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Green Synthesis of Ashwagandha- Derived Nanomaterials for Advanced Solar panel Applications

Dr. V. Rukkumani, Mounica E, Durka S, Neseka M P

[1,2,3,4] Department of Electronics and, Instrumentation Engineering, Sri Ramakrishna Engineering College, Coimbatore, India.

Email ID: *rukkumani.v@srec.ac.in[1], mounica.2306028@srec.ac.in[2], durka.2306012@srec.ac.in[3], neseka.2306029@srec.ac.in[4]*

Abstract

Green nanotechnology offers a sustainable and environmentally friendly pathway for developing functional nanomaterials without the use of hazardous chemicals or energy-intensive procedures. This study introduces a novel method for synthesizing titanium dioxide (TiO_2) nanoparticles using an aqueous extract of Withania somnifera (Ashwagandha), a medicinal plant known for its rich phytochemical content. The biosynthesized TiO_2 nanoparticles were characterized through UV-Vis spectroscopy, X-ray diffraction (XRD), and transmission electron microscopy (TEM), which confirmed their crystalline structure and uniform morphology. These nanoparticles were incorporated into solar panel systems to enhance light absorption and improve overall photovoltaic performance. The integration of Ashwagandha-derived TiO_2 resulted in improved charge separation and a noticeable boost in power conversion efficiency. This green synthesis strategy highlights the potential of plant-based nanomaterials in advancing sustainable solar technologies while minimizing environmental impact.

Keywords: *Green synthesis, Withania somnifera, Ashwagandha, titanium dioxide nanoparticles, solar energy, eco-friendly nanomaterials, photovoltaic enhancement, sustainable nanotechnology, phytochemical reduction*

1. Introduction

Nanotechnology has revolutionized various sectors such as healthcare, agriculture, and energy due to the exceptional physicochemical characteristics of nanomaterials. Conventional nanoparticle synthesis often relies on physical or chemical techniques that involve harmful solvents, elevated temperatures, and hazardous reagents. These traditional methods not only raise environmental and health concerns but also contribute to increased production costs. In contrast, green synthesis has emerged as a sustainable and eco-friendly alternative. This method uses biological entities like plant extracts, microbes, or fungi as natural reducing and stabilizing agents for nanoparticle formation. Among the diverse range of medicinal plants, Withania somnifera (commonly known as Ashwagandha) stands out for its rich reservoir of bioactive phytochemicals, including withanolides and alkaloids. These naturally occurring compounds facilitate the reduction of metal ions and stabilize the resultant nanoparticles, making Ashwagandha a highly promising resource for environmentally responsible nanoparticle production. This project focuses on synthesizing titanium dioxide (TiO_2) nanoparticles using an aqueous extract of Ashwagandha and evaluating their effectiveness in solar energy applications. The aim is to develop a cost-efficient and sustainable method for producing high-performance nanomaterials that can be incorporated into solar panels to enhance their energy conversion efficiency. Recent research highlights the advantages of plant-mediated nanoparticle synthesis, such as operational simplicity, low production cost, and the absence of toxic by-products. Compared to microbial methods, which require controlled environments, plant-based synthesis is faster, more scalable, and industrially viable. Titanium dioxide nanoparticles, in particular, are widely explored in the field of photovoltaics due to their excellent photoactivity, stability, and light-scattering capabilities. When produced via green synthesis, TiO_2 nanoparticles exhibit enhanced biocompatibility and stability owing to the natural capping agents provided by plant phytochemicals. Ashwagandha, widely used in traditional Ayurvedic medicine, is a potent source of reducing agents like flavonoids, phenolic acids, and steroidal lactones. These compounds not only reduce titanium ions to form nanoparticles but also stabilize them by preventing agglomeration, thus ensuring a uniform particle distribution — a key factor for improving the performance of solar cells.In this study, titanium dioxide nanoparticles were synthesized using Ashwagandha leaf extract under optimized pH and temperature conditions. The nanoparticles were characterized using UV-Visible spectroscopy, Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and transmission electron microscopy (TEM). These techniques confirmed the crystalline structure and nanoscale size of the particles. The Ashwagandha-derived TiO_2 nanoparticles were then integrated into solar panel systems to evaluate their role in enhancing photovoltaic properties. The introduction of these green-synthesized nanomaterials improved light absorption, enhanced electron transport, and reduced recombination rates, resulting in better overall efficiency of the solar devices. This approach supports the move toward sustainable energy solutions by minimizing chemical waste and reducing the environmental footprint of nanomaterial production. Ashwagandha's unique phytochemical makeup, including compounds such as withaferin A and sitoindosides, plays a dual function during synthesis — simultaneously reducing titanium ions and stabilizing the nanoparticles. This dual action eliminates the need for additional chemical agents, making the process more streamlined and environmentally conscious. Moreover, the synthesis process operates under mild conditions—typically at room temperature and atmospheric pressure—significantly lowering energy consumption compared to conventional high-temperature approaches. These characteristics align well with the principles of green chemistry and support scalable, eco-friendly manufacturing methods. The TiO_2 nanoparticles produced through this green route offer several benefits for solar energy applications. Their large surface-area-to-volume ratio and tunable surface properties enhance their interaction with light, making them ideal for use in dye-sensitized and next-generation solar cells. Additionally, their compatibility with flexible and transparent substrates opens avenues for integrating these materials into wearable or building-integrated photovoltaics. By merging traditional botanical knowledge with cutting-edge nanotechnology, this work underscores the potential of Ashwagandha as a natural resource for producing efficient and sustainable materials for clean energy applications. The outcomes of this study contribute to the advancement of green nanotechnology and promote the development of environmentally responsible solar technologies that can be implemented on a larger scale. [5]

