Article

Enhancement of Polyacrylic Acid/Silicon Carbide Nanocomposites' Optical Properties for Potential Application in Renewable Energy

Farhan Lafta Rashid [1], Ahmed Hashim [2], Anmar Dulaimi [3,4,*], Aseel Hadi [5], Hamed Ibrahim [6], Mudhar A. Al-Obaidi [7,8] and Arman Ameen [9,*]

[1] Petroleum Engineering Department, College of Engineering, University of Kerbala, Karbala 56001, Iraq; farhan.lefta@uokerbala.edu.iq

[2] Department of Physics, College of Education for Pure Sciences, University of Babylon, Babylon 51002, Iraq; ahmed_taay@yahoo.com

[3] College of Engineering, University of Warith Al-Anbiyaa, Karbala 56001, Iraq

[4] School of Civil Engineering and Built Environment, Liverpool John Moores University, Liverpool L3 2ET, UK

[5] Department of Ceramic and Building Materials, College of Materials Engineering, University of Babylon, Babylon 51002, Iraq; mat.aseel.hadi@uobabylon.edu.iq

[6] Department of Scientific Affairs, Al-Zahraa University for Women, Karbala 56001, Iraq; hamed16564@yahoo.com

[7] Technical Institute of Baquba, Middle Technical University, Baquba 32001, Iraq; dr.mudhar.alaubedy@mtu.edu.iq

[8] Technical Instructor Training Institute, Middle Technical University, Baghdad 10074, Iraq

[9] Department of Building Engineering, Energy Systems and Sustainability Science, University of Gävle, 801 76 Gävle, Sweden

* Correspondence: a.f.dulaimi@ljmu.ac.uk (A.D.); arman.ameen@hig.se (A.A.)

Abstract: Composites made from polymers and nanoparticles have promise to be effective solar collectors and thermal energy storage devices due to benefits including improved thermal characteristics and increased structural stability. This study intends to fabricate polyacrylic acid/silicon carbide (PAA−SiC) nanocomposites and examine the optical properties for use in solar collectors and thermal energy storage (TES) fields. The optical properties of PAA−SiC nanocomposites are investigated within the wavelength between 340 and 840 nm. The findings indicate that an increase in SiC concentration in the PAA aqueous solution to 50 g/L at a wavelength of λ = 400 nm causes an increase in the absorption by 50.2% besides a reduction in transmission by 6%. Furthermore, the energy band gaps were reduced from 3.25 eV to 2.95 eV to allow for the transition, and subsequently reduced from 3.15 eV to 2.9 eV to allow for forbidden transition as a result of the increasing SiC concentration from 12.5 g/L to 50 g/L. The optical factors of energy absorption and optical conductivity were also enhanced with a rising SiC concentration from 12.5 to 50 g/L. Specifically, an improvement of 61% in the melting time of PAA−SiC−H_2O nanofluids is concluded. Accordingly, it can be said that the PAA−SiC−H_2O nanofluids are suitable for renewable energy and TES systems.

Keywords: polyacrylic acid/silicon carbide (PAA−SiC); nanofluids; thermal energy storage (TES); absorption; nanostructures

1. Introduction

The interaction of the world's conventional energy sources, which are largely derived from fossil fuels, and the growth of renewable energy sources is strongly connected to the awareness of energy depletion [1]. The primary source of historical global energy use has been fossil fuels, which include coal, oil, and natural gas. However, a concerted effort to transition towards renewable alternatives has been motivated by the finite nature of these resources, as well as environmental concerns and geopolitical consequences. Securing sustainable energy sources is increasingly important as fossil fuel supplies are depleted and

their exploitation becomes more difficult, expensive, and harmful to the environment. The development of renewable energy sources like solar, wind, hydro, and geothermal energy, which provide cheap, clean, and limitless alternatives, is driving this energy transformation [2–4]. The development of renewable energy sources is an important step in reducing climate change and creating a more resilient and just global energy system, in addition to being a response to energy depletion [5]. Specifically, this trend may be helped by reducing thermal waste.

The use of phase change materials (PCMs), which store latent heat, to mitigate thermal waste has been shown to be effective. PCMs are suitable for thermal energy storage (TES) because they can absorb, collect, or release latent heat in a limited temperature range during the phase transition process. Possible leaking of molten PCM during the phase transition process lowers TES in the following operations. PCM is heavily enclosed in an additional container to reduce the likelihood of leaking. This procedure is referred to as PCM form or nature stabilization. The form-stabilized PCM's composite characteristics are influenced by the PCM's container [6]. PCMs are divided into three groups: eutectic PCMs, inorganic PCMs, and organic PCMs. Organic PCMs are exceptional in storing thermal energy and have a broad melting variety not including any super cooling problems. Nevertheless, they have certain drawbacks, including poor light absorption and limited heat conductivity [7]. They are also combustible. These disadvantages prevent PCMs from being widely used in solar-thermal application systems. To compete with these demerits, composite PCMs made by incorporating nanoparticles into a supporting matrix were innovated to enhance the mechanical properties, such as thermal stability, capacity to absorb light, and high specific surface area [8–10]. Examples of these nanoparticles are organic dyes, graphite foam, biomass carbon, graphene aerogels, nanotube sponge, and carbon. Furthermore, nanoparticles can lower the phase change rate and increase the surface area-to-volume ratio. An encouraging method for improving the thermal efficiency and thermal conductivity of the solution is to disperse elevated-thermal-conductive nanoparticles into PCMs. Therefore, nano-enhanced organic PCMs are regarded to be the most effective materials for energy storage in comparison to the shortcomings of organic PCMs. The nanoparticles and their compatibility with one another regulate the thermal conductivity of organic PCMs that have undergone nanotechnology [11].

In recent decades, polymers have emerged as crucial research materials across a range of disciplines. This is a consequence of its desirable qualities, which include flexibility, environmental friendliness, ease of processing at low temperatures, and cheap price. The process of the energy conversion of polymers also has essential technical applications in biosensors, solar cells, and photovoltaics [12]. The development of polymeric composite materials, on the other hand, derived from two or additional polymer material variations, indicates a range of amazing chemical and physical features. Long-term durability is thus essential for the ongoing usage of composite substances. Moreover, polymeric composites are required to have important qualities including corrosion resistance, sturdiness, and quicker assembly [13].

