International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Green Chemistry and Human Health: A Sustainable Equation

Dr. Atanu Saha[1], Dr. Piyali Ghosh[2]

[1]Assistant Professor, Post Graduate Department of Physiology, Hooghly Mohsin College, Hooghly, West Bengal, India
[2]Associate Professor, Department of Chemistry, Nabagram Hiralal Paul College, Konnagar, Hooghly, West Bengal, India

Abstract
Scientific and technological advancements have undoubtedly accelerated human development, yet they have also contributed significantly to environmental degradation—manifesting as air and water pollution, climate change, loss of biodiversity, and toxic waste accumulation. Such environmental harm directly threatens human physiology by degrading air quality, contaminating food and water, and increasing exposure to hazardous chemicals that act as endocrine disruptors or contribute to respiratory, cardiovascular, and neurological disorders. Green chemistry has emerged as a vital discipline aimed at minimizing the production and use of toxic substances through sustainable chemical design and processes. The twelve principles of green chemistry focus on the prevention of waste, safer chemical synthesis, renewable resources, and energy efficiency, all of which contribute to protecting human health and preserving ecological balance. Modern research integrates artificial intelligence and green nanotechnology to further optimize these processes, offering cleaner, safer alternatives in fields such as pharmaceuticals, materials science, and environmental remediation. Together, these approaches align with global efforts toward sustainable development by promoting human well-being alongside industrial progress.

Keywords: Green Chemistry, Green Principles, Green Policies, Environmental Sustainability, Nano Materials, Artificial Intelligence

1. Introduction

Scientific and technological advancements have been crucial in driving human progress. However, these achievements often come with unintended consequences that negatively impact the environment. The effects of industrialization and modern development—such as pollution of air and water, global climate change, depletion of the ozone layer, global warming, declining soil health, acidification of oceans, deforestation, biodiversity loss, and the accumulation of toxic waste—have become critical global concerns. In many agriculture-focused nations, large-scale methane emissions and the extensive use of pesticides contribute significantly to environmental degradation. These pollutants not only contaminate the soil and water but also endanger ecosystems, harming both plant and animal life. Likewise, industrialized countries are major emitters of carbon dioxide and various harmful gases, which intensify global warming, damage the ozone layer, and promote smog formation [1].

Petrochemicals, obtained from fossil fuels like petroleum and natural gas, form the backbone of industries that produce plastics, fertilizers, pharmaceuticals, cosmetics, and many other essential goods. Yet, the manufacturing and use of these materials are major contributors to environmental pollution. Thus, economic development driven by agriculture or industry often comes at the cost of environmental integrity—resulting in cleaner air, water, and food becoming scarce, and compromising human health. While nature can persist without human interference, human survival is intricately tied to the health of natural ecosystems. It is therefore crucial to curb the reckless exploitation of natural resources in the name of development and adopt eco-friendly practices [2].

One of the most promising responses to this realization is the rise of *green chemistry*. This field focuses on designing chemical processes and products that minimize or eliminate the creation and use of hazardous substances. Green chemistry, championed by Paul Anastas and John Warner in the early 1990s, gained widespread recognition with their introduction of twelve guiding principles in 1998. These principles provide a framework for advancing chemical practices that are safer, more efficient, and environmentally responsible [3].

Nanotechnology has emerged as a significant area of interest for researchers across chemical, biological, and physical sciences due to the unique properties and versatile applications of nanoparticles. Metals such as silver, gold, platinum, and various metal oxides have been successfully transformed into nanoparticles. A major challenge in nanoparticle synthesis is preventing their aggregation or oxidation, which often requires the use of capping agents, inert environments, or reducing substances. Green nanotechnology addresses this by employing natural, non-toxic agents like polysaccharides, antioxidants, and biopolymers derived from plants, microbes, or other biological sources. These eco-friendly methods not only make nanoparticle production safer but also improve the environmental compatibility of the final products. Researchers continue to explore new ways to synthesize nanoparticles sustainably using extracts and fluids from bacteria, fungi, and algae [4].

Artificial intelligence (AI) has become an increasingly powerful tool in chemistry, including green chemistry. By integrating AI, scientists can design more efficient synthetic routes, identify promising molecules with desired properties, and reduce the environmental impact of chemical processes. Machine learning applications support tasks such as pollution assessment, predicting health impacts from environmental exposure, improving wastewater treatment, developing new biodegradable materials, and evaluating toxicity. AI's role in green chemistry has evolved beyond theory; it is now actively applied in research and industry to promote sustainable innovation. Studies suggest that AI and machine learning have immense potential to reshape green chemistry and engineering, offering smarter, cleaner solutions for the future [5].

2. The Twelve Principles of Green Chemistry

Green chemistry emerged with the goal of creating chemical products and processes that limit or eliminate the creation and use of substances harmful to people or the environment [1,6]. Its guidelines are not restricted to laboratory work — they have influenced sectors like healthcare, farming, and manufacturing, continuously inspiring safer and eco-friendlier chemical innovations.

