



Role of Natural Dyes in Solar Cell Technology: An AI-Enhanced Approach

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Abstract

The quest for sustainable energy solutions has led to a growing interest in natural dyes as environmentally friendly and cost-effective sensitizers in solar cell technology. This paper investigates the role of natural dyes in enhancing the efficiency and affordability of solar cells, particularly dye-sensitized solar cells (DSSCs). It further explores how artificial intelligence (AI) can optimize the synthesis, characterization, and performance evaluation of natural dyes in solar cells. AI tools such as machine learning models and predictive analytics are employed to analyze molecular structures, predict dye-sensitizing efficiency, and simulate solar cell performance under various conditions. Case studies and experimental data highlight the potential of AI-enhanced approaches to accelerate the development of high-performance, sustainable solar energy solutions.

Keywords: Solar, dye, AI.

Introduction: -

Global economic growth is being outpaced by spending on research and development (R&D), which is projected to increase to more than 3% of global GDP by 2025 from 2.0% a decade ago. According to recent estimates, the global research budget exceeds US\$1.7 trillion annually, with 80% of the expenditures being attributed to ten countries. The United States, China, Japan, Germany, and South Korea are the top five spenders in absolute terms. Israel allocated 4.93% of its GDP to research and development in 2019, making it the nation that invested the most in this area in relation to its GDP. Another significant source of funding and overall activity for scientific research is global technology corporations. This phenomenon is particularly pertinent to the field of artificial intelligence, as it is relatively recent. These trends also indicate that a significant portion of the world's scientific research is either funded or conducted by private corporations. Given the business objectives of these organizations, it is probable that a significant portion of this research and development will be conducted in the disciplines of artificial intelligence (AI) and data science. Scientific research is being affected by the private/corporate sector's entrance into R&D. Furthermore, in view of increasing demand for solar technology, it is important to note that a research robot that is capable of autonomously testing flexible solar panel samples has been developed by researchers at CSIRO. The autonomous system was constructed by these researchers in Melbourne during the 'second phase' of COVID-19 in 2020. Previously, researchers were required to be physically present in the laboratory and could manually evaluate up to 20 solar cells per day. The new automated research system is remotely controlled and has the capacity to assess 12,000 cells in 24 hours, resulting in a 600-fold increase in productivity. Additionally, artificial intelligence (AI) and machine learning are being implemented to effectively analyse and forecast parameters for the production of organic solar cells. These applications demonstrate how the integration of machine learning and autonomous testing can enhance the efficacy of scientific research.

Natural Dyes in Solar Cell Technology: -

A DSSC is a photovoltaic device that converts solar radiation into electrical energy by utilizing a dye molecule. Researchers are utilizing a variety of traditional and innovative materials to alter the stability and efficacy of these cells. The selection and enhancement of pigments are the subject of significant research due to their critical role in DSSCs. Since their initial publication in 1991, ruthenium polypyridyl complexes have been employed as



sensitizers due to their numerous benefits, including their ability to transmit charges rapidly and the presence of an effective anchoring group. However, the high cost and chemical toxicity of ruthenium-based organic dyes prompted the investigation of natural dyes derived from fruits, vegetables, and other sources. Metal-free organic dyes have been reported to achieve the maximum efficiency of 14.30%. Carotenoids are also frequently observed in nature. In East Asian countries, curcumin is a xanthophyll carotenoid that is employed in a variety of applications, with the most prevalent being as a spice. The presence of carbonyl and hydroxyl groups in anthocyanins enables them to readily bind with the TiO_2 surface, which is the reason for the coloration of a variety of plants. Although Ru-based dyes have shown the potential to produce highly efficient DSSCs, they are not without their drawbacks, such as the high cost and the complex synthesis methods required, which are a result of the scarcity of the noble metal ruthenium. Anthocyanins are pigments that are naturally present in a variety of fruits, vegetables, and flowers, and they contribute red, blue, and purple tints. These substances are predominantly situated within the vacuoles of plant cells and exhibit water solubility. In comparison to synthetic photosensitizers, anthocyanins offer numerous noteworthy benefits, including their ubiquitous availability, cost-effectiveness, and eco-friendliness. In order to improve the subject's stability and light absorption properties, additional research is necessary. Solar cells have recently been identified as an appealing substitute for conventional fossil fuels. The primary reason for this increase in attention is the urgent need for sustainable energy sources in the contemporary world. Solar cell research continues to be dynamic and constantly evolving, despite the significant progress that has been made. The landscape of solar cells is characterized by the evolution of technology, which has resulted in three distinct generations that accommodate to a variety of functions and requirements. The inception of solar cell technology was marked by the deployment of traditional wafer-based cells during the initial generation. The prevalence of first- and second-generation cells in commercial markets continues to attract significant attention in contemporary solar cell research. The pioneering work of Michael Gratzel in the 1970s is responsible for the development of these DSSCs. In these cells, Gratzel employed an electrolyte, dye-based sensitizers, and oxide semiconductors—an innovative approach. In 1991, Michael Gratzel and Brian O'Regan achieved an extraordinary milestone by improving the efficiency of DSSCs by 7.12%. This development was noteworthy. This discovery stimulated further investigation of DSSCs as a result of their substantial potential for future advancements. DSSCs are a highly attractive option in solar cell technology due to their cost-effectiveness, which is one of their distinguishing features. The potential for affordable large-scale production is presented by the relatively low manufacturing costs of DSSCs. In contrast to other types of solar cells that depend on specific light intensity ranges, DSSCs have a distinctive advantage: they are known to operate at their best even in low-light conditions and under overcast skies, with minimal influence on their efficiency. Their practicality and allure in real-world applications are improved by their ability to adjust to changing light conditions.