As silicon carbide (SiC) is a material with the potential for improving corrosion resistance, it is employed as a heat exchanger module. SiC also has good qualities such as high specific heat conductivity and low density. SiC has good temperature stability and corrosion resistance [14]. In the same aspect, polyacrylic acid (PAA), a completely biodegradable compound, is of special importance due to the high activity of the carboxylic acid. Precisely, this permits to have strong adhesive strength that licenses its utilisation in drug delivery devices [15]. In this aspect, PAA is a safe polymer for the environment with exceptional mechanical strength and clarity. As a result, PAA is utilised in different fields such as pharmaceuticals, packaging, adhesives, coatings, and biological and medical sectors. Several different kinds of artificial tears deploy PAA, either in cross-linked or linear form, due to its excellent qualities and high levels of water absorption [16].

Composites made from polymers and nanoparticles have the prospective to be operative solar collectors and thermal energy storage devices because of their advantages

including improved thermal features and improved structural stability [17]. Innovative solar collectors and thermal energy storage systems made of composites made of polymers and nanoparticles show excessive potential. The benefits of both polymers and nanoparticles are integrated in this developing area of materials science to generate multifunctional materials with a diversity of merits. Combining metal oxides or silicon carbide nanoparticles into polymer matrices generates composites with improved thermal features, such as increased thermal conductivity and specific heat capacity [18]. These enhancements are essential for prosperous thermal energy storage as well as successful heat absorption and transfer in solar collectors. These composite materials are an excessive option for operational solar energy absorption because their optical features may be adjusted to expand light absorption and lessen reflection. Furthermore, the addition of nanoparticles frequently gives the composite materials enhanced structural stability and resilience, assuring their long-term performance in demanding renewable energy applications [19]. Generally, the interaction between polymers and nanoparticles releases an exciting prospect for the creation of thermal energy storage devices and the next generation of solar collectors with augmented effectiveness and dependability. In a summary, the efficacy of renewable energy technology can be upgraded by using these composite materials, which can help with superior energy capture and storage.

To the best of the authors' knowledge, the notion of SiC-doped polymers and PAA with the implication on renewable energy has not been detailed in the open literature. Specifically, Ahmed and Hashim [20] prepared new types of nanocomposites of Polyvinyl alcohol/nano-fillers and SiC and investigated the optical properties. The outcomes proved that as the concentration of SiC nanoparticles increases, the optical absorbance of Polyvinyl alcohol/SiC rises. Moreover, as the concentration of SiC nanoparticles increases, the energy gap decreases, and the optical constants increase. Obaid and Hashim [21] presented the optical features of SiC/tantalum carbide (TaC) nanostructure-doped polycarbonate (PC). They demonstrated that a growth in the SiC/TaC NP content to 4.8 wt.% has introduced an approximate increase of 25% in PC's absorption spectrum. The PC/SiC/TaC nanostructures' energy gap was observed to decline from 3.69 eV for PC to 3.2 eV when attaining the ratio of 4.8 wt.% of SiC/TaC NPs. Hashim et al. [22] appraised the optical and electrical features of SiC and yttrium oxide (Y_2O_3) nanostructure-doped poly-methyl methacrylate (PMMA). The results assured that the absorbance of PMMA enlarged to 76.3% at photon wavelength (λ = 440 nm) when the SiC/Y_2O_3 NP content reached 4.8 wt.%. Following an addition of more SiC/Y_2O_3 NPs, the energy gap value of PMMA reduced from 4.3 eV to 3 eV. Furthermore, Hashim et al. [23] synthesised the nanocomposite of polystyrene (PS)-cerium oxide (CeO_2) and SiC to assess its influence on the electronic features. Consequently, the absorbance (A) was increased by approximately 46.1% at UV spectra (λ = 300 nm) and 59.1% at visible spectra (λ = 500 nm). When the ratio of CeO_2/SiC nanostructures was (4.8 wt.%), the energy gap of PS fell from 4 eV to 2.8 eV. Therefore, the purpose of this study is to synthesise the nanocomposites of PAA−SiC at various concentrations of SiC, with a possible heat transfer practice for thermal energy storage-based renewable energy applications.

2. Experimental Setup

2.1. Preparation of PAA−SiC Nanocomposites

A number of steps are necessary to create a PAA−SiC nanocomposite (solid materials known as nanocomposites are made of a polymer, ceramic, or metal matrix that has been strengthened with nanoparticles) using the casting method. The casting method was chosen because of its straightforward methodology, ease of manufacture, affordability, and superior film synthesis. The molecular weight of PAA is 100,000 g/mol. A polymer aqueous solution was produced by dissolving PAA in distilled water at 25 °C. This solution served as the polymer matrix for the nanocomposite. The SiC (beta, 99+%, <80 nm, cubic, was purchased from US Research nanomaterials) nanoparticles were initially dispersed in the PAA solvent utilising the ultrasonication method. This step intends to attain a uniform dispersion of

