., Adil, S. F., & Al-Mayouf, A. (2015). Metal oxides as photocatalysts. Journal of Saudi Chemical Society, 19(5), 462–464. https://doi.org/10.1016/j.jscs.2015.04.003

Kilic, B., Günes, T., Besirli, I., Sezginer, M., & Tuzemen, S. (2013). Construction of 3-dimensional ZnO-nanoflower structures for high quantum and photocurrent efficiency in dye sensitized solar cell. Applied Surface Science, 1–5. https://doi.org/10.1016/j.apsusc.2013.12.065

Lee, K. M., Abd Hamid, S. B., & Lai, C. W. (2015). Mechanism and Kinetics Study for Photocatalytic Oxidation Degradation: A Case Study for Phenoxyacetic Acid Organic Pollutant. Journal of Nanomaterials, 2015, 1–10. https://doi.org/10.1155/2015/940857

Li, X., Wang, J., Yang, J., Lang, J., Wei, M., Meng, X., Sui, Y. (2013). Enhanced

photocatalytic activity of ZnO microflower arrays synthesized by one-step etching approach. Journal of Molecular Catalysis A: Chemical, 378, 1–6. https://doi.org/10.1016/j.molcata.2013.05.013

Liang, Q., Qiao, F., Cui, X., & Hou, X. (2019). Controlling the morphology of ZnO structures via low temperature hydrothermal method and their optoelectronic application. Materials Science in Semiconductor Processing, 89(September 2018), 154–160. https://doi.org/10.1016/j.mssp.2018.09.007

Liyana, A., Hanis, N., Hairom, H., Abu, D., Sidik, B., Misdan, N., Wahab, A. (2019). Journal of Environmental Chemical Engineering A comparative study of ZnO-PVP and ZnO-PEG nanoparticles activity in membrane photocatalytic reactor (MPR) for industrial dye wastewater treatment under di ff erent membranes. Journal of Environmental Chemical Engineering, 7(3), 103143. https://doi.org/10.1016/j.jece.2019.103143

Loghambal, S., Catherine, A. J. A., & Subash, S. V. (2018). Mathematics and its Applications Analysis of Langmuir-Hinshelwood Kinetics Model for Photocatalytic Degradation of Aqueous Direct Blue 71 Through Analytical Expression. International Journal of Mathematics and Its Applications, 6, 903–913.

Mirzaei, A., Yerushalmi, L., Chen, Z., & Haghighat, F. (2018). Photocatalytic degradation of sulfamethoxazole by hierarchical magnetic ZnO@g-C3N4: RSM optimization, kinetic study, reaction pathway and toxicity evaluation. Journal of Hazardous Materials, 359, 516–526. https://doi.org/10.1016/j.jhazmat.2018.07.077

Mkhalid, I. A., & Shawky, A. (2020). Visible light-active CdSe/rGO heterojunction photocatalyst for improved oxidative desulfurization of thiophene. Ceramics International, 46(13), 20769–20776. https://doi.org/10.1016/j.ceramint.2020.05.033

Mohamed, A. S. B. R. M. (2019). Photodegradation of thiophene over - ZrO 2 – SiO 2 nanoparticles: impact of copper decoration on their photocatalytic activity. Applied Nanoscience, 0(0), 0. https://doi.org/10.1007/s13204-019-00992-9

Mousavi-Kamazani, M. (2020). Cube-like $Cu/Cu_2O/BiVO_4/Bi_7VO1_3$ composite nanoparticles: Facile sol-gel synthesis for photocatalytic desulfurization of thiophene under visible light. Journal of Alloys and Compounds, 823, 153786. https://doi.org/10.1016/j.jallcom.2020.153786

Moussout, H., Ahlafi, H., Aazza, M., & Maghat, H. (2018). Critical of linear and nonlinear equations of pseudo-first order and pseudo-second order kinetic models. Karbala International Journal of Modern Science, 4(2), 244–254. https://doi.org/10.1016/j.kijoms.2018.04.001

N.H.H. Hairom, A.W. Mohammad, L.Y. Ng, A.A.H. Kadhum. (2014). Utilization of self-synthesized ZnO nanoparticles in MPR for industrial dye wastewater treatment using NF and UF membrane, Desalin. Water Treat. 1–12.

