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Perspective

Fullerene hits for green energy—Marching towards solar cells

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Abstract: Since discovery and after decades of scientific endeavors on fullerene and derived nanomaterials, we note wide-span high-tech applications in the fields of energy/electronic devices—to—space/defense/engineering—to—medical areas. These days, conformist explorations on carbon nanoparticles, like fullerene, trend towards the use of green synthesis methods and sources, leading to the development of environmentally friendly nanomaterials and applications. Fullerene, as one of the most remarkable nanotechnological breakthroughs, has emerged as a leading competitor for designing ecofriendly or green energy devices and systems. Looking at the current scientific demand for fullerene in one of the most efficient ecological energy conversion systems, like solar cells, we plan this perspective manuscript to unveil the true state-of-the-art and progress on green-sourced fullerene nanomaterials for photovoltaics. As per expanded research over the past few decades, manufacturing/application of fullerene nanomaterials via sustainable ecological sources/techniques led to next-level utilization for green energy devices, especially for high-performance solar cells with notably high power conversion efficiencies, photovoltaic parameters, low price, light weight, nontoxicity, and fine processability. Despite the research progress so far, commercialization and real-world utilization of fullerene-derived green solar cells seem to be reliant upon overcoming challenges for integrating these nanomaterials into today's most scorching next-generation green energy devices or assemblies.

Keywords: green energy; fullerene; nanomaterials; synthesis; solar cell; performance

1. Introduction

Solar cells (or photovoltaics) have been categorized as the most promising green energy systems of the current age due to outstandingly efficient solar-to-electrical energy/power conversions [1]. In recent decades, we observe significant and repeated scientific efforts to enhance the solar cell or photovoltaic efficiencies beyond 20%, using advanced nanomaterials and techniques [2]. Recently, fullerene and related nanostructures subsidized the state-of-the-art of green solar cell designs/architectures having superior device parameters and power conversion efficiencies. Fullerene (buckminsterfullerene discovered in 1985) is a unique zero-dimensional nanoallotrope of carbon having notable structural and physical (optical, electronic, thermal, mechanical, etc.) characteristics and countless materials/nanotechnology applications [3].

Relative to commercial inorganic photovoltaic systems [4], incorporating fullerene nanostructures depicted merits of low cost/weight, flexibility/transparency, fine processability, and thermal, photo, or chemical stability features. Especially, research progressions on fullerene-based solar cells unfolded technically significant ecological/sustainable designs in due course for green energy applications. All these structural and physical attributes of fullerene nanomaterials rendered them attractive towards commercialization of green photovoltaic devices. Nevertheless, using fullerene and related nanostructures in solar cells suffers from a number of challenges, including limited lifetime or functioning depending upon environmental variations in sunlight, temperature, or weather, as well as a lack of comprehensive working/degradation mechanisms. Unfortunately, all these factors appear to cause major hurdles towards promising practical deployment of fullerene in industrial-level photovoltaics.

This perspective manuscript comprehensively showcases multiscale structural/physical properties and performance of green-derived fullerene nanomaterials towards today's most demanding ecological and sustainable solar cell devices/systems. Therefore, we plan this systematic article covering essential design/property/functional features of green fullerene-based solar cells to offer an all-inclusive guide for struggling scientists/researchers towards innovative future opportunities in this field. By judging the current state of fullerene-based green energy technologies, we can say that more comprehensive investigations must be performed for designing functional green and sustainable fullerene nanomaterials for future marketable green energy devices.

2. About green energy

The concept of green energy (clean energy) has been considered across-the-board for natural sources (sun, wind, water) and ensuing advanced renewable technologies of solar energy along with traditional biomass energy or wind power resources [5]. Recently, green energy relying on sustainable/renewable technologies has attained notable worth in scientific communities owing to the utmost desires of the present age for a green ecosystem. Since green energy sources are naturally replenished without harming ecosystems, recent research endeavors greatly focus on replacing traditional non-green energy systems with green energy technologies to prevent their hazardous environmental effects causing global warming [6]. It is believed that green or clean energy has almost no greenhouse emissions affecting our natural ecosystem. Following that, we notice recently trending research on innovative nanomaterials (like fullerene) that can be safely used in today's high-end energy systems, endorsing green energy perceptions.