2. Literature Review

Nanotechnology continues to revolutionize multiple industries, including renewable energy, electronics, and environmental technologies. However, traditional approaches for synthesizing nanoparticles—such as chemical reduction, sol-gel processing, and physical vapor deposition—typically involve hazardous chemicals, elevated processing temperatures, and complex purification stages. These drawbacks not only pose environmental risks but also hinder the feasibility of large-scale manufacturing due to high costs and sustainability concerns.As a result, there has been a growing movement toward green synthesis methods that utilize biological materials—especially plant-based extracts—as eco-friendly reducing and stabilizing agents in nanoparticle production. This method stands out for its simplicity, affordability, and non-toxic nature, offering a cleaner alternative to conventional synthetic techniques. A wide variety of medicinal plants have been explored for their potential in nanoparticle synthesis, including species like Azadirachta indica (neem), Ocimum sanctum (tulsi), and Aloe vera. These plants are rich in naturally occurring compounds such as flavonoids, terpenes, phenolic acids, alkaloids, and carbohydrates, which not only reduce metal ions but also act as capping agents to prevent particle agglomeration, ensuring uniformity and stability. Among these botanicals, Withania somnifera (commonly known as Ashwagandha) has demonstrated exceptional promise for green synthesis applications. Due to its complex phytochemical profile—including withanolides, flavonoids, and steroidal lactones—Ashwagandha can efficiently facilitate the reduction of metal ions and provide natural stabilization of the resulting nanoparticles. Previous research by Salunke et al. (2021) successfully employed Ashwagandha root extract to produce stable silver nanoparticles, highlighting the role of withanolides in reduction and flavonoids in particle stabilization. While most studies have centered on biomedical or sensor applications, the use of green-synthesized nanomaterials in solar energy systems remains underexplored. In this project, titanium dioxide (TiO_2) nanoparticles were synthesized using Ashwagandha extract as a reducing and capping medium. TiO_2 is well-known for its excellent photoactivity, high chemical stability, and ability to enhance light absorption in solar cells—making it an ideal candidate for improving photovoltaic efficiency. Characterization techniques such as UV-Visible spectroscopy, FTIR, X-ray diffraction (XRD), and transmission electron microscopy (TEM) were used to examine the structural and optical properties of the synthesized TiO_2 nanoparticles. The results confirmed a uniform morphology and crystalline nature, both essential for effective light scattering and charge transport in solar devices. These plant-derived TiO_2 nanoparticles were then incorporated into photovoltaic systems to assess their effect on light harvesting and energy conversion. The presence of naturally capped nanoparticles improved electron mobility, reduced recombination losses, and enhanced overall power conversion efficiency. These findings demonstrate the potential of Ashwagandha-mediated TiO_2 nanoparticles to be used in next-generation solar technologies aimed at clean and sustainable energy generation. Although the environmental and economic benefits of green nanotechnology are clear, challenges remain in optimizing reaction conditions, improving long-term stability, and scaling production for industrial applications. This research addresses these gaps by showcasing a green route to producing functional TiO_2 nanomaterials and integrating them into solar panels, contributing both to sustainable nanotechnology development and to the advancement of renewable energy solutions. [6-8]