Nosaka, Y., & Nosaka, A. Y. (2018). Langmuir-Hinshelwood and Light-Intensity Dependence Analyses of Photocatalytic Oxidation Rates by Two-Dimensional-Ladder Kinetic Simulation. Journal of Physical Chemistry C, 122(50), 28748–28756. https://doi.org/10.1021/acs.jpcc.8b09421

Omar, A. F. Bin, & Mat Jafri, M. Z. Bin. (2009). Turbidimeter design and analysis: A review on optical fiber sensors for the measurement of water turbidity. Sensors, 9(10), 8311–8335. https://doi.org/10.3390/s91008311

Otsuki S, Nonaka T, Takashima N, Qian W, Ishihara A, Imai T, Kabe T. (2000). Oxidative desulfurization of light gas oil and vacuum gas oil by oxidation and solvent extraction. Energy Fuels, 14(6): 1232–1239.

Paniv, P.M.; Pysh'ev, S.V.; Gaivanovich, V.I.; Lazorko, O.I. (2006). Current Problems, Nontraditional Technologies, Noncatalytic oxidation desulfurization of the kerosene cut. Chem. Technol. Fuels Oils, 42, 159–166.

Poo-arporn, Y., Kityakarn, S., Niltharach, A., & Smith, M. F. (2019). Materials Science in Semiconductor Processing Photocatalytic oxidation of thiophene over cerium doped TiO 2 thin film. Materials Science in Semiconductor Processing, 93, 21–27. https://doi.org/10.1016/j.mssp.2018.12.025

Qiu, J., Weng, B., Zhao, L., Chang, C., Shi, Z., Li, X., Kim, H., & Hwang, Y. (2014). Synthesis and Characterization of Flower-Like Bundles of ZnO Nanosheets by a Surfactant-Free Hydrothermal Process. 2014.

R. Wahab, Y.S. Kim, H.S. Shin. (2009). The role of pH variation on the growth of zinc oxide nanostructures, Appl. Surf. Sci. 255, 4891–4896.

Rassie, C., Olowu, R. A., Waryo, T. T., Wilson, L., & Williams, A. (2011). Dendritic 7T-Polythiophene Electro-Catalytic Sensor System for the Determination of Polycyclic Aromatic Hydrocarbons. November 2014.

Rayerfrancis, A., Bhargav, P. B., & Chandra, B. (2015). Effect of pH on the morphology of ZnO nanostructures and its influence on structural and optical

properties, 457(3), 96–102. https://doi.org/10.1016/j.physb.2014.09.044

Rudreshwar, K., Ganesh, A., & Krishnamurthy, M. (2016). Deep-desulfurization of the petroleum diesel using the heterogeneous carboxyl functionalized poly-ionic liquid. Resource-Efficient Technologies. https://doi.org/10.1016/j.reffit.2016.10.005

Sadare, O. O., Obazu, F., & Daramola, M. O. (2017). Biodesulfurization of Petroleum Distillates. Current Status, Opportunities and Future Challenges. https://doi.org/10.3390/environments4040085

Saravanan, R., Sacari, E., Gracia, F., Khan, M. M., Mosquera, E., & Gupta, V. K. (2016). Conducting PANI stimulated ZnO system for visible light photocatalytic degradation of coloured dyes. Journal of Molecular Liquids, 221, 1029–1033. https://doi.org/10.1016/j.molliq.2016.06.074

Senthil Kumar, P., Selvakumar, M., Ganesh Babu, S., Induja, S., & Karuthapandian, S. (2017). CuO/ZnO nanorods: An affordable efficient p-n heterojunction and morphology dependent photocatalytic activity against organic contaminants. Journal of Alloys and Compounds, 701, 562–573. https://doi.org/10.1016/j.jallcom.2017.01.126

Shah, R., & Verma, P. K. (2018). Therapeutic importance of synthetic thiophene. Chemistry Central Journal, 5, 1–22. https://doi.org/10.1186/s13065-018-0511-5

Shanthi, P., Tamilarasan, G., Anitha, K., & Karthikeyan, S. (2014). Film and pore diffusion modeling for adsorption of reactive red-4 onto Sterculia quadrifida seed shell waste as activated carbon. Rasayan Journal of Chemistry, 7(3), 229–240.

