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Nanocarbon Architectures for Sustainable Energy Systems: Graphene, Carbon Nanotubes, and Carbon Quantum Dots in Storage and Conversion Technologies

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Abstract

The shift of the world to carbon-neutral energy systems requires materials with high electrical conductivity, structural robustness, electrochemical stability, scalability, and environmental friendliness all at the same time. Nanocarbon material (such as graphene, carbon nanotubes (CNTs), and carbon quantum dots (CQDs)) has become a transformative material that can fulfil these multi-dimensional needs. Their tuneable electronic properties, high surface to volume ratios, mechanical strength and chemical stability make it possible to incorporate them into the energy storage and energy conversion systems. In this review, the author has critically evaluated and analysed the nanocarbon materials in the context of Lithium-ion and beyond-lithium batteries, supercapacitors, electrocatalysis, photovoltaic systems, and green hydrogen production technologies. It focuses on the correlations among structure and, property and performance, the challenges of scale-up synthesis, sustainability of lifecycle, technological economic viability and future research directions. The paper concludes that nanocarbon-based materials framework with the principles of green chemistry and the strategies of the circular economy can boost the energy transition in the world considerably faster.

Keywords:

Nanocarbon materials, Graphene, Carbon nanotubes, Carbon quantum dots, Energy storage, Green hydrogen, Sustainability, Electrocatalysis.

1. Introduction

The growing demand of energy in the world due to fast industrialization, urbanization and population increase has increased the strain on the available energy systems and natural resources. The energy infrastructures that are in use today are highly reliant on fossil fuels, which include coal, oil and natural gases, which are all associated with a high level of greenhouse emission and environmental pollution. It is well known that further burning of fossil fuels is one of the biggest contributors to climate change that causes global warming, severe weather conditions, and ecological imbalance over the long term. As a result, the scientific community, policy makers, and industrial stakeholders all over the world are paying more attention to the transition to sustainable and carbon-neutral energy systems that are capable of guaranteeing energy security, environmental safety, and economic feasibility at the same time [1,2].

Materials science is a core part of the development of next-generation energy technologies, such as next-generation batteries, supercapacitors, hydrogen production systems, and renewable electricity generation devices. The energy storage and conversion devices require materials with a combination of desirable properties that include; high electrical conductivity, structural strength, chemical stability, large surface area, fast electron transport rate, and being environmentally friendly. All these qualities are difficult to attain in conventional bulk materials at the same time. As such, the study of nanostructured materials has emerged as a key issue in current energy studies [3,5].

The nanocarbon materials have become one of the most promising nanomaterials in energy applications because of their remarkable structural diversity and distinct electronic properties among various families of nanomaterials that have been studied. Carbon can generate a variety of hybridized bonding structures (sp, sp^2, and sp^3) and as a consequence, a large variety of nanostructures with variable physical and chemical properties can be formed. It is worth noting that graphene, carbon nanotubes (CNTs) and carbon quantum dots (CQDs) are three of the most significant groups of nanocarbon architectures, whose dimensional regimes are in the two-dimensional (2D), one-dimensional (1D), and zero-dimensional (0D) classes, respectively [4]. All these collectively offer complementary features which can be harnessed in energy storage and energy conversion technologies.

Graphene is the single layer of sp^2 -hybridized carbon atoms in a hexagonal honeycomb structure that was first experimentally isolated in 2004. It has a very high electrical conductivity, carrier mobilities, thermal conductivity and mechanical strength [3,7]. Graphene has a very high potential theoretical specific surface area (2630 m 2 -1) and therefore presents a great deal of utility in electrochemical energy storage applications as either lithium-ion batteries or supercapacitors and where it is required that the ion adsorption and fast electron movement be optimized. Also, due to the tuneable electronic structure made possible by defect engineering and heteroatom doping (e.g., nitrogen, sulphur, or phosphorus), graphene can be used as an efficient electrochemical catalyst or catalyst support in a wide range of electrochemical processes [8,10].