3. Fullerene

In simple words, fullerene is a nanocarbon nanostructure, just like graphene (two-dimensional), carbon nanotubes (one-dimensional), and other carbon nanoparticles [7]. All these nanocarbons have different shapes and dimensionalities, in turn affecting their structural, physical, and applied aspects. Looking at fullerene, it is a hollow, spherically symmetrical, zero-dimensional nanostructure with a structural composition of sp^2 hybridized carbon atoms, just like graphene and carbon nanotube structural constitution [8]. Accordingly, fullerene molecules own π conjugated nanostructures [9]. Different types of fullerene molecules have been discovered so far, depending upon the number of carbon atoms in their hollow globular structure. For example, smaller fullerene analogues, like C_{20}, C_{24}, C_{28}, etc., and larger fullerene molecules, such as C_{60}, C_{70}, C_{84}, C_{120}, etc., have been reported (**Figure 1**). Out of these, fullerene C_{60} (sixty carbon atoms), also known as

Buckminster fullerene due to its soccer ball-like appearance, is the most widely studied nanocarbon due to its inimitable nanostructure and surface, electronic, optoelectronic, thermal, and countless physical characters [10].

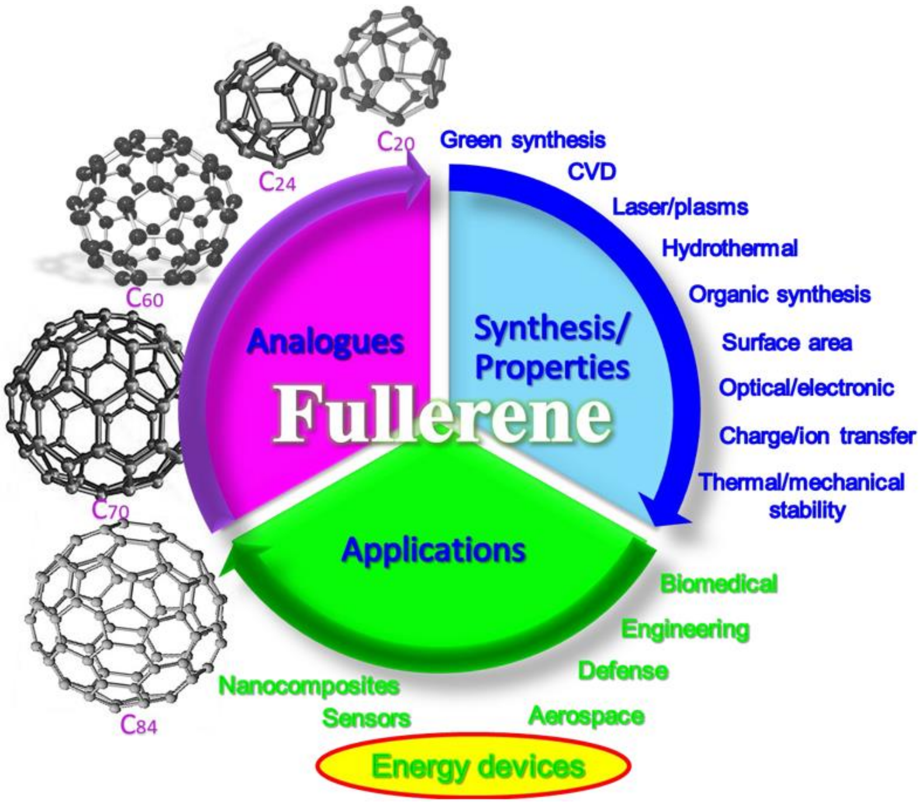

Figure 1. Aspects of fullerene.

Herein, research progress on fullerene begins with its synthesis using assorted top-down/bottom-up procedures like nano-cutting, laser/plasma, chemical vapor deposition, arc discharge, and chemical synthesis strategies [11]. Owing to the structure-property uniqueness of fullerene molecules, researchers from varying nanotechnological disciplines investigated noteworthy applications in photovoltaics, supercapacitors, batteries, sensors, and innumerable other device-related and structural/engineering applications [12]. Particularly, due to electronic, optoelectronic, and electrical properties, notable research seen to date on the utilization of fullerene molecules in advanced optoelectronic devices, like solar cells, as we debated in other sections of this novel manuscript.