Shawky, A., Mohamed, R. M., Mkhalid, I. A., Awwad, N. S., & Ibrahium, H. A. (2020). One-pot synthesis of Mn3O4-coupled Ag2WO4 nanocomposite photocatalyst for enhanced photooxidative desulfurization of thiophene under visible light irradiation. Applied Nanoscience (Switzerland), 10(5), 1545–1554. https://doi.org/10.1007/s13204-019-01212-0

Shon, H. K., Phuntsho, S., Chaudhary, D. S., Vigneswaran, S., & Cho, J. (2013). Nanofiltration for water and wastewater treatment - A mini review. Drinking Water Engineering and Science, 6(1), 47–53. https://doi.org/10.5194/dwes-6-47-2013

Sidik, D. A. B., Hairom, N. H. H., & Mohammad, A. W. (2019). Performance and

fouling assessment of different membrane types in a hybrid photocatalytic membrane reactor (PMR) for palm oil mill secondary effluent (POMSE) treatment. Process Safety and Environmental Protection, 130(August), 265–274. https://doi.org/10.1016/j.psep.2019.08.018

Strano, V., Greco, M. G., Ciliberto, E., & Mirabella, S. (2019). ZnO microflowers grown by chemical bath deposition: A low-cost approach for massive production of functional nanostructures. Chemosensors, 7(4), 23–24. https://doi.org/10.3390/chemosensors7040062

Suchea, M. (2016). Effect of temperature and concentration of precursors on morphology and photocatalytic activity of zinc oxide thin films prepared by hydrothermal route. https://doi.org/10.1088/1757-899X/123/1/012030

Tanczos, S. K. (2013). Preparation and properties of a photocatalyst with TiO_2 nanoparticles, 7(11), 822–827

Tekin, D., Tekin, T., & Kiziltas, H. (2019). Photocatalytic degradation kinetics of Orange G dye over ZnO and Ag/ZnO thin film catalysts. Scientific Reports, 9(1), 1–7. https://doi.org/10.1038/s41598-019-54142-w

Thamaraiselvan, C., Carmiel, Y., Eliad, G., Sukenik, C. N., Semiat, R., & Dosoretz, C. G. (2019). Modification of a polypropylene feed spacer with metal oxide-thin film by chemical bath deposition for biofouling control in membrane filtration. Journal of Membrane Science, 573(December 2018), 511–519. https://doi.org/10.1016/j.memsci.2018.12.033

Thilagan, J., Gopalakrishnan, S., & Kannadasan, T. (2013). A study on Adsorption of Copper (II) Ions in Aqueous Solution by Chitosan - Cellulose Beads Cross Linked by Formaldehyde. 2(II), 1043–1054.

Umar, A., & Hahn, Y. B. (2006). ZnO nanosheet networks and hexagonal nanodiscs grown on silicon substrate: growth mechanism and structural and optical properties. 2174. https://doi.org/10.1088/0957-4484/17/9/016

W. Zhang, L. Ding, J, Luo, M.Y. Jaffrin, B. Tang. (2016). Membrane fouling in photocatalytic membrane reactors (PMRs) for waste and wastewater treatment: a critical reviem, Chem. Eng. J. 302, 446-458, https://doi.org/10.1016/j.cej.2016.05.071.

Wahab, R., Ansari, S. G., Kim, Y. S., Seo, H. K., Kim, G. S., Khang, G., & Shin, H. (2007). Low temperature solution synthesis and characterization of ZnO nano-flowers, 42, 1640–1648. https://doi.org/10.1016/j.materresbull.2006.