Another relevant category of nanocarbon substances is carbon nanotubes, which Sumio Iijima first identified in 1991, and they consist of cylindrical sheets of graphene with diameters of the order of nanometers and very high aspect ratios [11]. NTs are highly mechanically strong, highly electrically conductive and highly chemically stable. Their chirality and diameter would make them very dependent in their electronic properties and thus they can either act as metallic or semiconducting material [12,13]. The aforementioned properties render CNTs very useful in conductive networks, electrode structures, and nanocomposite materials in batteries, supercapacitors and fuel cells. Also, CNT networks have the potential to deliver sustained electron-carrying routes and mechanical strengthening to electrochemical systems and enhance the performance and stability of the device [14].

Contrary to graphene and CNTs, carbon quantum dots (CQDs) are the zero-dimensional carbon nanostructures that are typically less than 10 nm in diameter. CQDs have special quantum confinement and edge effects which gives them unique optical and electronic characteristics with a size dependent photoluminescence and tuneable band gaps [15]. They have a lot of functional groups on their surfaces like hydroxyl, carboxyl and amino groups, which contribute to their solubility, chemical reactivity and catalytic activity [16,17]. These qualities allow CQDs to act as an effective charge transfer catalyst, sensitizer and catalytic promoter in energy conversion reactions like photocatalysis, photoelectrochemical water separation and solar energy capture.

Nanocarbon architectures compared to traditional bulk carbon materials (like graphite) have a number of fundamental benefits to electrochemical energy systems. The quantum confinement effects and large surface-to-volume ratio as well as high density of active sites are created by nanoscale dimensions of these materials, leading to increased electrochemical reactivity and charge transport. Surface functionalization and defect engineering can as well provide a fine control over the electronic structures, catalytic activity and interfaces with other materials. It is due to such capabilities that nanocarbon materials have made them very flexible platforms in designing more advanced electrodes, catalyst supports and hybrid nanocomposites in energy storage and conversion technologies [6].

The incorporation of the nanocarbon materials in the storage devices used in energy production had been proven to be significantly enhancing the electrochemical performance. Graphene-based Networks and CNTs can be used in the formation of lithium-ion batteries to increase the electrical conductivity, allow the volume variation during charge-discharge processes, and structural stability of the electrode materials. Likewise, with supercapacitors, the large surface area and network conductive graphene and CNTs allow the fast movement of ion and the high- power density. Hybrid materials that contain CQDs have demonstrated higher capacitance and enhanced charge transfer properties as well because they exhibit special interactions with the host materials of their electronic properties [18,24].

In addition to energy storage, nanocarbon materials are also important in energy conversion technologies, especially in electrocatalytic reactions of the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) that are at the heart of water electrolysis to produce green hydrogen. Graphene and CNTs may be used as very conductive catalyst support to enhance the rate of electron transfer and to enhance catalyst dispersion. In the meantime, heteroatom-doped nanocarbon structures can serve as metal-free electrocatalysts and have a high catalytic activity, which is a cheaper alternative to precious metal catalysts. CQD-based hybrid catalysts have been reported to exhibit promising electrocatalytic activity since they can be easily tuned and have a large number of active sites [25,27].

Besides the electrochemical uses of the nanocarbon materials, there has been a wide application of the nanocarbon materials in photovoltaic systems. Graphene is a promising material to substitute the traditional transparent conducting electrode, including indium tin oxide (ITO) due to its high optical transparency and the electrical conductivity. Equally, CQDs have been exploited as sensitizers or charge transport materials in solar cell architectures that are emerging as the future, and in such applications, they improve light harvesting and charge separation mechanisms [29,31].