4. Fullerene and present day green energy trends

As per literature to date, we note that customary research on the synthesis and utilization of fullerene for technological purposes mostly adopts non-green or non-ecological routes, chemicals, and reagents [13]. For solar cells, fullerene molecules have been usually prepared through arc discharge of graphite or laser vaporization of carbon precursors. However, using these methods has drawbacks of air pollution due to carbon nanoparticle emissions, the need for high-purity carbon precursors, expensive carbon source purification techniques, and large energy consumption. Consequently, the use of renewable resources, water-based solvents, and one-pot green techniques must be preferred for fullerene manufacturing. Here, appropriate environmentally friendly and sustainable sources or means need to be focused on for fullerene deployment in modern high-tech applications. We suggest a few indispensable green strategies to be implemented for sustainable and green use of fullerene molecules, like (i) applying well-defined and well-controlled ecological or green synthesis techniques instead of traditional methods, (ii) using green/sustainable chemicals or reagents in fullerene fabrication processes, or (iii) surface functionalization of fullerene to transform it into more ecofriendly, sustainable, and environmentally compatible nanomaterials [14]. Nevertheless, for green synthesis of fullerene, definitely concentrated scientific efforts seem indispensable to devise techniques involving all green steps and desirable sources. In the case of green/sustainable chemicals/reagents, several ongoing research projects have been noticed in the literature regarding the use of biowastes (leaves, fruit/plant extracts, etc.) [15] and renewable carbon sources in common fabrication practices for fullerene, such as chemical/physical vapor deposition, laser ablation, organic synthesis, and the like [16].

In line with scientific efforts so far, eco-friendly designs of fullerene nanocomposites have also been investigated by the field researchers [17]. For instance, efficient fullerene-derived nanomaterials have been designed for energy devices using green approaches. Among the most frequently used nanocomposites for such systems, conjugated polymer/fullerene hybrids have been considered owing to superior surface properties, electrical conduction, charge/heat transference, and durability. In this case, using green solvents (e.g., water), renewable precursors, and green manufacturing strategies may lead to environmentally benign designs of polyaniline/fullerene or polythiophene derivatives/fullerene nanocomposites meeting sustainability demands of the current green era [18]. Among the safest routes for large-scale ecological fullerene and related nanomaterial development, techniques like chemical vapor deposition with all green precursors/chemicals and micromechanical exfoliation have been found successful. However, commercialization and scalability of green techniques for fullerene synthesis may include limitations of low efficiency, complexity, and material stability issues. Specifically, using simple green methods may cause complications in energy level control of fullerene-based materials, leading to low open-circuit voltage and overall poor solar cell performance. Despite these limitations, recent scientific trends seem drifting toward deployment of green-derived fullerene nanomaterials in energy devices/systems, as argued in the following section.

5. Success of fullerene in present green energy scenarios—Solar cells

In pursuit of eras of successful investigations on fullerene, myriads of efficient energy systems have been documented employing green fullerene nanocomposites/hybrids. Predominantly, out of energy production devices, fullerene nanocomposites have been practiced for solar cell designs (**Figure 2**). At this juncture, literature foretells the industrial-scale potential of solar cells for pollutant-free electricity generation in sustainable/ecological ways to meet present-day green energy demands. Among solar cells, we note miracles of green fullerene hybrids for polymer solar cells, dye-sensitized solar cells, perovskite solar cells, and other types of photovoltaics [19].