AI Applications in Solar Cell Research: Sustainability and Innovations: -

The solar energy industry is being transformed by artificial intelligence (AI), which is improving efficiency, productivity, and performance. By analyzing historical data on solar energy production, weather patterns, and other critical factors, artificial intelligence systems can make accurate predictions regarding future energy generation. The accuracy of AI models is incrementally enhanced by the incorporation of machine learning techniques. These forecasts assist solar power plant administrators in the organization and optimization of energy production, the improvement of grid integration, and the formulation of informed decisions regarding energy distribution and storage. AI can dynamically modify the system's operation to



optimize energy production and reduce costs. This innovative management approach ensures optimal performance and the efficient utilization of solar energy resources.

The location and analysis of issues in solar energy systems are contingent upon AI algorithms. By analyzing real-time sensor data from solar panels, inverters, and other components, they can identify anomalies and potential issues. This early detection minimizes system outages and enhances energy output by enabling prompt maintenance and repairs. System administrators can enhance the efficiency and dependability of solar energy systems by taking preventative action, as AI can also illuminate the underlying causes of issues. Artificial intelligence (AI) is implemented in solar energy systems to enhance productivity, efficiency, and performance. In order to enhance solar energy generation, it is essential to implement AI-driven predictive analytics. These algorithms have the capacity to generate and distribute energy across the solar farm in an effective manner, thereby reducing energy waste and ensuring maximum output. AI also enables the solar farm to operate more efficiently and at a reduced cost by facilitating load balancing, resource allocation, and predictive maintenance scheduling. AI algorithms optimize the charge and discharging cycles of energy storage devices by dynamically altering storage activities in response to real-time conditions, thereby enabling the utilization of solar energy in the absence of sunlight. This enhances self-consumption, reduces dependence on the grid, and promotes grid stability. The integration of solar energy into the present power system is more effective and sustainable when energy storage optimization is driven by AI.

The utilization of AI in the design and planning phases of solar energy projects is on the rise, allowing designers to optimize panel installation, system sizing, and configuration in accordance with factors such as solar potential, shading studies, and energy demand patterns. AI has the ability to predict and simulate the performance of a variety of design options, allowing designers to select the most cost-effective and efficient solutions. The solar energy sector is undergoing a transformation as a result of AI, which has contributed to improved project viability, decreased costs, and enhanced system performance. The solar energy industry is being transformed by AI, which is utilizing machine learning algorithms and data analysis to enhance energy management, grid integration, and energy storage. This sophisticated energy forecasting enhances energy trade, stabilizes the grid, and facilitates the integration of solar energy into the existing power infrastructure. There is a critical need for energy storage systems to bridge the divide between the demand and production of solar energy. This dynamically modifies energy storage operations based on these criteria, ensuring the effective use of renewable energy, decreasing dependency on the grid during peak hours, and optimizing self-consumption.