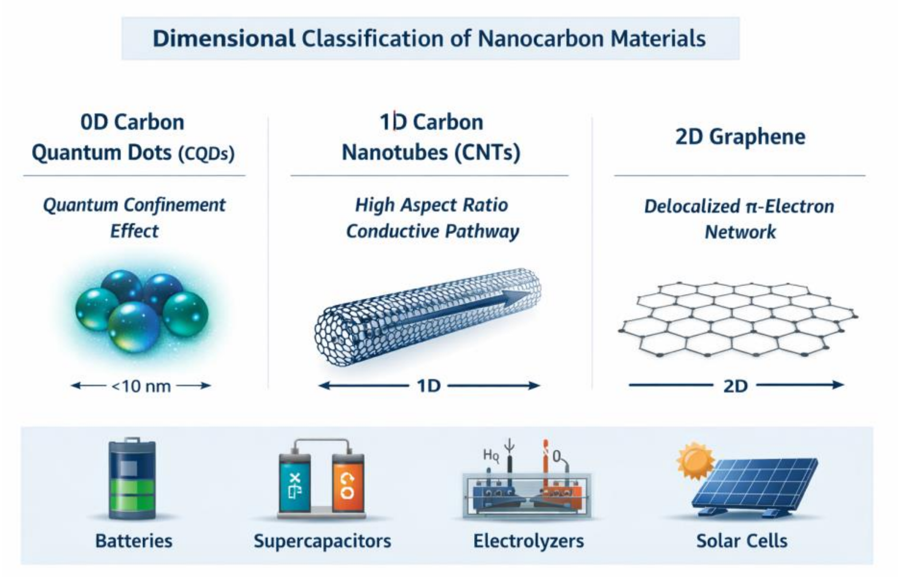
Although this makes the large-scale use of nanocarbon materials in energy technologies very promising, there are numerous challenges that are associated with it. Most of the synthesis processes such as chemical vapor deposition and high temperature graphitization processes are energy intensive processes and may contain chemicals that are harmful to the environment. In addition, concerns of scalability, material reproducibility, lifecycle sustainability, and techno-economic feasibility will have to be considered before nanocarbon technologies can be extensively commercialized [32,37]. Biomass-derived carbon quantum dots and green chemical processing techniques are thus becoming increasingly popular as far as sustainable synthesis methods are concerned.

The convergence of nanotechnology with the principles of green chemistry and circular economy provides the prospective opportunities amid the creation of the environmentally responsible nanocarbon materials. The sustainable approaches in the design of materials focus on renewable feedstocks, energy-efficient synthesis, recyclability and the overall minimum environmental impact of the lifecycle of nanomaterials. Also, new computational methods, such as machine learning and artificial intelligence, are speeding up the discovery and optimization of nanocarbon materials to energy conversion applications by making it possible to quickly predict structure property relationships [38,40].

Thus, nanocarbon structures are an ideal and disruptive platform of the energy systems of the next generation. Their special structural and electronic properties allow to achieve great enhancement of the performance of the energy storage devices, electrocatalytic systems, and renewable energy technologies. This has been critically reviewed in terms of the applications and roles of graphene, carbon nanotubes and carbon quantum dots in sustainable energy storage and conversion technologies. Special attention is given to structure-property-performance correlations, recent developments in the production of nanocarbon materials and their functionalization, sustainability, techno-economic viability, and the future research directions that could hasten the process of achieving sustainable energy in the future made of nanocarbon.

2. Structural and Electronic Characteristics of Nanocarbon Materials

Figure 1: Dimensional classification of nanocarbon materials (0D CQDs, 1D CNTs, 2D Graphene).



2.1 Graphene

The honeycomb structure composed of carbon atoms is the sp^2 -hybridized honeycomb of electronic atoms which gives a remarkable electrical conductivity and carrier mobility in graphene [7]. The material has virtually ballistic electron transport and high tensile strength. It has a theoretical specific surface area (~2630 m 2/g) which improves the ion adsorption in the electrochemical systems [8].

Addition of nitrogen, sulphur or phosphorus as dopants produces localized electronic states, which enhance catalysis [10].