nanoparticles in the liquid medium. In this regard, the SiC nanoparticles were added to the polymer solution and continuously stirred under carefully regulated conditions by using a magnetic stirrer to obtain a homogeneous solution. The mixing step is therefore important to ensure that the nanoparticles are evenly distributed within the polymer matrix. Figure 1 shows the FTIR analysis of PAA−SiC nanocomposites. The FTIR studies show that there are no new peaks, which means that there is no chemical reaction between the PAA–polymer matrix and SiC nanoparticles. Specifically, three different concentrations of SiC in the PAA aqueous solution were prepared (denoted by the letters C1, C2, and C3, equating to 12.5 g/L, 25 g/L, and 50 g/L, respectively) by increasing the PAA volume.
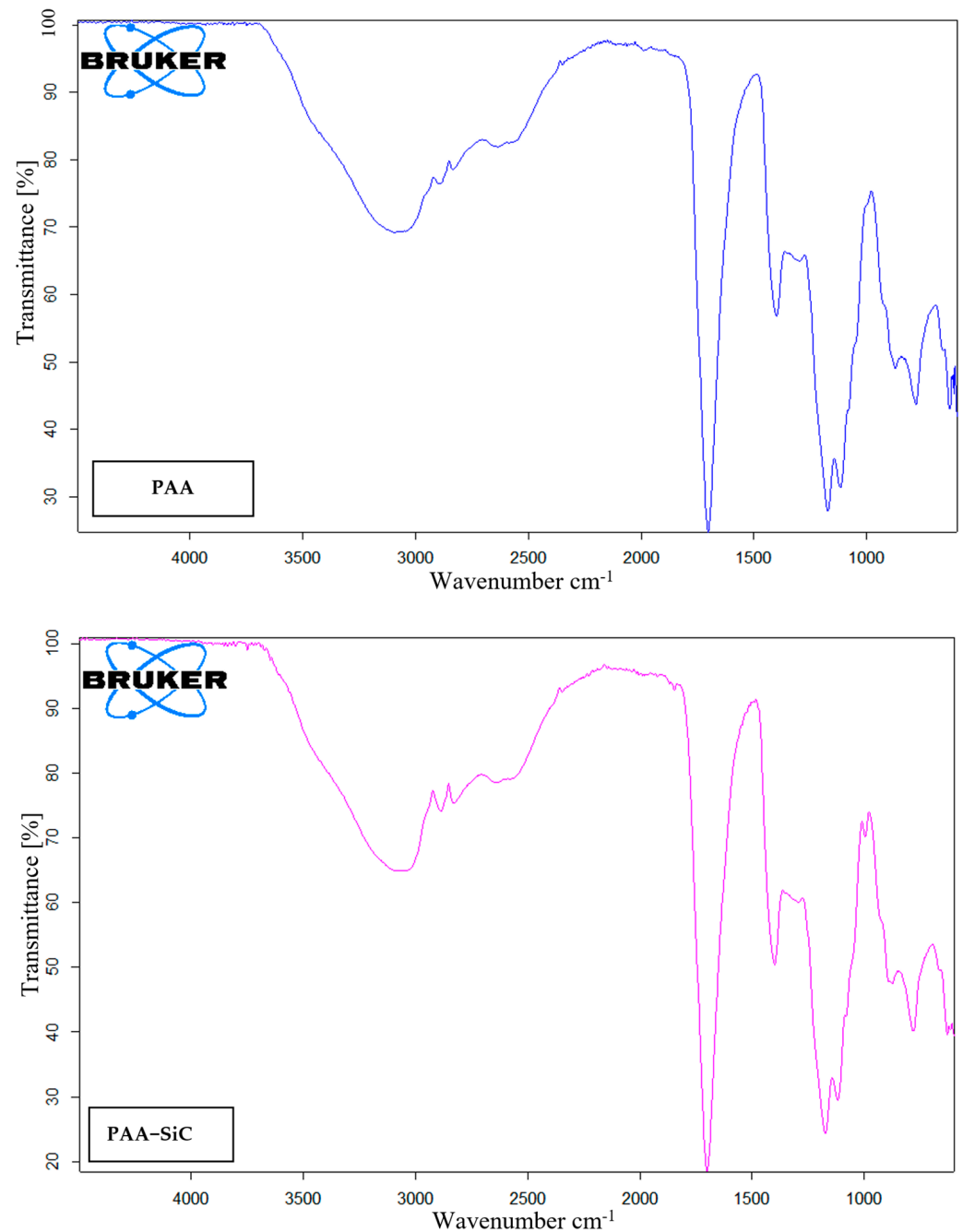

Figure 1. FTIR analysis of PAA−SiC nanocomposites.

2.2. Measurement of Optical Features and Energy Absorption

Maximising the capture of sunlight is essential and critical in solar energy systems for high energy conversion efficiency. To effectively use synthesized polyacrylic acid/silicon carbide nanocomposites in renewable energy systems, it is essential to measure the optical properties and energy absorption of these materials. Undoubtedly, studying the optical properties of the synthesised nanocomposite is important to optimise the ratio of mixed compounds. Also, designing nanocomposites that improve light harvesting by ensuring that a greater proportion of incident light is absorbed and transformed into energy is made possible by measuring optical characteristics.

The measurements of the optical characteristics were analysed by casting the PAA$-$SiC on glass slides and analysing the data using a spectrophotometer (UV-1800A-Shimadzu). The wavelength ranges between 340 and 840 nm. In the context of using TES, the melting characteristics of PAA$-$SiC$-$H$_2$O nanofluids (nanofluid refers to a liquid suspension of nanoparticles, often oxide or metallic nanoparticles, spread inside a base fluid, such as water) were investigated by subjecting them to a heating procedure. The nanofluids were employed at variable temperatures ranging between 30 °C and 100 °C using a stirrer. The temperature of the nanofluids was measured using a digital instrument while they were being heated.

The coefficient of energy absorption (α) is found by using Equation (1) [24]:

$$\alpha = 2.303 \, (A/d) \tag{1}$$

The energy separation may be determined using the formula [25]:

$$\alpha h\upsilon^{1/r} = C\big(h\upsilon - E_g\big) \tag{2}$$

The formula for the refractive index (n) is as follows [26]:

$$n = \frac{1 + \sqrt{R}}{1 - \sqrt{R}} \tag{3}$$

Assuming reflectance to be R. The formula for the extinction coefficient (k) is [27]:

$$k = \frac{\alpha\lambda + \sqrt{R}}{4\pi} \tag{4}$$

λ is the wavelength of the incident photon. Both the real (ε_1) and imaginary (ε_2) components of the dielectric constant are provided by [28]:

$$\varepsilon_1 = n^2 - k^2 \tag{5}$$

$$\varepsilon_2 = 2nk \tag{6}$$

The optical conductivity (σ_{op}) [29] can be estimated using the following equation:

$$\sigma_{op} = \frac{\alpha nc}{4\pi} \tag{7}$$

3. Results and Discussion

Figure 2 displays the absorption spectra for PAA$-$SiC nanocomposites against wavelength. For the low range of wavelength, Figure 2 shows a clear reduction in absorbance as a result of increasing wavelength. Basically, a common phenomenon is that absorbance initially decreases as the wavelength increases, which usually means that the substance is transparent or has low absorption in that part of the spectrum. This implies that the nanocomposite may permit light to flow through with little absorption in the shorter wavelength region. This phenomenon might be brought on by the composite's molecular interactions or electrical structure, which produces low absorption in this spectral band.