1. **Waste Prevention:** Focus on designing processes that avoid waste generation rather than managing waste after it forms.
2. **Atom Economy:** Strive for maximum utilization of starting materials in the end product.

3. **Safer Synthesis:** Choose methods that produce little or no harmful substances, reducing risks to health and nature.
4. **Designing Benign Chemicals:** Develop substances that perform their function without being toxic.
5. **Safer Solvents and Additives:** Either avoid or replace hazardous solvents and auxiliary materials with safer options.
6. **Energy Efficiency:** Aim for reactions that proceed at room temperature and standard pressure to minimize energy use.
7. **Renewable Raw Materials:** Where possible, opt for renewable rather than exhaustible feedstocks.
8. **Minimize Derivatization:** Cut down on unnecessary modifications that require extra reagents and create by-products.
9. **Catalysis:** Prefer catalytic processes over those needing large amounts of reagents.
10. **Design for Breakdown:** Ensure products break down into harmless materials after use.
11. **In-Process Monitoring:** Develop real-time analytical tools to detect and prevent pollution during production.
12. **Built-in Safety:** Select substances and conditions that reduce the risk of accidents like fires or explosions.

These principles contribute to cleaner air and water, safer foods, less toxic consumer goods, and lower exposure to harmful chemicals that can disrupt hormones.

3. Chemical Industries and Green Policies

The chemical sector is vital worldwide, supplying key goods like medicines, fertilizers, plastics, coatings, dyes, and fuels. Yet, this industry is also a major source of pollutants affecting our air, water, and soil, linking environmental damage closely to economic progress and public health challenges. To tackle these issues, the chemical sector is increasingly adopting eco-friendly policies and strategies shaped by governments, institutions, and global organizations to curb pollution, support sustainability, and fight climate change [7].

These green shifts depend on partnerships among scientists, industry leaders, and policymakers [8]. Tools like green chemistry metrics have been introduced to measure how efficiently and cleanly chemical processes perform, helping industries track their progress.

In India, the **National Action Plan on Climate Change (NAPCC)**, launched in 2008, sets out eight interconnected missions covering renewable energy, efficient energy use, sustainable cities, water resources, Himalayan ecosystems, forestry, farming, and climate science.

Rising carbon emissions not only contribute to global warming — leading to disasters like glacier melt, flooding, drought, and rising seas — but also directly threaten human health. As a result, stricter limits on pollutants such as CO_2, SO_2, and NO_x are being enforced [9,10]. India's government has signed many international and domestic agreements signaling its dedication to sustainable development [11]. Measures to cut emissions include support for clean energy through subsidies and tax breaks for solar, wind, and hydro power, alongside plans to gradually end fossil fuel use. Green hydrogen is also being promoted as a promising clean energy source [12]. The **Jawaharlal Nehru National Solar Mission**, launched on 11 January 2010 under the NAPCC, is part of these efforts [13].

4. Applications of Green Chemistry in Sustainable Development

In the past two decades, *green chemistry* has evolved into a contemporary and sophisticated concept, fir-

st gaining popularity among chemists in the United States and the United Kingdom. Today, its principles are widely accepted across Europe, Asia, and India. The idea of *sustainable development*, however, dates back further — originating in forest economics, where it meant harvesting only as many trees as could naturally be replaced. The core message of sustainable development is to fulfill current needs without compromising the ability of future generations to meet their own. It promotes the creation of a fair and healthy society that preserves ecological harmony. In the modern industrialized era, protecting natural resources and ecosystems has become more important than ever. The 12 principles of green chemistry play a key role in turning this vision of sustainability into reality [14,15].
Green chemistry supports sustainable development through several vital applications:

4.1 Bio degradable plastic:

These plastics can break down into carbon dioxide (CO_2), methane (CH_4), and microbial biomass through microbial action, whether in oxygen-rich (aerobic) or oxygen-poor (anaerobic) environments. Biopolymers like polylactic acid (PLA), polyhydroxyalkanoates (PHA), polybutylene adipate terephthalate (PBAT), and polybutylene succinate (PBS), typically produced by microbial fermentation, are emerging as eco-friendly alternatives to conventional petroleum-based plastics for packaging [16]. Solving the global plastic pollution crisis requires a multi-faceted strategy that includes prevention, reuse, recycling, recovery, and proper disposal — within which biodegradable plastics play a vital supporting role.

4.2 Environmentally Safer Pharmaceuticals:

Pharmaceuticals have long been central to advancing public health by preventing, treating, and managing diseases — ultimately saving lives and improving well-being. However, their widespread use has sparked concerns about environmental pollution, as improper production, consumption, and disposal can contaminate ecosystems and endanger both environmental and human health. The development of safer and more affordable medicines is being achieved through enzymatic catalysis and the use of renewable raw materials, which helps reduce both toxicity and manufacturing costs. Between 2000 and 2024, 43 studies focusing on *sustainable medicines use* were published, with the United Kingdom, United States, India, Italy, Portugal, and Switzerland leading the way in research and collaboration [17]. A total of 92 institutions have contributed to this growing area of global focus. Greater cooperation between academia, industry, and international agencies is essential to develop practical strategies in this field.