2.2 Carbon Nanotubes (CNTs)

The CNTs have excellent aspect ratios and mechanical strength [11,12]. Electrical properties are chiral, and they affect the semiconducting or metallic behaviour [13]. Multi-walled CNTs are a high-conductive electrode architecture network [14].

2.3 Carbon Quantum Dots (CQDs)

CQDs exhibit quantum confinement and photoluminescence with respect to size [15]. Their water solubility and catalytic amplification are made possible through their surface functional groups [16,17].

3. Nanocarbon Materials in Energy Storage Systems

Figure 2: Role of nanocarbons in energy storage and conversion systems.

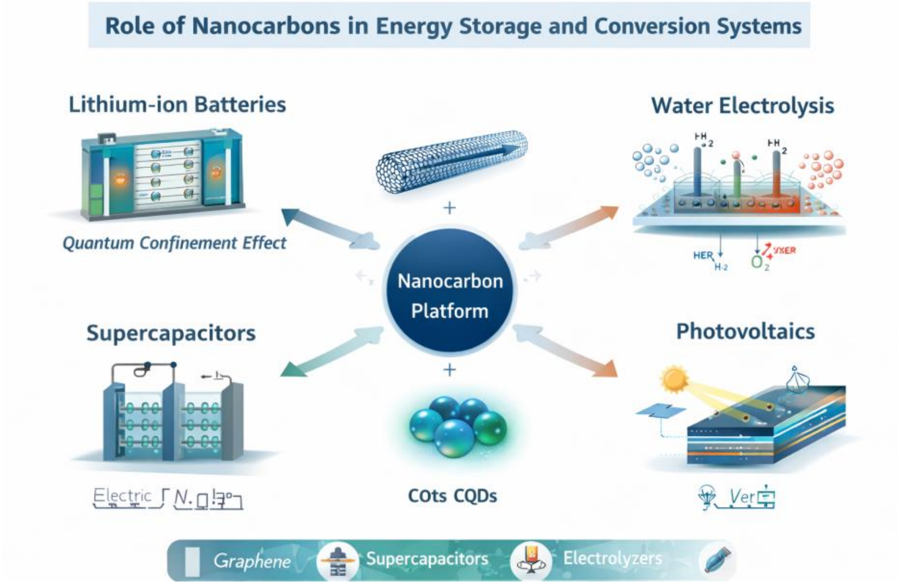
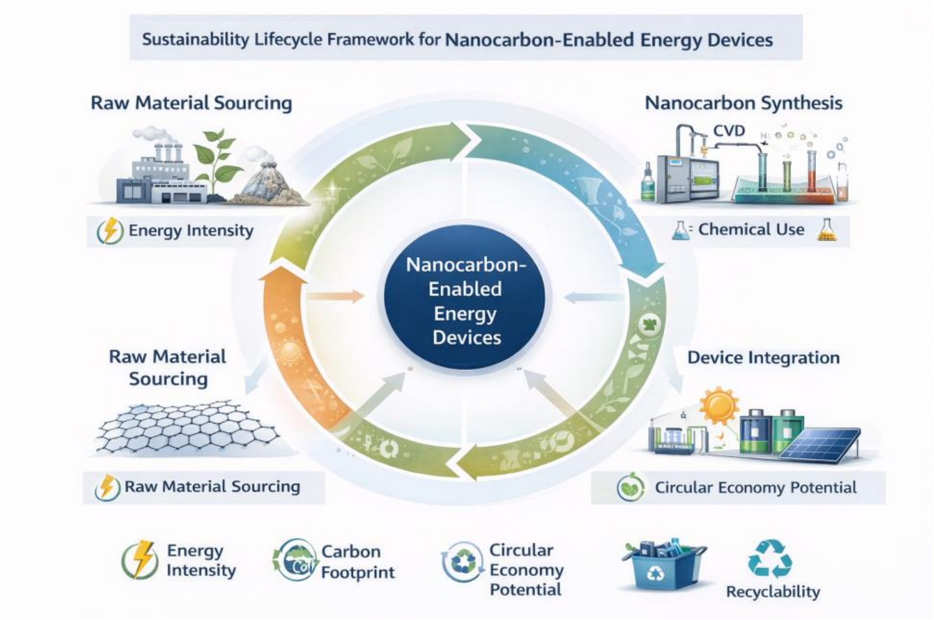


Figure 3: Sustainability lifecycle framework for nanocarbon-enabled energy devices.