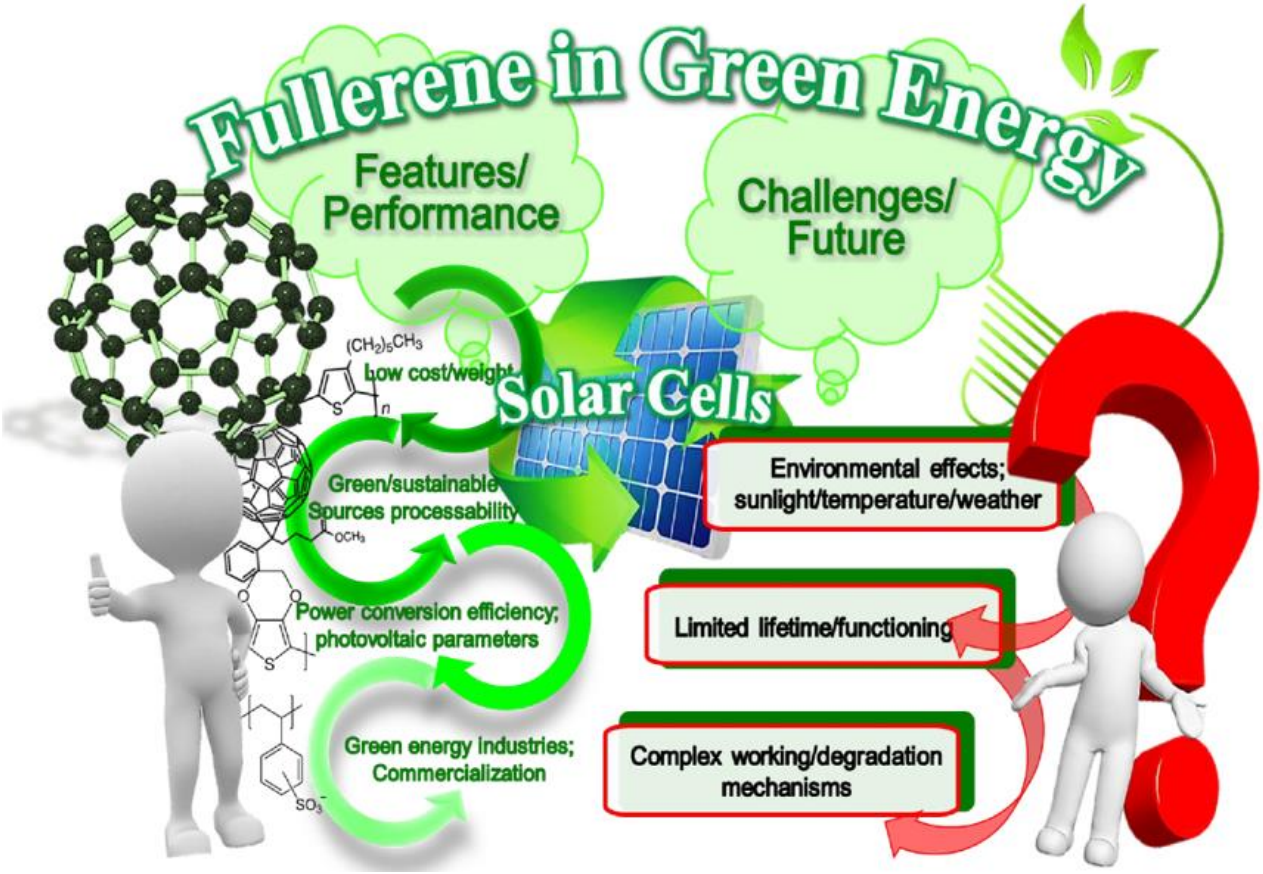

Figure 2. Fullerene nanotechnology for green energy—solar cells.