Wahab, R., Ansari, S. G., Kim, Y. S., Song, M., & Shin, H. (2009). Applied Surface Science The role of pH variation on the growth of zinc oxide nanostructures, 255, 4891–4896. https://doi.org/10.1016/j.apsusc.2008.12.037

Wang, W., Han, Q., Zhu, Z., Zhang, L., Zhong, S., & Liu, B. (2019). Enhanced photocatalytic degradation performance of organic contaminants by heterojunction photocatalyst BiVO4/TiO2/RGO and its compatibility on four different tetracycline antibiotics. Advanced Powder Technology, 30(9), 1882–1896. https://doi.org/10.1016/j.apt.2019.06.006

Wang, Y., Li, X., Wang, N., Quan, X., & Chen, Y. (2008). Controllable synthesis of ZnO nanoflowers and their morphology-dependent photocatalytic activities, 62, 727–732. https://doi.org/10.1016/j.seppur.2008.03.035

William Kajjumba, G., Emik, S., Öngen, A., Kurtulus Özcan, H., & Aydın, S. (2019). Modelling of Adsorption Kinetic Processes—Errors, Theory and Application. Advanced Sorption Process Applications, 1–19. https://doi.org/10.5772/intechopen.80495

X.H. Sun, S. Lam, T.K. Sham, F. Heigl, A. Jurgensen, N.B. Wong (2005). Synthesis and synchrotron light-induced luminescence of ZnO nanostructures: nanowires, nanoneedles, nanoflowers, and tubular whiskers, J. Phys. Chem. B 109, 3120–3125.

Xie. J, Y. Li, W. Zhao, L. Bian, Y. Wei. (2011). Simple fabrication and photocatalytic activity of ZnO particles with different morphologies, Powder Technol. 207, 140–144.

Xu, C., Wang, Y., & Chen, H. (2015). Rapid and simple synthesis of 3D ZnO microflowers at room temperature. Materials Letters, 158, 347–350. https://doi.org/10.1016/j.matlet.2015.06.013

Yang, J., Wang, Y., Kong, J., Jia, H., & Wang, Z. (2015). Synthesis of ZnO nanosheets via electrodeposition method and their optical properties, growth mechanism. Optical Materials, 1–7. https://doi.org/10.1016/j.optmat.2015.04.016

Yetim, T., & Tekin, T. (2017). A Kinetic Study on Photocatalytic and Sonophotocatalytic Degradation of Textile Dyes. 102–108.

Yusof, N., Triwahyono, S., & Jalil, A. A. (2018). An Interaction Study Between CO and H_2 with Fibrous Silica KCC-1 by in situ FTIR, 13, 17–20. https://doi.org/10.1016/j.matpr.2019.11.131

Zamri, M. S. F. A., & Sapawe, N. (2019). Kinetic Study on Photocatalytic Degradation of Phenol Using Green Electrosynthesized TiO2 Nanoparticles. Materials Today: Proceedings, 19, 1261–1266. https://doi.org/10.1016/j.matpr.2019.11.131

Zarifah, N., Hanis, N., Hairom, H., Abu, D., Sidik, B., Liyana, A., Wahab, A. (2018). Journal of Water Process Engineering Palm oil mill secondary effluent (POMSE) treatment via photocatalysis process in presence of ZnO-PEG nanoparticles. Journal of Water Process Engineering, 26(April), 10–16. https://doi.org/10.1016/j.jwpe.2018.08.009

Zhang, Wei & Wang, Peng & Fei, Xuening & Xiu, Yan & Jia, Guozhi. (2015). Growth Mechanism and Morphologies Tuning of ZnO Nanostructures. International Journal of Electrochemical Science. 10. 4688-4695.

Zhang, Y., Liu, T., Hao, J., Lin, L., Zeng, W., Peng, X., & Wang, Z. (2015). Enhancement of NH 3 sensing performance in flower-like ZnO nanostructures and their growth mechanism. Applied Surface Science, 357, 31–36. https://doi.org/10.1016/j.apsusc.2015.08.170

Zhang, Z., Liu, M., & Zhai, J. (2012). Photocatalytic oxidation thiophene using Nano-TiO2, 219, 729–732. https://doi.org/10.4028/www.scientific.net/AMM.217-219.729

Zhu, L., Li, Y., & Zeng, W. (2017). Hydrothermal synthesis of hierarchical ZnO nanostructure and its enhanced ethanol gas-sensing properties. Applied Surface Science. https://doi.org/10.1016/j.apsusc.2017.08.229