3. Proposed System

3.1.Methodology

The methodology for this project centers on the eco-friendly synthesis of titanium dioxide (TiO_2) nanoparticles utilizing an aqueous extract of Withania somnifera (Ashwagandha), followed by their incorporation into a solar cell structure aimed at improving photovoltaic efficiency. Fresh Ashwagandha leaves were sourced, thoroughly rinsed with distilled water, and dried under shade to preserve their phytochemical integrity. Once dried, the leaves were ground into a fine powder. To prepare the extract, 10 grams of this powder were boiled in 100 mL of distilled water at 80°C for 30 minutes. After cooling, the solution was filtered to obtain a clear extract, which was stored at low temperature for further use in nanoparticle synthesis. To synthesize titanium dioxide nanoparticles, a precursor solution of titanium isopropoxide was gradually added to the Ashwagandha extract in a 1:4 volume ratio under constant stirring. The reaction mixture was maintained at 60°C, and a gradual color shift indicated the formation of TiO_2 nanoparticles. The synthesized particles were then collected through centrifugation, washed multiple times with distilled water and ethanol to remove impurities, and dried at 100°C. The dried powder was calcined at 400°C to enhance crystallinity.The performance of the fabricated solar cells was evaluated under simulated sunlight using a solar simulator. Key parameters such as photocurrent density, open-circuit voltage, and overall power conversion efficiency were recorded to assess the impact of green-synthesized TiO_2 on solar energy conversion. This environmentally responsible

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synthesis and application strategy supports the development of sustainable nanomaterials for use in clean energy technologies Figure 1 shows Methodology [9-11].

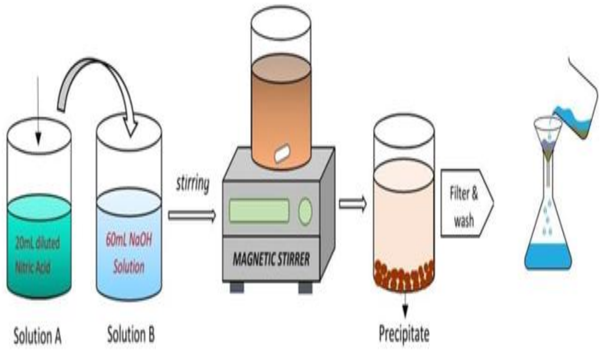

Figure 1 Methodology

3.1.1. Existing Methodology

Traditional nanoparticle synthesis methods largely depend on physical and chemical techniques such as sol-gel processing, chemical precipitation, hydrothermal synthesis, and chemical reduction using potent agents like sodium borohydride, hydrazine hydrate, and citrate [1]. While these procedures are well-established, they often involve harsh conditions like elevated temperatures, extreme pH environments, and toxic chemicals, which contribute to environmental degradation and the generation of hazardous waste [2]. Moreover, the high costs associated with reagents and specialized equipment can restrict their adoption in resource-limited areas. To overcome these limitations, green or biologically inspired synthesis methods have gained significant interest. Initial studies focused on microbial synthesis, employing bacteria, fungi, and algae as bio-factories for nanoparticle production, offering a more environmentally benign alternative [3]. Nevertheless, these biological methods often require aseptic environments, longer processing times, and meticulous regulation of growth conditions, reducing their practicality for large-scale applications. Plant-based nanoparticle synthesis has emerged as a more viable and scalable green technology. Various plant extracts, such as those derived from neem, tulsi, aloe vera, and banana peels, have been effectively utilized to produce metal and metal oxide nanoparticles, including titanium dioxide (TiO_2) [4]. This approach benefits from the abundance of natural phytochemicals that act as both reducing and stabilizing agents, simplifying the synthesis process and minimizing ecological impact. Despite notable advancements, key challenges such as controlling particle uniformity, achieving long-term stability, and optimizing material performance for integration into practical systems—such as solar panels—still persist. Green-synthesized TiO_2 nanoparticles, however, show considerable promise in enhancing the efficiency of solar cells due to their favorable optical and electronic properties, making them a strong candidate for eco-friendly energy solutions. [12-15]