3.1 Lithium-Ion Batteries

Graphene electrodes with improved conductivity are made to reduce volume swelling [18,19]. NT structures enhance mechanical strength and electron conduction [20].

Table 1: Comparative Nanocarbon based LIB anodes performance.

Material	Specific Capacity (mAh/g)	Cycle Stability	Key Strength.
Graphene composites	5001000 500 cycles	High-rate capability	High electrical conductivity and excellent rate capability
CNT networks	400800 >700 cycles	Mechanical survivability.	Superior mechanical flexibility and structural survivability
Graphene-Si	>1500 300 cycles	Volume buffering	Effective volume buffering and enhanced lithium storage capacity

3.2 Supercapacitors

Graphene supercapacitors have high power density because they have a fast ion transportation [22,23].

Table 2: Supercapacitor Performance Indicators.

Material	Specific Capacitance (F g^{-1})	Energy Density (Wh kg^{-1})	Cycling Stability
Graphene EDLC	150–300	5–10 (Moderate)	Excellent (>90% retention after 10,000 cycles)
CNT-based Electrodes	100–250	4–8 (Moderate)	High (>85–95% retention over 8,000–15,000 cycles)
CQD Hybrid (Carbon Quantum Dot Hybrid)	250–400	10–20 (Improved)	Stable (>85–90% retention after 5,000–10,000 cycles)

4. Nanocarbon Materials in Energy conversion.

4.1 Green Hydrogen and Electrocatalysis.

Nanocarbons serve as the support of catalysts in the reaction of HER and OER [25,26]. Doping increases the active site density [27].

Table 3: Indicators of Electrocatalytic Performance.

Catalyst	Overpotential @10 mA cm^{-2} (mV)	Tafel Slope (mV dec^{-1})	Stability (Chrono test / Cycling)
N-doped Graphene	<150	60–90	High (≥90% activity retention after 10–20 h operation)
CNT-Supported Metal Nanoparticles	~120	50–80	Excellent (minimal degradation over 20–50 h; >95% retention)
CQD Hybrid Catalyst	<180	70–100	Good (≥85–90% retention after 10–20 h testing)

4.2 Photovoltaics

Graphene transparent electrodes replace indium tin oxide [29]. CQDs enhance visible absorption [30,31].

5. Sustainability and Lifecycle Assessment

Nanocarbon synthesis often involves high energy input [32,33]. Biomass-derived CQDs provide greener alternatives [34].

Sustainable polymeric and biodegradable research efforts support environmentally responsible materials innovation [41,45].

Table 4: Sustainability Comparison

Parameter	Graphene	CNT	CQD
Energy-intensive synthesis	High	High	Moderate
Biomass-derived option	Limited	Limited	Strong
Recyclability	Emerging	Emerging	Promising

6. Techno-Economic Analysis

Large-scale commercialization requires cost reduction [36]. Manufacturing standardization and material reproducibility remain barriers [37]. Machine learning tools accelerate discovery [38]. Policy frameworks emphasize clean energy materials [39,40].

