Bayero Journal of Physics and Mathematical Sciences / Vol. 17, No. 1 / Feb., 2026. ISSN: 1597 – 9342, Online ISSN: 2795 - 3866

BAJOPMAS JOURNAL 17(1): 146 – 152
Printed in Bayero University, Kano - Nigeria.

EVALUATION OF OPTICAL ABSORPTION OF SINGLE METAL OXIDE NANOFLUIDS

[*1]Umar, Y., [*2]Darma, T. H. and [*3]Chyi, J. L. Y.
[1]Department of Applied Physics, School of Applied Sciences, Federal Polytechnic Nasarawa, Nigeria.
[2] Department of Physics, Faculty of Physical Sciences, Bayero University Kano, Nigeria.
[3] Department of Physics, Faculty of Science, Universiti Putra Malaysia.
*Corresponding Author:
Yakubu Umar
[1]Department of Applied Physics, School of Applied Sciences, Federal Polytechnic Nasarawa, Nigeria
Email: uyakubu2017@gmail.com; Phone number: +2348039635596

ABSTRACT
Metal oxides nanoparticles have been recognized as suitable materials for improving thermos-physical properties of working fluids in solar thermal application due to their excellent light absorption, thermal stability, and ease of preparation. This research presents the optical absorption of Aluminum oxide (Al_2O_3), Nickel oxide (NiO), and Antimony oxide (Sb_2O_3) nanoparticles each as a single nanofluids. The study was carried out using COMSOL Multiphysics software, where the optical absorption of the single nanofluid having equal mass fraction (100mg) were evaluated. Results revealed that the Al_2O_3 nanofluid exhibited low absorption of 11% due to its wide band gap (5.3eV) and optical transparency in the visible region. NiO and Sb_2O_3 oxide nanofluid due to their narrower band gaps (3.4eV to 1.5eV) also enhanced the absorption to 19% and 20% respectively. The study establishes that metal oxides nanoparticles can significantly improve the optical performance of the nanofluid which later influence optical-thermal conversion for photothermal application.

Keywords: COMSOL Multiphysics, Photothermal conversion, Metal oxide, Nanofluids, Optical absorption.

1.0 INTRODUCTION
Energy is one of the basic needs for the functioning of society and the amount of its usage is closely linked to the quality of life [1]. Over 70% of world's energy demand is supplied by fossil fuels (such as coal, oil and gas) which relates to fields of human endeavors like industry, transport, agriculture and residential [2]. The fossil fuels are non-renewable with supply sources likely to be depleted and eventually exhausted and no tendency to be replenished once they are used up [3]. The consumption of coal, oil and gas over several decades has been on the rise resulting in ever increasing carbon dioxide emissions [4]. Large emissions of carbon dioxide sources are believed to lead to significant pollution and is a serious global threat for a clean and sustainable environment [5]. Consequently, the use of renewable energy sources is encouraged in order to resolve this serious issue [6].

Renewable energy sources comprised of biomass, wind, solar, hydroelectricity, oceans thermal, geothermal, wave and tidal energy [7]. Solar energy can be harvested by the use of photovoltaic cells and solar thermal collectors [8]. Photovoltaic device works by directly converting the solar energy to electrical energy [9] while solar thermal collector converts incident solar irradiation to useful thermal energy for a wide variety of applications like space heating/cooling, process heating, steam generation and electric power generation [10]. The energy of solar light consists of about 44% visible, 3% UV and 53% infrared radiation or heat. The common working fluids such as water, glycols, and thermal oils are good absorbers in the ultraviolet (UV) and infrared (IR) regions, both making up 56% of the total solar energy. However, the working fluids are transparent in the visible region, meaning that approximately 44% of the solar energy is not efficiently captured and is instead lost as transmitted light [11].

Nanoparticles are materials with at least one dimension between 1 and 100 nanometers. This incredibly small size bestows unique physical, chemical, and optical properties, distinct from their bulk counterparts, primarily due to their high surface area-to-volume ratio and quantum effects. Nanoparticles can be mixed with conventional energy transfer fluids (water, oil, glycol) to form nanofluids for solar energy applications [12]. Nanofluids are functional fluids obtained by steadily dispersing nanosized particles in the conventional fluids yielding better thermo-physical properties than the conventional fluids. Investigations have shown that nanofluids have the potential to improve liquid properties over a wide range and significant gain for their enhanced heat transfer, optical absorption, and photo thermal energy conversion capabilities, which made them suitable as a working medium for solar thermal collectors [13] and [14]. Metal oxides have been widely used as solid phase for nanofluid formulation owing to their advantages such as relatively lower density, chemical stability and ease of preparation. However, there were limited work of their photo-thermal absorption.