However, the absorbance has started to insignificantly rise after 600 nm of wavelength for the whole tested concentrations of C1, C2, and C3. This indicates that the nanocomposite begins to absorb more light in this region. This increase might be explained by particular electronic transitions or energy levels present in the substance that are more evident at longer wavelengths. In other words, the characteristics of silicon carbide nanoparticles, which can display distinctive optical phenomena, are used to improve the absorption. Also, the induction of electrons to higher energy states or other chemical interactions in the longer wavelength range can be attributed to this improved light absorption.
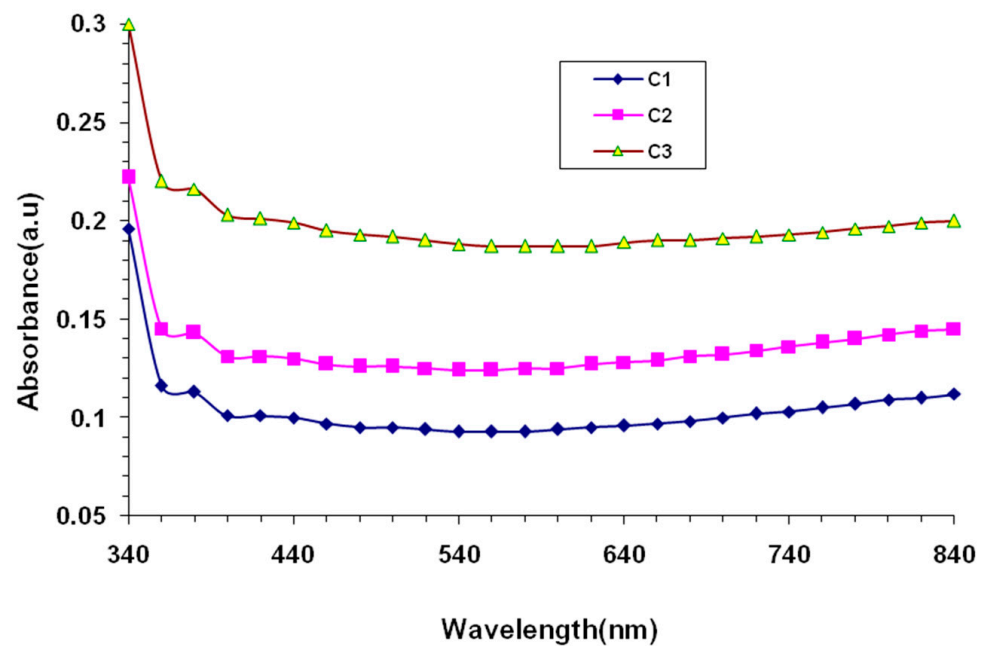
Figure 2. Performance of absorbance for PAA−SiC nanocomposites against wavelength.

Another important behaviour of Figure 2 is that the optical absorbance increases as the concentration of SiC rises due to the absorption and scattering of light photons brought on by an increase in the number of charge carriers [30]. This in turn causes a decrease in the transmission, as presented in Figure 3. The density of silicon carbide nanoparticles in the PAA−SiC composite would increase at greater silicon carbide concentrations. Given that there are more nanoparticles to absorb incident light at larger concentrations, silicon carbide is known to have strong absorption qualities in specific wavelength bands. Also, there can be more scattering centres or a larger density of nanoparticles in composites with high concentrations. These scattering centres have the ability to scatter light in different directions, resulting in a decrease in the amount of light that passes through the material and a corresponding decrease in transmittance. Concentration can affect how the silicon carbide nanoparticles interact with the polymer matrix (polyacrylic acid). These interactions, which may impact both transmittance and absorbance at larger concentrations, may alter how light moves through the material. Statistically, the maximum increase in the absorption of 50.2% is conducted when the concentration is 50 g/L at the wavelength ($\lambda = 400$ nm). Simultaneously, the transmission is decreased by 6% as a response to utilising 50 g/L. The absorbance of PAA−SiC nanocomposites has elevated values at the UV spectrum, then reduces at VIS and NIR spectra. These results of absorbance and transmittance are welcomed in a variety of optical and renewable approaches.
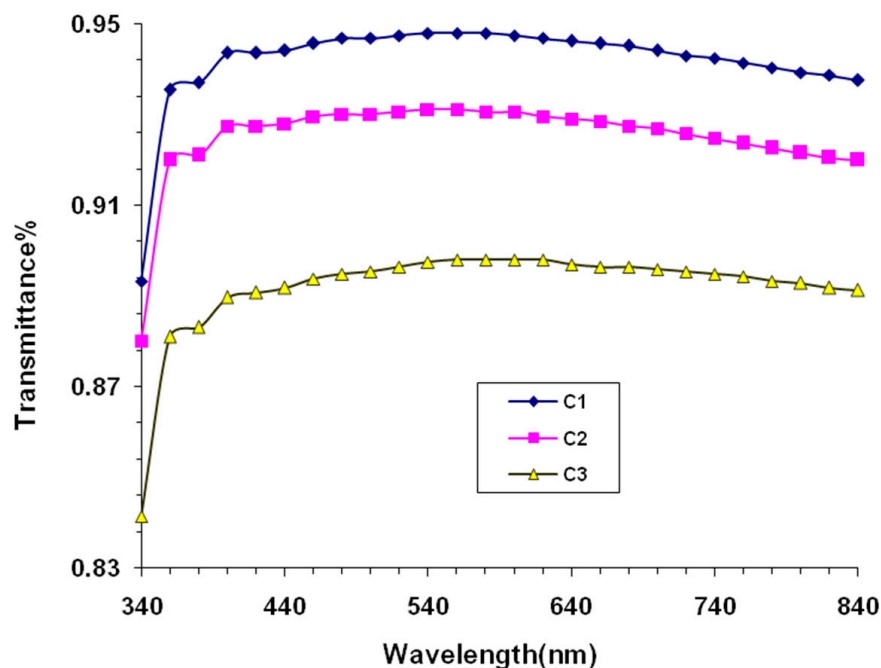
Figure 3. PAA−SiC nanocomposite wavelength-dependent transmittance.

The energy gaps of permitted and prohibited indirect transitions for various PAA−SiC nanomaterial concentrations are shown in Figures 4 and 5, respectively. According to these figures, the value of the energy gap (E_g) is reduced as concentration increases; this behaviour is ascribed to the localized level that is created in the nanocomposite structure, which causes the energy gap to be decreased [31]. Statistically, Figures 4 and 5 show that the energy band gaps have been reduced from 3.25 eV to 2.95 eV for permitted transition and from 3.15 eV to 2.9 eV for banned transition, respectively. It is important to note that the specific reduction in energy band gaps will depend on various factors, including the size and concentration of SiC nanoparticles, their surface properties, and the polymer matrix's electronic structure. To make it clearer, the energy levels of SiC nanoparticles are unique to their electrical structure. These energy levels might interact with the energy levels of the polymer when integrated into the matrix of the polymer. Some energy bands may overlap, lessening the gaps between the energy bands, depending on how these energy levels coordinate. The dielectric constant of the nanocomposite can change when SiC nanoparticles are included. The interaction between electrons and holes in the material is specifically affected by variations in the dielectric constant, and this can lead to variations in the energy band gaps. SiC nanoparticles can improve electron-hole excitations by supplying extra energy levels and potential charge carrier routes. This may result in a decrease in the amount of energy needed for electron transitions.