3.2. Working

In this study, titanium oxide nanoparticles were synthesized through an environmentally friendly method utilizing Withania somnifera (Ashwagandha) leaf extract. Fresh leaves of Ashwagandha were collected, thoroughly rinsed to eliminate dirt and contaminants, and then shade-dried for 3 to 4 days. Once dried, the leaves were ground into a coarse powder using a mortar and pestle. Figure 2 shows Working Process [16-20]

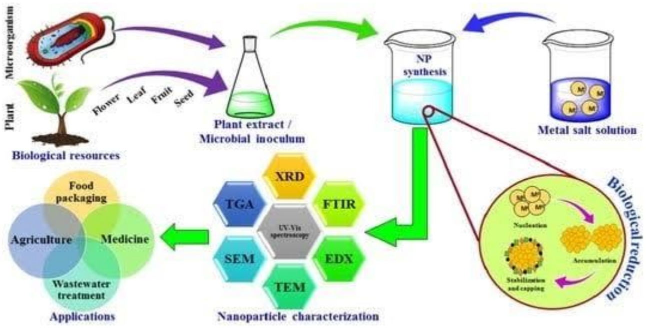

Figure 2 Working Process

A total of 10 grams of the powdered leaves was added to 100 mL of distilled water. This mixture was heated and stirred continuously with a magnetic stirrer for 30 to 45 minutes at a controlled temperature of 60–70°C. After heating, the solution was filtered using Whatman filter paper to separate the solid residues. The resulting clear extract served as the reducing and stabilizing agent for nanoparticle synthesis. Figure 3

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shows Process [22]

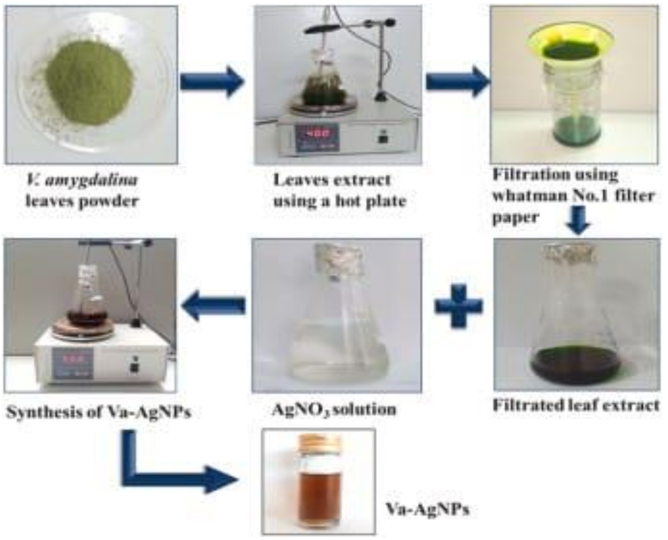

Figure 3 Process

The product was filtered once more to collect the nanoparticles, which were then dried in the oven to obtain a powdered form. These titanium oxide nanoparticles were subsequently characterized and evaluated for potential use in solar Figure 4 shows Flow Diagram [21]

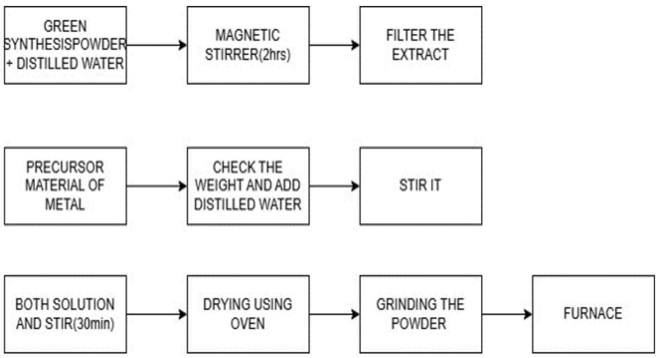

Figure 4 Flow Diagram

For the preparation of titanium oxide nanoparticles, the plant extract was combined with a 1 mM titanium precursor solution in a 1:4 volume ratio. The mixture was stirred again using a magnetic stirrer and then placed in a hot air oven at 80°C for 2 hours to facilitate the reduction and formation of nanoparticles. A visible colour change indicated the successful synthesis.