Particularly for green solar cells, environmentally friendly fullerene-based nanocomposites have been manufactured using eco-friendly polymeric matrices, such as cellulose, poly(ethylene glycol), poly(vinyl alcohol), and conjugated polymers via green routes, as mentioned in earlier discussions [20]. Important literature attempts have been seen on green synthesis of solar cell-related fullerene nanocomposites via safe techniques, namely spinning, coating, three-dimensional printing, etc. [21], without involving any hazardous chemicals/reagents for solar cells. In addition, ecologically safe in situ and solution methods have also been applied for the formation of green fullerene based solar cell materials [22]. Among earlier attempts, for instance, Wang et al. [23] applied a solution technique for poly{4,8-bis[(2-ethylhexyl)oxy]benzodithiophene-2,6-diyl-alt-3-fluoro-2-[(2ethylhe xyl) -carbonyl]-thieno[3,4,[3,4-b]thiophene-4,6-diyl}:[6,6]-phenyl C_{71}-butyric acid methyl ester and functional fullerene C_{60} nanocomposites based on indium tin oxide electrodes for bulk heterojunction solar cells. The solar cell device performance was found to improve with an open circuit voltage of up to 0.71 V, a short circuit current density of up to 15.7 $mAcm^{-2}$, and a fill factor of > 67%. Consequently, high power conversion efficiency of > 7% was attained. These results can be credited to better contact between the polymer/C_{60}-modified electrode, leading to facilitated electron transport properties and solar cell performance. In recent years, Elessawy et al. [24] reported on green formation of magnetic fullerene-derived nanocomposites using sustainable plastic bottle wastes of poly(ethylene terephthalate). The resulting nanomaterials can be suggested for dye-sensitized solar cells. Another literature example reported by Sadegh et al. [25] mentioned a solvent-free green in situ route for the formation of polyaniline/Fe_3O_4 nanocomposites for polymer solar cells. The ensuing nanocomposite depicted power conversion efficiency of > 1.5% and short circuit current density of > 4 mA/cm^2. In recent times, Lee et al. [26] used phenyl-C_{61}-butyric acid methyl ester modified with benzothiadiazole functionalities for a bulk heterojunction organic solar cell. The functional fullerene-based hybrid revealed open circuit voltage, current density, and fill factor of 0.989 V, 12.90 mA cm^{-2}, and 56%, respectively. Moreover, significant power conversion efficiency of > 7% was observed. Chung et al. [27] prepared phenyl-C_{61}-butyric acid methyl ester:poly(3,4-ethylenedioxy thiophene)/indium tin oxide-coated glass substrate for bulk heterojunction solar cells. Consequently, current density, fill factor, and power conversion efficiency of ~ 11.3 mA cm^{-2}, 66%, and 4.7%, respectively, were obtained. More recently, Zhichun et al. [28] designed an organic-inorganic fullerene derivative (phenyl C_{61} butyric acid methyl ester) and indium phosphide/zinc sulfide-based hybrid for a bulk heterojunction solar cell. The resulting device had a fill factor of ~ 59% and a power conversion efficiency of ~ 4.2% under 1.5 AM (25 ℃).

As per our analysis, such ecological techniques and fullerene nanomaterials depicted suitable competence to substitute traditional commercially used hazardous inorganic silicon-based solar cell designs. It can be stated that synergistic structure-property associations in precisely designed green polymer/fullerene nanocomposites may play a crucial role in enhancing the solar cell efficiencies of relevant devices. Further, real-world solar cell application and commercialization of green fullerene-based devices rely upon their processing feasibility using ecological techniques, precise nanostructural designs, low cost, and environmental sustainability [29]. **Figure 3** portrays some important real-world applications of solar cells. Nevertheless, practically replacing universally traditional non-green solar cell devices with green fullerene nanomaterials via green routes seems challenging due to lifetime/functional limitations, light/temperature/weather sensitivity, complex functional/degradation mechanisms, and the overall nascent stage of scientific research in this field of fullerene. Despite the success of fullerene in solar cells, it is important to mention competing materials in today’s solar cell devices. To overcome the challenges of high cost and limited stability of fullerene in photovoltaics, non-fullerene acceptors (line Y6, Y7, indene-based compounds, etc.) have been recently focused on in the literature [30]. However, functional fullerene derivatives have been focused on to attain high-performance solar cells compared with any commercially known competing materials.