Interestingly, due to the reduction in energy band gaps, PAA−SiC nanocomposites are well-suited for use in a number of renewable industries.

Figures 6 and 7 show how the extinction coefficient and refractive index of PAA−SiC nanocomposites change as a function of wavelength, respectively. The refractive index (n) values of PAA−SiC nanocomposites increase with increasing concentration; this can be attributed to the shape of the clusters and agglomeration of nanoparticles throughout the polymer medium [32]. Furthermore, the extinction coefficient (k) values of PAA−SiC nanocomposites increase with rising concentration. In the nanocomposite, stronger optical interactions may result from the presence of silicon carbide nanoparticles. Light scatters and interacts with the surfaces of the nanoparticles as they come into contact with the composite. The amount of light that is absorbed by the substance is measured by its extinction coefficient (k), which rises as a result of this scattering and interaction. The likelihood of scattering and absorption events rise with increasing nanoparticle concentration, which

raises the extinction coefficient [33,34]. In other words, the increase in k values of PAA−SiC nanocomposites is an indication of an elevated light dissipation ascribed to absorption scattering and using a SiC nanostructure.
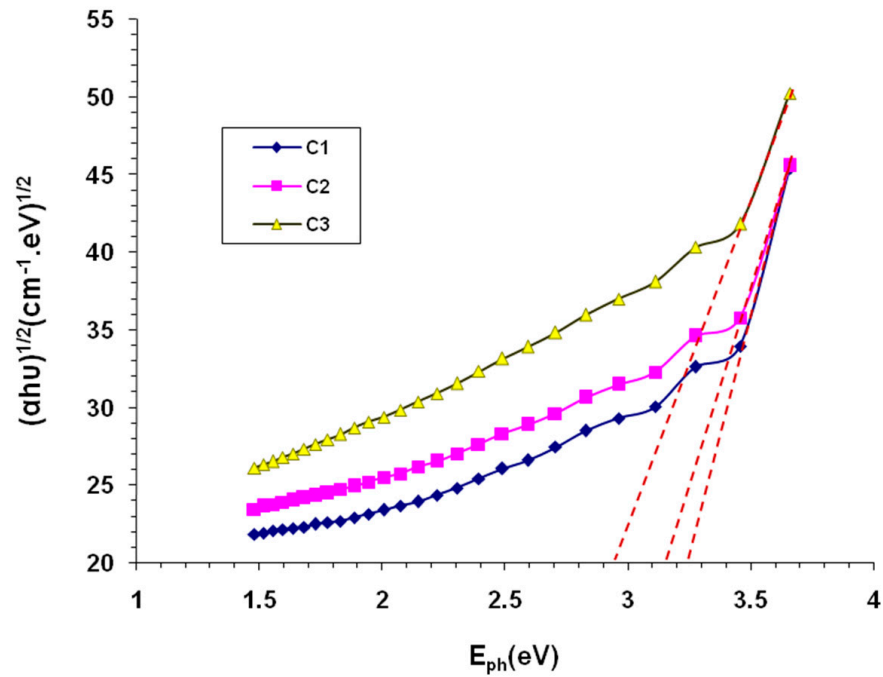

Figure 4. Energy gaps for PAA−SiC nanocomposites allowed indirect transition (the dotted lines and the points of contact of these lines with the x axis represent the energy gap).
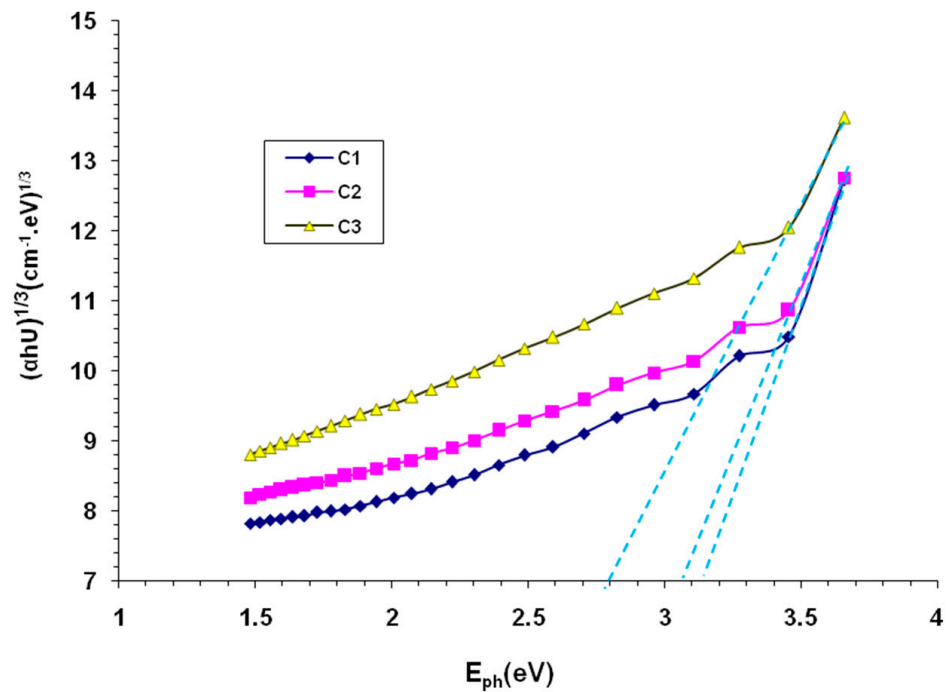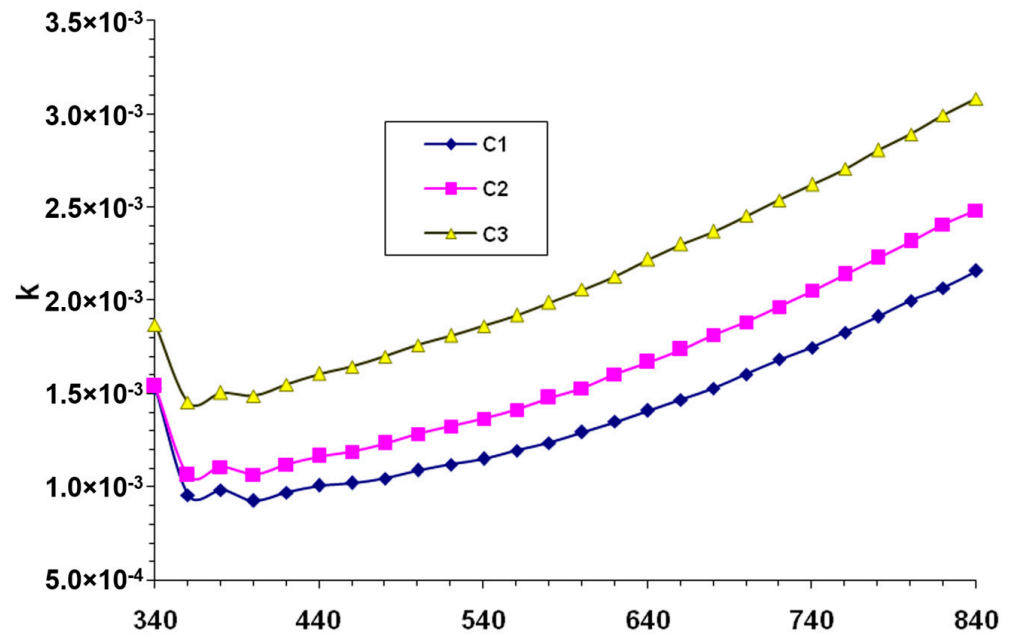