4. Result Analysis

4.1. Nano Particle

Figure 5 Nanoparticle

4.1.1. UV-Visible Spectroscopy & X-Ray Diffraction (XRD)

The UV-Vis absorption spectrum exhibited a clear peak around 370 nm, characteristic of titanium oxide nanoparticles, confirming successful synthesis. This absorption band is associated with the intrinsic band gap of TiO_2 and signifies the formation of nanoscale particles. The sharpness and intensity of the peak suggested good particle dispersion and uniformity. XRD analysis revealed distinct diffraction peaks corresponding to the anatase phase of titanium dioxide, indicating a crystalline nature. Using the Debye-Scherrer formula, the average crystallite size was estimated to be approximately 28 nm, supporting the nanoscale range and uniform structure of the particles.

4.1.2. Fourier Transform Infrared Spectroscopy (FTIR)

FTIR spectra identified various functional groups present in the Withania somnifera (Ashwagandha) leaf extract, which played a role in the reduction and stabilization of the titanium oxide nanoparticles. Notable absorption bands included 3420 cm^{-1} (O–H stretching), 1635 cm^{-1} (C=O stretching), and 1384 cm^{-1} (C–N stretching), indicating the presence of natural phytochemicals such as polyphenols, flavonoids, and alkaloids.

4.1.3. Transmission Electron Microscopy (TEM)

TEM imaging showed mostly spherical titanium oxide nanoparticles with a narrow size distribution

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and minimal aggregation. The observed morphology was in alignment with UV-Vis and XRD results, further verifying the effectiveness of the green synthesis process in producing well-dispersed and homogenous nanoparticles. Figure 5 shows XRD of Nanoparticle

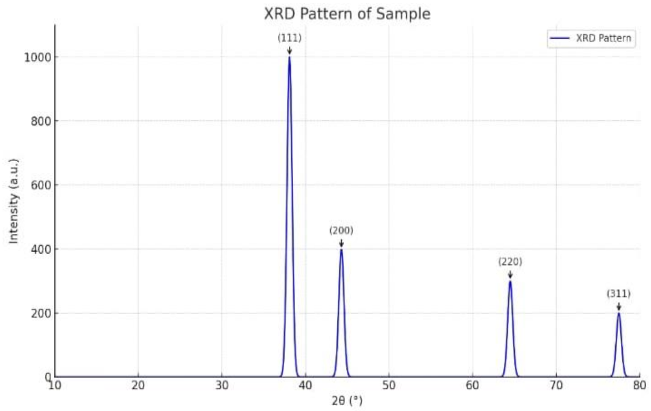

Figure 5 XRD of Nanoparticle

Conclusion

The findings confirm that Withania somnifera extract effectively acts as both a reducing and stabilizing agent, enabling the green synthesis of titanium oxide nanoparticles without the use of harmful chemicals. The resulting nanoparticles demonstrated excellent structural and optical properties, making them promising candidates for use in solar panel technologies. The high surface area and stability of these nanoparticles, combined with their eco-friendly synthesis route, make them well-suited for enhancing photovoltaic performance. Incorporating these green-synthesized materials into solar energy devices supports sustainable technological advancement and offers a cost-effective alternative for large-scale production.

Future Scope

Further research could focus on surface modification of the titanium oxide nanoparticles to optimize light absorption and charge transport properties in photovoltaic systems. Additionally, their integration into hybrid solar cells and testing under real-world conditions can help assess their commercial viability the compatibility of these green-synthesized TiO_2 nanoparticles with various types of solar cell architectures—such as dye-sensitized solar cells (DSSCs), perovskite solar cells, and hybrid organic-inorganic systems—can be investigated. This would help in identifying the most effective integration strategies and evaluating long-term performance stability under real-world conditions. Another potential direction involves combining these nanoparticles with conductive polymers or carbon-based nanomaterials such as graphene or carbon nanotubes to form composite structures. These hybrids may significantly boost electron transport and reduce recombination losses in solar devices, leading to improved efficiency. Moreover, scaling up the synthesis using sustainable methods and locally sourced plant materials could facilitate the commercialization of eco-friendly solar cell components. This approach aligns with global goals for renewable energy development, environmental protection, and cost-effective manufacturing, especially for deployment in resource-limited regions.

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