Some studies on the optical absorption and solar thermal efficiency of oxide nanomaterials have been reported. For the single nanofluids, [15] investigated alumina-water (Al_2O_3-H_2O) nanofluid used in parabolic trough collectors, resulting in enhanced heat absorption and a 15% increase in thermal efficiency compared to the base fluid. [16] studied carbon nanotube-water (CNT-H_2O) nanofluid in evacuated tube collectors, observing enhanced heat transfer performance and an 8% improvement in thermal efficiency. In an experimental investigation of natural convection of iron III oxide-water (Fe_3O_4-H_2O) nanofluid in a cubic cavity reported an 18.6% thermal efficiency. Therefore, there is need to evaluate the optical absorption which can lead to photo-thermal conversion of nanofluid.

This work evaluate the optical absorption of Al_2O_3, NiO, and Sb_2O_3 nanofluids using COMSOL Multiphysics software. The study would help in improving the photo-thermal conversion efficiency of the nanofluid.

2.0 BACKGROUND THEORY

The optical to thermal energy conversion of nanofluids are dominated by how the nanoparticles interact with light, which is precisely described by Rayleigh scattering, and electromagnetic absorption theories [17].

2.1. Light scattering

Light scattering is a phenomenon where light interacts with particles in a medium, causing it to deviate from its original path. The way light scatters depend on the size of the scattering particles relative to the wavelength of the light [17].

2.1.1 Raleigh-scattering: Occurs when the scattering particles are much smaller than the wavelength of the incident light (typically particle diameter < λ/10).[2] This is common for gas molecules (like oxygen and nitrogen in the atmosphere) and very small colloids, [18].

$$C_{sa} = \frac{8\pi^3 a^6}{3\lambda^4}\left|\frac{m^2-1}{m^2+2}\right|^2 \qquad (1)$$

where: a is the particle radius, λ is the wavelength of light in the surrounding medium, $m = \frac{n_p}{n_m}$ is the relative refractive index (particle/medium) and C_{sa} is the scattering cross-section (m^2) per particle).

Compton-scattering: The scattering effects occurring during the light matter interaction were governed by the concept of Compton Scattering, also known as the Compton effect, which is a phenomenon that occurs when a high-energy photon (such as an X-ray or gamma ray photon) collides with a charged particle, typically an electron. The Compton's equation is given by [17].

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - cos\theta) \quad (2)$$

where: λ′, is the wavelength of the scattered photon, λ is the wavelength of the incident photon, h is Planck's constant (6.626×10−34J s), m_e is the rest mass of the electron (9.11×10−31kg), c is the speed of light in a vacuum (3.00×108m/s), θ is the scattering angle of the photon, which is the angle between the incident photon's direction and the scattered photon's direction. Angstrom, [17].

2.1.2 Light Absorption in Nanofluids

When an electromagnetic wave propagates through a nanofluid, part of the incident energy is absorbed, scattered, or transmitted depending on the optical constants of the medium. The attenuation of light intensity within the medium is governed by the Beer–Lambert law [17] as

$$I = I_o e^{-\alpha L} \quad (3)$$

where: I_o is the incident intensity, I is the transmitted intensity, L is the optical path length, α is the absorption coefficient.

The absorption coefficient α is relates to the imaginary part of the refractive index k given as [17].

$$\alpha = \frac{4\pi n}{\lambda} \quad (4)$$

where: λ is the wavelength of the incident light, and k corresponds to the extinction coefficient of the medium.

From equation (1) the transmittance (T) of the nanofluid can be expressed as [17].

$$T = \frac{I}{I_o} = e^{-\alpha L} \quad (5)$$

While the absorbance (A) is given by [19].

$$A = -Log_{10}(T) \quad (6)$$

2.2 Optical-to-Thermal Energy Conversion

The absorbed optical energy per unit volume, Q_{abs}, can be expressed as [19].

$$Q_{abs} = \alpha I_{o(1-e^{-\alpha L})} \quad (7)$$

The heat conduction equation accounting for optical heating is given by [18]

$$\rho c_p \frac{\partial T}{\partial t} = k_{eff} \nabla^2 T + Q_{abs} \quad (8)$$

where: ρ is the density, c_p is the specific heat capacity, k_{eff} is the effective thermal conductivity, T is the local temperature, and Q_{abs} is the volumetric heat generation due to absorbed light.

3.0 MATERIALS AND METHOD

This section presents the materials and method adopted for the research work.