Figure 5. PAA−SiC nanomaterial energy gaps of prohibited indirect transitions (the dotted lines and the points of contact of these lines with the x axis represent the energy gap).

Figure 6. PAA−SiC nanocomposites' wavelength-dependent extinction coefficient.
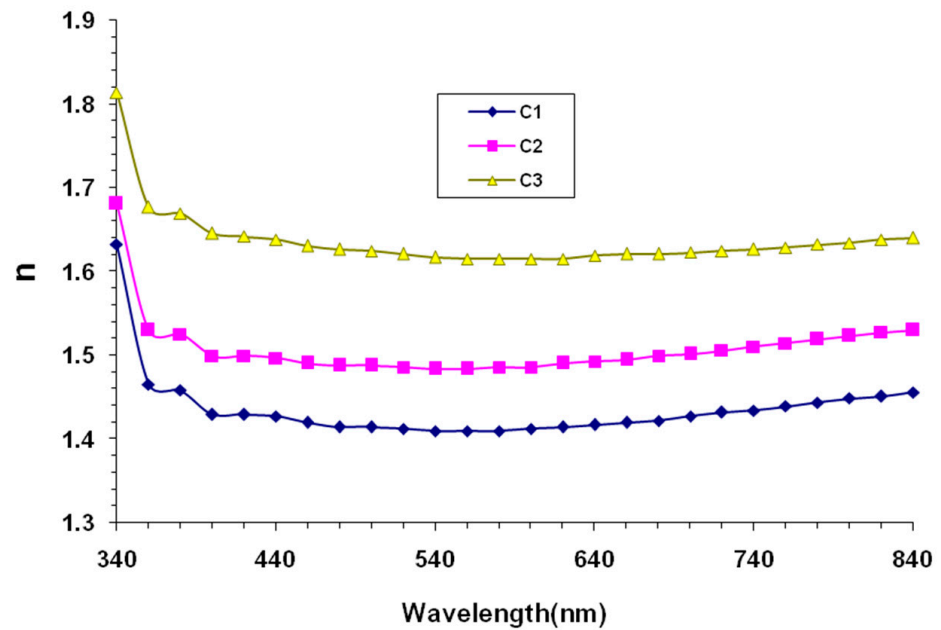
Figure 7. Refractive index performance for PAA−SiC nanocomposites with wavelength.

Crystallinity and, by extension, band and absorption structure have fluctuated between PAA and SiC nanoparticles as a result of the higher dosing [32]. Indeed, the growth in the values of n and k with rising concentration makes the PAA−SiC nanocomposites suitable in a variety of optical fields.