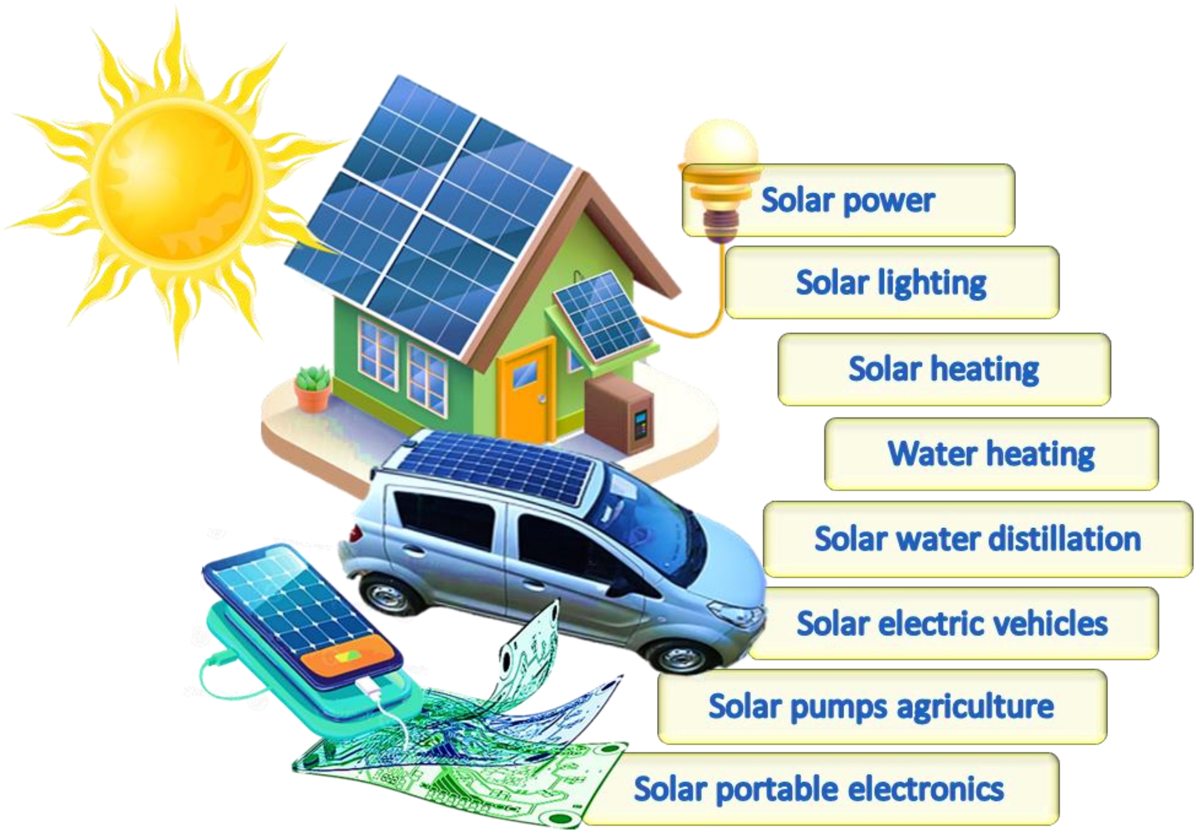

Figure 3. Practical applications of solar cells.

6. Summation

Categorically, this perspective manuscript discusses the evolution of green fullerene technologies in the arenas of solar cell devices/systems. In this, we surveyed a noticeable nanotechnological trend of shifting traditional solar cell energy devices/systems to green fullerene-based devices. Looking at nowadays green energy trends, we can say that the technical worth of fullerene nanomaterials is enormously cumulating in industrial/commercial solar cell marketplaces due to valued low cost, structural/physical features, and power efficiency characteristics. In spite of the scientific progress seen up till now on green fullerene nanomaterials-based solar cells, we suggest indispensable, incessant, ongoing, and future research activities to resolve underlying design/character/performance challenges in order to develop promising next-generation future solar cell devices/systems. In a few words, the key role of fullerene molecules and derived materials has been identified as acceptor or electron transport materials in organic photovoltaics. For future advancement in this field, functional fullerene materials must be designed having superior stability, light absorption, and charge transfer features, thereby leading to superior power conversion efficiencies for long-term functioning photovoltaics. Fullerene research seems to have practical implications for energy markets in the form of organic solar cells and perovskite solar cells, bulk heterojunction solar cells, and inverted polymer solar cells. Particularly, fullerene-based materials have been practically applied as electron transport/acceptor materials to enhance photovoltaics efficiency.

Conflict of interest: The authors declare no conflict of interest.

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