MATERIALS

The materials used include COMSOL Multi-physics software version 5.6, virtual Al_2O_3, NiO and Sb_2O_3, cuvette and deionized water as nanofluid.

METHOD

The simulation was performed using COMSOL Multiphysics (version 5.6) to analyze the optical absorption behavior of Al_2O_3, NiO, and Sb_2O_3 nanofluids in their individual compositions. A two-dimensional rectangular geometry (10 mm × 20 mm) was created to represent the nanofluid domain, with Perfectly Matched Layers (PMLs) applied to eliminate boundary reflections. Material properties, including density, thermal conductivity, heat capacity, and relative permittivity, were defined for each component and combined using the Maxwell–theory to obtain the composite optical constants for the nanofluids. The Electromagnetic Waves, Frequency Domain and Heat Transfer in Fluids physics interfaces were coupled through an electromagnetic heat source node to capture both optical and photothermal interactions.

A plane electromagnetic wave was incident normally on the nanofluid domain across a wavelength range of 400–1400 nm, and the resulting field distributions were computed in the frequency domain. An optimal constant mass fraction obtained from the experimental result of the single nanofluids was used to simulate the single nanofluids. The absorbed power density and electric field intensity were extracted to calculate the absorption coefficient and absorbance using equations 3 and 4. Finally, the data were post-processed to generate absorption spectra for all nanofluid configurations, enabling comparative evaluation of their wavelength-dependent absorption performance.

4.0 RESULTS AND DISCUSSIONS

This section presents the absorption performance of aluminium oxide, nickel oxide and antinomy oxide as single metal oxide nanoparticles in deionized water to make efficient nanofluid for solar energy absorption.

4.1. Single Nanofluids

Nanofluids are new type of functional fluids obtained by steadily dispersing nano-sized particles in the conventional working fluids, such as water and oils yielding better thermo-physical properties than the conventional fluids without impurities.

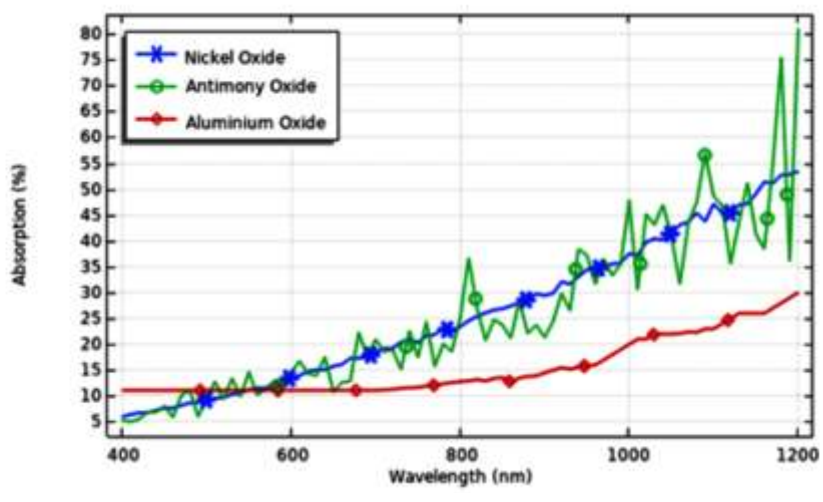

Figure 1: Absorption of single metal oxides nanofluid.

Figure 1 presents the **a**bsorption of single metal oxides nanofluid. Looking at figure 1**,** the absorption spectrum of Al_2O_3 nanofluid shows a low absorption of about 11% across the visible region (400–700 nm). The gradual increase in absorption of the Al_2O_3 nanofluid beyond 700 nm toward the near-infrared region can be attributed to the large bandgap (

5.3eV) and colloidal nature of nanofluids causes Mie scattering, especially in the infrared region where particle size and wavelength become comparable enhancing the apparent absorption

For NiO nanofluid the optical absorption spectrum within the same wavelength range of 400–1200 nm exhibits a steady absorption of approximately 19% across the visible region (400–700 nm), followed by a progressive increase toward the near-infrared region up to 1200 nm. This behavior indicates enhanced absorption due to NiO narrow bandgap energy (3.4eV). The optical behaviour of NiO nanofluid demonstrates its dual optical nature, which is moderately scattering in the visible and strongly absorbing in the near-infrared. This behaviour makes NiO-based nanofluids attractive for photothermal and solar energy harvesting applications**,** where both absorption and subsequent heat generation are desired across the solar spectrum.