Figures 8 and 9 show how the real and imaginary dielectric constants of PAA−SiC nanocomposites change as a function of wavelength. The dielectric constants for PAA−SiC nanocomposites are increased with rising concentration. Dipolar polarization, which primarily occurs at shorter wavelengths of light and rises as concentration grows, can be linked to the increase in dielectric constants. Space charge polarization is a likely origin for this anomalous polarization.
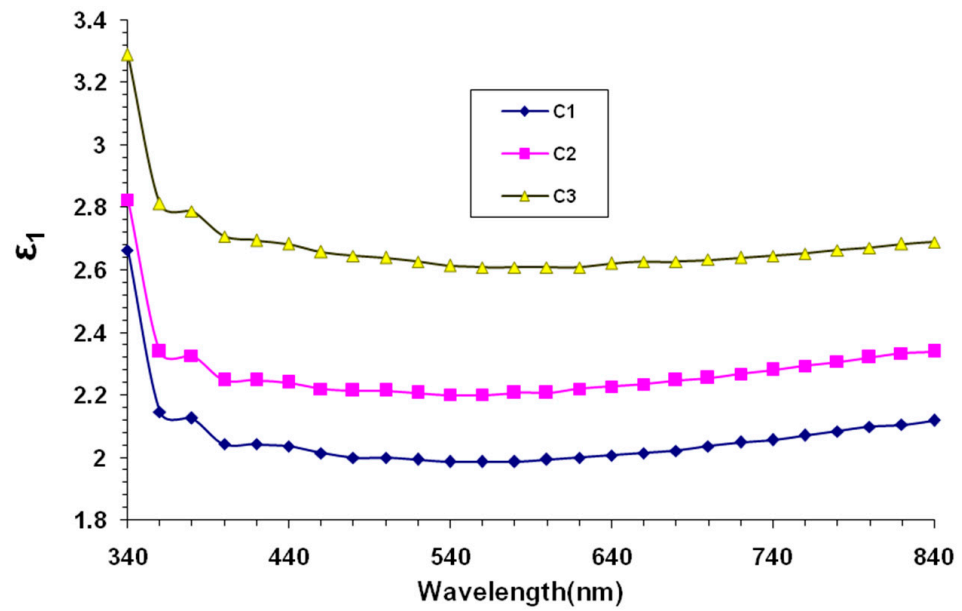
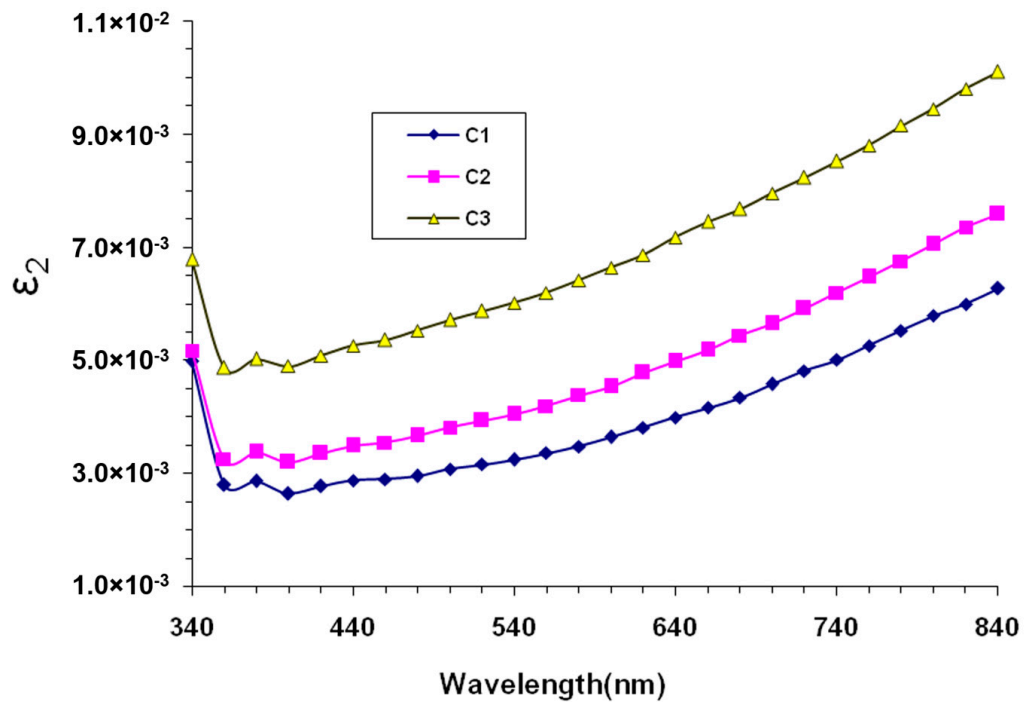**Figure 8.** PAA−SiC nanocomposites' wavelength-dependent actual dielectric constant.

Figure 9. Imaginary dielectric constant behaviour for PAA−SiC nanocomposites with wavelength.

In the fields of photonics and materials science, fundamental concepts include energy absorption and an improvement in optical conductivity with photon concentration. Materials may display a higher optical conductivity, or the ability to conduct light energy, when photon concentration, or the density of incoming photons, increases. Understanding and controlling these processes can result in the creation of photonic devices that are more effective and quicker, ultimately advancing the development of optical communication systems and renewable energy sources [35].

Energy absorption by a dielectric material from an electric field related to a dipole movement is controlled by the imaginary dielectric constant. In this regard, the real dielectric constant corroborates that the speed of light in the matter might be slowed down [36]. Figure 10 shows PAA−SiC nanocomposites' wavelength-dependent optical conductivity.

PAA−SiC nanocomposites increase optical conductivity with photon concentration and energy. For PAA−SiC nanocomposites, it might be seen as improving optical conductivity at higher energies wherever the increased absorption value produces an increase in the excitations of charge transfer. Enhanced optical conductivity with increasing concentration is linked to growing localized level densities within the band structure [37,38]. When exposed to light, silicon carbide nanoparticles can produce electron-hole pairs (excitons). The optical conductivity of the composite material can be greatly influenced by these excitons [39]. There are greater possibilities for light to interact with SiC nanoparticles as their concentration rises, which enhances the possibility of exciton formation. The optical conductivity results for PAA−SiC nanocomposites make them suitable for a variety of nano-electronic devices.
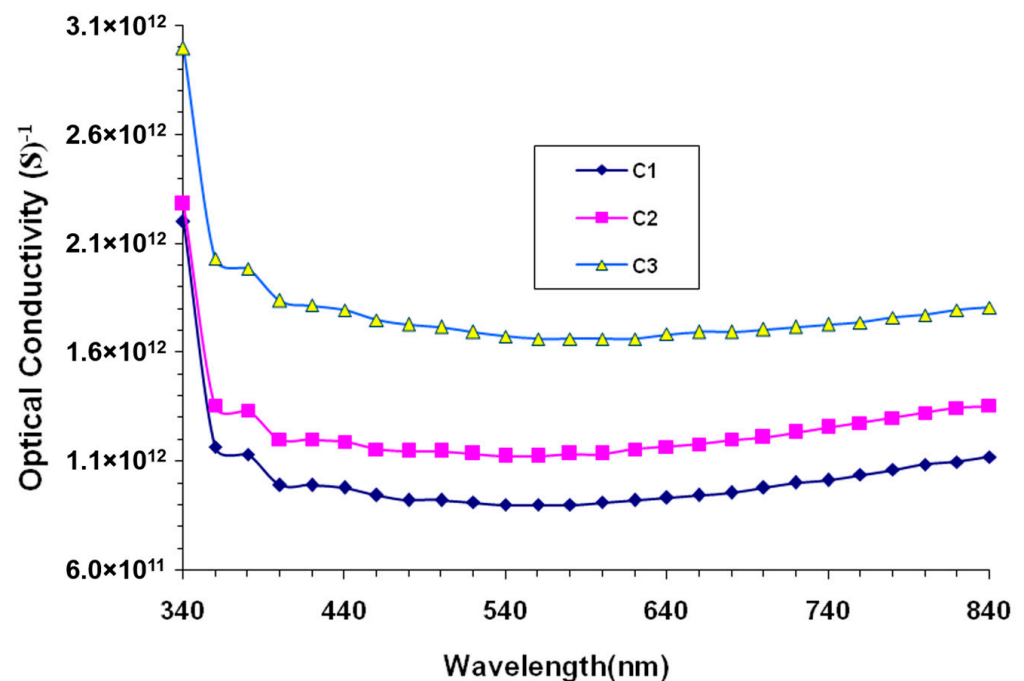

Figure 10. Performance optical conductivity for $PS/SiO_2/SrTiO_3$ nanocomposites with wavelength.