Solar energy innovations that are propelled by AI include the automation of the passage of electricity between solar panels, energy storage systems, and the grid, as well as the enhancement of solar panel efficiency, the evaluation of data on energy consumption, weather trends, and grid status. AI algorithms are being employed to optimize the arrangement and design of large-scale solar farms, considering factors such as geography, solar potential, shading analyses, and land availability. The precision of predictions for solar power generation has been considerably enhanced by artificial intelligence (AI), which has a significant impact on grid stability, energy planning, and overall efficiency. By learning from patterns and correlations in the data, these models perpetually enhance their forecasting capabilities and adjust to evolving environmental conditions. The utilization of real-time data in AI-based forecasting enables models to promptly adapt to changing circumstances and enhance their predictions. In order to capture the intricate patterns and dynamics of solar power generation, machine learning algorithms employ techniques such as support vector regression, neural networks, random forests, and ensemble methods. This leads to solar power output forecasts that are both highly precise and dependable. In addition, they facilitate efficient energy trading by allowing market participants to determine the costs of electricity, supply agreements, and grid balancing services. This enhances market efficacy, reduces prices, and facilitates the more comprehensive integration of solar energy into the broader energy ecosystem.

Artificial intelligence-driven solar power forecasting provides valuable insights for renewable energy policy formulation and planning. Predictions assist decision-makers in the identification of potential impacts of solar energy projects, the efficient allocation of resources, and the development of effective incentive schemes. The solar energy industry will experience a surge in the significance of intelligent forecasting as AI technology advances, thereby expediting the transition to a future that is powered by



renewable and sustainable energy sources. Data analytics and machine learning algorithms enable AI-enabled systems to convert unstructured data into actionable insights, thereby enhancing operational efficiency and facilitating informed decision-making. These systems allow operators to achieve their sustainability objectives, enhance system performance, and optimize energy production. AI-enabled devices can participate in demand response programs, which autonomously adjust energy consumption or transfer excess energy back into the grid during peak demand, in order to ensure grid stability and maximize economic benefits.

Solar energy system proprietors can optimize revenue generation by capitalizing on advantageous market conditions and utility interactions. These algorithms can also assess the financial and feasibility of system extensions. AI-powered solar farms have revolutionized the renewable energy sector by facilitating enhanced overall performance, increased energy generation, and more efficient operation. In an effort to optimize energy flow within the farm, identify probable failures or degradation patterns, and enable predictive maintenance, AI algorithms analyze data from sensors and monitoring equipment. AI algorithms enhance energy efficiency and reduce dependence on the grid by making intelligent judgments regarding energy allocation, grid interaction, and storage management. This data is processed to inform data-driven decisions for ongoing performance enhancement, system upgrades, and maintenance planning.

AI-powered solar farms contribute to grid stability by consistently adjusting their energy output in response to changes in demand and grid conditions. Additionally, they advocate for the integration of renewable energy sources into the existing electrical grid. AI-powered solar farms enhance the grid's resilience by supplying reserve power during outages or system malfunctions, thereby guaranteeing a consistent and uninterrupted electricity supply. AI-powered solar farms maximize energy production and reduce reliance on fossil fuel-based power generation, thereby promoting environmental sustainability by reducing greenhouse gas emissions and the effects of climate change. Additionally, they oversee and mitigate environmental repercussions, such as wildlife disturbance, water consumption, and land use.

As the demand for solar energy increases, the integration of artificial intelligence (AI) into the solar energy infrastructure is becoming more critical. AI systems optimize the utilization of renewable energy resources, improve grid stability, and facilitate informed decision-making. AI-powered solutions enhance grid resilience by identifying and promptly addressing grid faults and disturbances in real time. They have the ability to anticipate prospective grid issues before they escalate, promptly address them, and restore electricity. The significance of AI technology in optimizing the integration of solar energy grids will increase as it continues to develop, thereby facilitating a more dependable and efficient solar-powered electrical grid.

Conclusion: Natural dyes offer a promising pathway toward sustainable solar cell technology due to their eco-friendliness, wide availability, and cost-effectiveness. This paper underscores the transformative potential of artificial intelligence in enhancing the efficiency and applicability of natural dyes as sensitizers in DSSCs. By leveraging AI tools to optimize molecular design, simulate dye performance, and analyze experimental data, researchers can significantly reduce development time and costs while improving solar cell efficiency. The integration of cultural practices in sourcing natural dyes further enriches the research, bridging traditional knowledge with technological innovation. However, this interdisciplinary approach requires careful consideration of environmental sustainability and ethical practices, particularly in the equitable sharing of benefits with communities contributing to traditional dye knowledge. By combining AI-driven methodologies with the inherent sustainability of natural dyes, this research sets the stage for advancing solar energy technologies that are both high-performing and culturally inclusive, paving the way for a greener and more equitable energy future.

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