In the case of Sb_2O_3 nanofluid, it exhibits a constant absorption of nearly 20% across the visible band (400–700 nm) with a progressive increase in absorption toward the near-infrared up to 1200 nm. This behaviour results from the combined action of broadband scattering from nanoparticles and substantive intrinsic absorption associated with Sb_2O_3 nanoparticles. Antimony oxide nanoparticles possess defect- and surface-related electronic states and charge-transfer transitions that extend absorption into the visible and NIR. Additionally, free-carrier absorption mechanisms can cause the absorption to rise at longer wavelengths.

In contrast, NiO and Sb_2O_3 nanofluids exhibit higher absorption across the same region due to their narrower bandgaps (3.4eV and 2.3eV, respectively) and greater density of electronic defect states, which facilitate photon–electron interactions. All three nanofluids exhibit increasing absorption with wavelength, indicating a positive correlation between photon wavelength and light absorption. This trend suggests that as the photon energy decreases toward the near-infrared (NIR) region, enhanced photon–particle interactions and electronic transitions occur within the nanofluids.

The overall spectral response indicates that while Al_2O_3 contributes minimally to visible absorption, it enhances the thermal stability of the nanofluid system, whereas NiO and Sb_2O_3 dominate light absorption, thereby improving the absorption and thermal efficiency across the solar spectrum.

Table 1. Comparison of optical absorption of metal oxide single nanofluids

Author	Nanofluid	Optical Absorption
[15] Farooq *et al*. (2022)	Al_2O_3/water	15%
[16] Elshazly and El-mahallawi (2023)	CNT/water	8%
Kamran and Qayoum, (2024)	Fe_3O_4/water	18.6%
This work	Al_2O_3/DI water	11%
	NiO/DI water	19%
	Sb_2O_3/DI water	20%

The work of [15] in Table 1 found 15% optical absorption of Al_2O_3/water which is higher than that of Al_2O_3/DI water having 11%. This occurred due to the presences of impurities in tap water unlike in the deionize water. However, the NiO/DI water and Sb_2O_3/DI water demonstrated higher optical absorption of 19% and 20% respectively compere to the work of Kamran and Qayoum (2024) and [16] .

5.0 CONCLUSION

This research found that, the optical absorption of aluminum oxide (Al_2O_3), nickel oxide (NiO), and antimony oxide (Sb_2O_3) nanofluids enhanced the optical absorption of the working fluid (deionize water) from 0% to 11%, 19% and 20% respectively. The study was carried out in COMSOL Multiphysics software, where the metal oxides of equal mass fraction were each used as a single nanoparticle within deionized water. Results revealed that the single nanofluid, Al_2O_3 exhibited low absorption due to their wide band gap of 5.3eV and optical transparency in the visible region, while NiO and Sb_2O_3 due to their narrower band gaps of 3.4eV and 1.5eV respectively with moderate absorption behavior in the near-infrared were also enhanced absorption of the working fluid higher than the Aluminium oxide. The study establishes that metal oxide nanoparticles can significantly influence the optical–thermal conversion performance of nanofluid, offering promising prospects for solar and photothermal energy applications.

Acknowledgement

I wish to appreciate the Department of Physics, Universiti Putra Malaysia (UPM) for procuring all the reagents used for this research via TETFUND grant and most of the equipment used for synthesis and characterization of the metal oxide samples for XRD, FESEM, UV-Vis, Zeta Potential and Particle size in collaboration with Institute of Nanoscience and Nanotechnology (ION2), Institute of Biosciences (IBS) at UPM and other Research Organizations. I also acknowledge the Federal Government of Nigeria through Tertiary Education Trust Fund (TETFUND) for the sponsorship to go for this Research attachment.

REFERENCES

[1] Vogel, J., Steinberger, J. K., O'Neill, D. W., Lamb, W. F., & Krishnakumar, J. (2021). Socio-economic conditions for satisfying human needs at low energy use: An international analysis of social provisioning. *Global Environmental Change*, *69*, 102287. https://doi.org/10.1016/j.gloenvcha.2021.102287

[2] Billewar, S. R., Londhe, G., & Mane, P. S. (2023). World energy demand. *Integrated Green Energy Solutions Volume 2*, 275-316. https://doi.org/10.1002/9781394193738.ch36

[3] Agrawal, S., & Soni, R. (2021). Renewable energy: Sources, importance and prospects for sustainable future. *Energy: Crises, Challenges and Solutions*, 131-150. https://doi.org/10.1002/9781119741503.ch7