In the context of improving the thermal conductivity, which simply determines how effectively the material can conduct heat, it is vital to carry out a treatment or modification to enhance the ability of nanofluid to conduct heat. Undoubtedly, the improvement of heat conductivity is quite related to an increase in heat transfer. The crucial link in this situation is the decrease in the energy storage's melting time, which is connected to better thermal conductivity. This suggests that the energy storage material will melt faster because the nanofluid can transfer heat into it more quickly due to its increased thermal conductivity [40]. The melting process curves of PAA−SiC nanofluids are shown in Figure 11. This figure illustrates how the melting time reduces as concentration increases. The improvement in thermal conductivity, which resulted in an increase in heat transfer, was related to the reduction in melting time of energy storage in PAA−SiC nanofluids. The PAA−SiC nanofluids are suitable for heating and cooling systems due to the 61% increase in melting time with a concentration increase from 12.5 g/L to 50 g/L. Such findings can have major effects in a variety of industries, including thermal management and energy storage systems, where effective phase change and heat transfer processes are crucial for performance improvement.
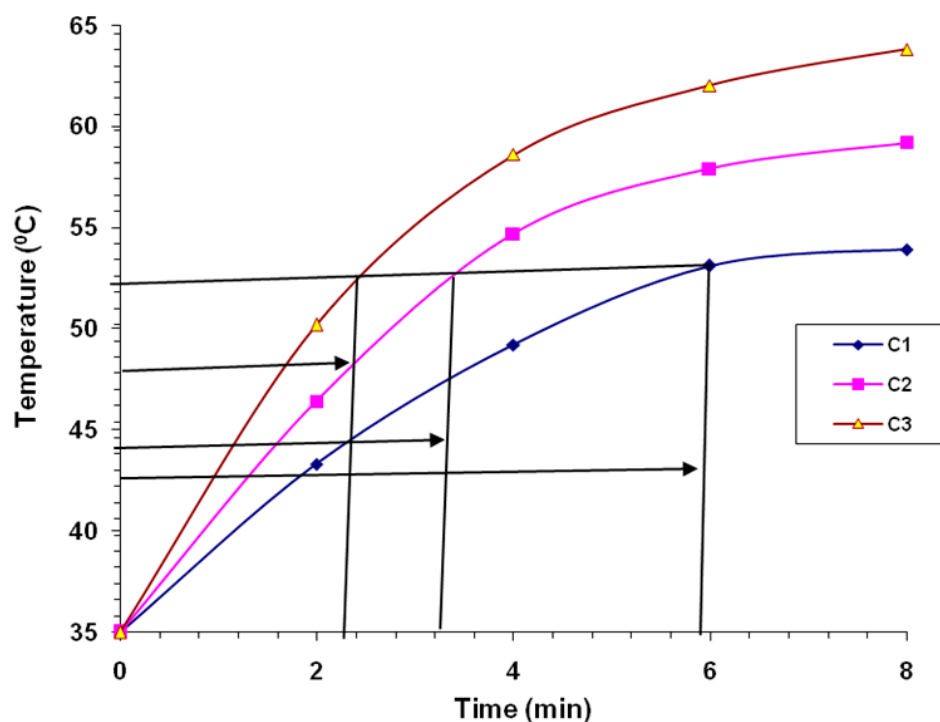
Figure 11. Curves of the melting process for PAA−SiC nanofluids (the falling lines on the x axis represent the time gain).

4. Conclusions

Due to advantages like enhanced thermal conductivity and better structural stability, composites formed from polymers and nanoparticles hold potential as efficient solar collectors and thermal energy storage devices. In this study, PAA−SiC nanocomposites were created, and their optical properties were examined for potential use in solar collectors and thermal energy storage systems. The transmittance characteristic of the PAA−SiC nanocomposite appears to indicate that it becomes more transparent at longer wavelengths, correlating with a decrease in absorption. However, at higher concentrations, the composite shows higher absorbance and lower transmittance due to enhanced light absorption brought on by the inclusion of more silicon carbide nanoparticles and potential scattering effects, which is a characteristic of concentrated composites with significant light-absorbing components. The results elucidated an increase in the absorption by 50.2% in addition to a decrease in transmission by 6% at wavelength (λ = 400 nm) and maximum utilised concentration of 50 g/L. Concentration dependence has reduced the energy band gaps from 3.25 eV for permitted transition to 2.95 eV, and from 3.15 eV to 2.9 eV for prohibited transition, rendering these compounds well-suited for use in a wide range of renewable applications. The optical factors of energy absorption and optical conductivity were also enhanced at 50 g/L of SiC concentration. The energy storage results showed that the melting time gain for PAA−SiC−H_2O nanofluids reached 61%, with the growth of concentration reaching 50 g/L. The findings ultimately proved that PAA−SiC−H_2O nanofluids are useful in the renewable energy and thermal energy storage sectors.

5. Recommendations for Further Research

For prospective use in renewable energy, the following suggestions to improve the optical characteristics of polyacrylic acid/silicon carbide nanocomposites are likely valid:

- As demonstrated in the current research, there is room to utilise the synthesised polyacrylic acid/silicon carbide nanocomposites in renewable energy systems due to an enhancement of optical properties. However, a useful assessment of their suitability for renewable energy systems should be addressed by integrating the improved

nanocomposites into the components of solar cells and gauge how they affect the effectiveness of energy conversion.

- A specific investigation is important to make polyacrylic acid/silicon carbide nanocomposites as efficient as possible. Specifically, this should consider the best ratio of polyacrylic acid to silicon carbide nanoparticles that enables the best optical characteristics.
- It would be interesting to examine how the shape and size of silicon carbide nanoparticles affect their optical characteristics. Greater light scattering or absorption can be achieved using smaller nanoparticles and regulated shapes.
- Since there is a possible utilisation of polyacrylic acid/silicon carbide nanocomposites in renewable energy systems, evaluating their stability and durability under a variety of environmental factors, including temperature, humidity, and UV exposure, is vigorous.

These suggestions are meant to direct future research into improving the optical characteristics of polyacrylic acid/silicon carbide nanocomposites, ultimately opening the road for their successful application in renewable energy systems.

Abbreviation

Symbol	Definition
NIR	Near-infrared
PAA	Polyacrylic acid
PCM	Phase change material
PMMA	Poly-methyl methacrylate
SiC	Silicon carbide
TES	Thermal energy storage
UV	Ultraviolet
VIS	Visible

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