7. Future Research Directions

- Hybrid nanocarbon-biopolymer composites
- Green electrochemical synthesis routes
- Integration in decentralized hydrogen systems
- AI-driven materials optimization

8. Conclusion

Recent publications in nanocarbon architectures that include graphene, carbon nanotubes (CNTs), and carbon quantum dots (CQDs) have been identified as highly promising materials to improving sustainable energy technologies due to their high electrical conductivity, structural stability, tuneable electronic properties, and a high surface area. Their unusual dimensional structures facilitate great advances in energy storing systems such as lithium-ion batteries and supercapacitors, in which they improve charge transportation, structural integrity and electrochemical functionality. Besides this, nanocarbon materials are also useful in energy conversion technology e.g. in electrocatalysis to hydrogen evolution reactions, oxygen evolution reactions, and in photovoltaic systems to enhance the transfer of charges and light gathering efficiency.

Although these benefits exist, there are issues associated with large-scale synthesis, price, reproducibility, and lifecycle sustainability that need to be overcome to use it in a larger industrial scale. The emerging perspectives in the green chemistry and the principles of the circular economy suggest that future studies ought to address green synthesis, use of carbon sources based on biomass and development of manufacturing plans that can be scaled-up. As further material design, hybrid nanocarbon structures, and AI-enabled materials discovery progress, nanocarbon systems will become a key ingredient to a faster global process of efficient, low-carbon, and sustainable energy systems.

References

1. Chu S, Majumdar A. Opportunities and challenges for a sustainable energy future. Nature. 2012;488:294–303. doi:10.1038/nature11475
2. Turner JA. Sustainable hydrogen production. Science. 2004;305:972–974. doi:10.1126/science.1103197
3. Novoselov KS, et al. Electric field effect in atomically thin carbon films. Science. 2004;306:666–669. doi:10.1126/science.1102896
4. Geim AK. Graphene: status and prospects. Science. 2009;324:1530–1534. doi:10.1126/science.1158877
5. Dresselhaus MS, et al. Perspectives on carbon materials. Acc Chem Res. 2013;46:112–123. doi:10.1021/ar300020p
6. Armaroli N, Balzani V. The future of energy supply. Energy Environ Sci. 2011;4:3193–3222. doi:10.1039/C1EE01249E
7. Castro Neto AH, et al. The electronic properties of graphene. Rev Mod Phys. 2009;81:109–162. doi:10.1103/RevModPhys.81.109
8. Stoller MD, Ruoff RS. Best practice methods for graphene. Energy Environ Sci. 2010;3:1294–1301. doi:10.1039/C0EE00074D
9. Li X, et al. Large-area synthesis of graphene. Science. 2009;324:1312–1314. doi:10.1126/science.1171245
10. Wang H, et al. Doped graphene electrocatalysts. ACS Nano. 2012;6:4940–4947. doi:10.1021/nn300687w
11. Iijima S. Helical microtubules of graphitic carbon. Nature. 1991;354:56–58. doi:10.1038/354056a0
12. Dai H. Carbon nanotubes: synthesis and properties. Acc Chem Res. 2002;35:1035–1044. doi:10.1021/ar0101640
13. Avouris P. Molecular electronics with CNTs. Chem Rev. 2002;102:1649–1662. doi:10.1021/cr010329z
14. De Volder MFL, et al. Carbon nanotubes: present and future. Science. 2013;339:535–539. doi:10.1126/science.1222453
15. Baker SN, Baker GA. Luminescent carbon nanodots. Angew Chem Int Ed. 2010;49:6726–6744. doi:10.1002/anie.200906623
16. Lim SY, et al. Carbon quantum dots and applications. Chem Soc Rev. 2015;44:362–381. doi:10.1039/C4CS00269E
17. Sun YP, et al. Quantum-sized carbon dots. J Am Chem Soc. 2006;128:7756–7757. doi:10.1021/ja062677d
18. Yoo E, et al. Graphene-based lithium storage. Nano Lett. 2008;8:2277–2282. doi:10.1021/nl801047t
19. Raccichini R, et al. Graphene for batteries. Nat Mater. 2015;14:271–279. doi:10.1038/nmat4170