[4] Gür, T. M. (2022). Carbon dioxide emissions, capture, storage and utilization: Review of materials, processes and technologies. *Progress in Energy and Combustion Science*, *89*, 100965. https://doi.org/10.1016/j.pecs.2021.100965

[5] Kabir, M., Habiba, U. E., Khan, W., Shah, A., Rahim, S., Patricio, R., ... & Shafiq, M. (2023). Climate change due to increasing concentration of carbon dioxide and its impacts on environment in 21st century; a mini review. *Journal of King Saud University-Science*, *35*(5), 102693. https://doi.org/10.1016/j.jksus.2023.102693

[6] Al-Shetwi, A. Q. (2022). Sustainable development of renewable energy integrated power sector: Trends, environmental impacts, and recent challenges. *Science of The Total Environment*, *822*, 153645. https://doi.org/10.1016/j.scitotenv.2022.153645

[7] Rahman, A., Farrok, O., & Haque, M. M. (2022). Environmental impact of renewable energy source based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic. *Renewable and Sustainable Energy Reviews*, *161*, 112279. https://doi.org/10.1016/j.rser.2022.112279

[8] Ahmad, L., Khordehgah, N., Malinauskaite, J., & Jouhara, H. (2020). Recent advances and applications of solar photovoltaics and thermal technologies. *Energy*, *207*, 118254. https://doi.org/10.1016/j.energy.2020.118254

[9] Rathore, N., Panwar, N. L., Yettou, F., & Gama, A. (2021). A comprehensive review of different types of solar photovoltaic cells and their applications. *International Journal of Ambient Energy*, *42*(10), 1200-1217. https://doi.org/10.1080/01430750.2019.1592774

[10] Kumar, L., Hasanuzzaman, M., & Rahim, N. A. (2019). Global advancement of solar thermal energy technologies for industrial process heat and its future prospects: A review. *Energy conversion and management*, *195*, 885-908. https://doi.org/10.1016/j.enconman.2019.05.081

[11] Rubbi, F., Das, L., Habib, K., Aslfattahi, N., Saidur, R., & Rahman, M. T. (2021). State-of-the-art review on water-based nanofluids for low temperature solar thermal collector application. *Solar Energy Materials and Solar Cells*, *230*, 111220. https://doi.org/10.1016/j.solmat.2021.111220

[12] Khan, I., Saeed, K., & Khan, I. (2019). Nanoparticles: Properties, applications and toxicities. *Arabian journal of chemistry*, *12*(7), 908-931. http://dx.doi.org/10.1016/j.arabjc.2017.05.011

[13] Rubbi, H. M. F., Sahin, A. Z., Yilbas, B. S., & Al-Sharafi, A. (2021). Methods for the determination of nanofluid optical properties: a review. International Journal of Thermophysics, 42(1), 9. https://link.springer.com/article/10.1007/s10765-020-02762-0

[14] Younes, H., Mao, M., Murshed, S. S., Lou, D., Hong, H., & Peterson, G. P. (2022). Nanofluids: Key parameters to enhance thermal conductivity and its applications. *Applied Thermal Engineering*, *207*, 118202. https://doi.org/10.1016/j.applthermaleng.2022.118202

[15] Farooq, M., Farhan, M., Ahmad, G., Usman, M., Sultan, M., Hanif, M. S., ... & Shakir, M. A. (2022). Thermal performance enhancement of nanofluids based parabolic trough solar collector (NPTSC) for sustainable environment. Alexandria Engineering Journal, 61(11), 8943-8953. https://doi.org/10.1016/j.aej.2022.02.029

[16] Elshazly, E., & El-Mahallawi, I. (2023). Thermal performance enhancement of evacuated tube solar collector using MWCNT, Al2O3, and hybrid MWCNT/Al2O3nanofluids. International Journal of Thermofluids, 17, 100260. https://doi.org/10.1016/j.ijft.2022.100260

[17] Khalid, K., Ishak, R., & Chowdhury, Z. Z. (2024). UV–Vis spectroscopy in non-destructive testing. In *Non-destructive material characterization methods* (pp. 391-416). Elsevier. https://doi.org/10.1016/B978-0-323-91150-4.00021-5

[18] Bohren, C. F., & Huffman, D. R. (2008). *Absorption and scattering of light by small particles*.
John Wiley & Sons. Edition: Reprint, revised Pg **3-7.** ISBN:3527618163, 9783527618163

[19] Mayerhöfer, T. G., Pahlow, S., & Popp, J. (2020). The Bouguer-Beer-Lambert law: Shining light on the obscure. *ChemPhysChem*, *21*(18), 2029-2046. https://doi.org/10.1002/cphc.202000464