20. Zhang Q, et al. CNT electrodes. Energy Environ Sci. 2012;5:8869–8890. doi:10.1039/C2EE22900E

21. Slater MD, et al. Sodium-ion batteries. Adv Funct Mater. 2013;23:947–958. doi:10.1002/adfm.201200691

22. Conway BE. Electrochemical Supercapacitors. Springer; 1999. doi:10.1007/978-1-4757-3058-6

23. Simon P, Gogotsi Y. Materials for supercapacitors. Nat Mater. 2008;7:845–854. doi:10.1038/nmat2297

24. Li H, et al. CQDs in supercapacitors. Energy Environ Sci. 2016;9:2732–2737. doi:10.1039/C6EE01346A

25. Seh ZW, et al. Catalysis for hydrogen evolution. Science. 2017;355:eaad4998. doi:10.1126/science.aad4998

26. Zou X, Zhang Y. Electrocatalysis review. Chem Soc Rev. 2015;44:5148–5180. doi:10.1039/C4CS00448E

27. Qu L, et al. N-doped graphene catalysis. ACS Nano. 2010;4:1321–1326. doi:10.1021/nn901850u

28. Wang Y, et al. CQDs for catalysis. Adv Mater. 2019;31:1808185. doi:10.1002/adma.201808185

29. Bonaccorso F, et al. Graphene photonics. Nat Photonics. 2010;4:611–622. doi:10.1038/nphoton.2010.186

30. Kamat PV. Quantum dot solar cells. J Phys Chem Lett. 2013;4:908–918. doi:10.1021/jz400052r

31. Li X, et al. Photoelectrochemical water splitting. Nano Energy. 2018;50:519–529. doi:10.1016/j.nanoen.2018.05.052

32. Arvidsson R, et al. Environmental assessment graphene. Environ Sci Technol. 2014;48:4529–4536. doi:10.1021/es4053383

33. Keller AA, et al. Environmental implications CNTs. Environ Sci Technol. 2013;47:1309–1317. doi:10.1021/es302971t

34. Sahu S, et al. Biomass carbon dots. Chem Commun. 2012;48:8835–8837. doi:10.1039/C2CC33796G

35. Upadhyayula VKK, et al. Sustainability nanomaterials. ACS Sustain Chem Eng. 2018;6:8364–8373. doi:10.1021/acssuschemeng.7b04748

36. Ferrari AC, et al. Science and technology roadmap graphene. Nanoscale. 2015;7:4598–4810. doi:10.1039/C4NR01600A

37. Xia Y, et al. Nanomaterials energy systems. Energy Environ Sci. 2015;8:1837–1866. doi:10.1039/C5EE00726G

38. Butler KT, et al. Machine learning materials. Nature. 2018;559:547–555. doi:10.1038/s41586-018-0337-2

39. International Energy Agency. Energy Technology Perspectives. 2020. doi:10.1787/ab43a9a5-en

40. Jacobson MZ, et al. Renewable systems roadmap. Energy Environ Sci. 2017;10:2099–2117. doi:10.1039/C7EE01283J

41. Sharma P. Editor and chapter author. *Recent Advances in Green Technology and Sustainable Development*. MGM Publishing House; 2024. ISBN: 978-81-967940-4-0.

42. Sharma P, Singh C, Bagaria A. Synthesis and characterization of ecofriendly and biodegradable soy protein isolate film. J Nano Electron Phys. 2021;13(2):0201.

43. Sharma P, Dhaka S. Isolation and identification of steroids from *Euphorbia hirta*. Int J Sci Technol Res. 2019;8(12).

44. Sharma P, Dhaka S. Antimicrobial study of *Euphorbia hirta* and *Leucas aspera*. Int J Res Anal Rev. 2019;6(2).

45. Sharma P, Dhaka S. Estimation of primary metabolites and antioxidant potential of *Euphorbia hirta* and *Leucas aspera*. Int J Recent Sci Res. 2018;9(1K).