4.3 Green Solvents:

Solvents are crucial to chemical processes, yet many traditional solvents — like acetone, DMSO, DMF, benzene, toluene, and chlorinated compounds — are volatile, flammable, and harmful to plants, animals, and humans. Despite their risks, these solvents remain common in chemical synthesis. Green chemistry aims to reduce reliance on such hazardous solvents by replacing them with safer alternatives that aid sustainable development. Recommended green solvents include water, supercritical fluids, ionic liquids, and non-toxic liquid polymers [18]. Among these, ionic liquids are especially valued for their stability, biodegradability, low vapor pressure, and minimal toxicity.

5. Modern Advances in the Green Synthesis of Nanomaterials

In recent years, research on nanoparticles (NPs) has emerged as a promising and dynamic field across disciplines like physics, chemistry, biology, biomedical sciences, engineering, toxicology, environmental cleanup, and other interdisciplinary areas. Nanoparticles are remarkable due to their unique characteristics — including their size, structure, surface properties, and composition. These materials are widely applied as catalysts, components in electronic devices, biomedical agents, and functional materials in material science. Typically, NPs are synthesized by reducing their precursor ions, and stabilizing agents are crucial to prevent their clumping. Embracing green chemistry principles in nanoparticle synthesis provides an eco-friendly and sustainable approach, producing functional nanomaterials with a minimal environmental footprint. This is achieved by using natural, biodegradable agents — such as plant extracts, sugars, vitamins, or agricultural waste — as reducing and stabilizing substances, which also enhance the biocompatibility of the final products.

Key examples include:

5.1 Raveendran et al. pioneered green nanoparticle synthesis by using D-glucose as a reducing agent and starch as a capping agent to generate starch-stabilized silver nanoparticles (AgNPs) [19].

5.2 Dextran, a polysaccharide mainly made of α-D-glucopyranosyl units, acts as a stabilizer. Dex-EPS (Dextran exopolysaccharide) derived from *Bacillus anthracis* helps stabilize AgNPs during synthesis [20].

5.3 Ascorbic acid (vitamin C), with its antioxidant properties, has been effectively used in producing copper nanoparticles (CuNPs). This antioxidant ability helps protect CuNPs from oxidation, which can easily occur during or after synthesis, especially in the presence of air or water [21].

5.4 Xylan, a major hemicellulose found in plant cell walls, is the second most abundant renewable polysaccharide after cellulose. In a 2% sodium hydroxide solution, xylan serves as a green reducing and stabilizing agent for producing stable and well-dispersed gold nanoparticles (AuNPs) [22].

5.5 Cellulose, a natural biopolymer with β-glycosidic bonds, is employed in alkaline solution (pH 12 at 65°C) for synthesizing silver nanoparticles (AgNPs) [23].

5.6 Palladium nanoparticles (PdNPs), notable for their biocompatibility and stability, can be synthesized in flower-like shapes using ascorbic acid as a reducer and chitosan as a stabilizer [24]. Chitosan, a biodegradable polysaccharide derived from chitin (found in crustacean shells), forms a protective barrier that prevents the aggregation of metal nanoparticles by limiting van der Waals interactions.

6. Artificial Intelligence (AI) and Green Chemistry:

In today's technology-driven world, AI is more than just a tool — it's transforming how we address sustainability challenges. AI is becoming a key contributor to green chemistry and environmental science.

6.1 Chemical industries and AI:

AI applications in chemistry mainly aim at technical progress [25]. Though AI holds great promise for advancing sustainability, its use comes with certain challenges that need careful planning. For industries aiming to shift from traditional processes to AI-powered operations, clear strategies are necessary to understand how various AI technologies impact sustainability indicators. A review by **Liao et al.** examined 63 studies exploring how AI adoption influences sustainability in the chemical sector [26].

6.2 Water treatment and AI:

Machine learning models, including multivariate regression, have been applied to predict water quality in large-scale wastewater treatment systems, monitoring parameters like total phosphorus, nitrogen, and suspended solids [27,28].

6.3 Surface chemistry and AI:
In green catalysis and surface chemistry, AI tools assist researchers in analyzing catalyst properties (e.g., phase, porosity, surface area, conductivity) and in determining the best reaction conditions — such as temperature, pressure, solvent, or support material — for environmentally friendly processes. Machine learning has also deepened our understanding of adsorption in surface science [29].

6.4 Pharmaceuticals And AI:
AI is increasingly used to predict **chemical biodegradability**. Reliable environmental degradation data is vital for building such models [30]. These models help assess the environmental fate, breakdown rates, and degradation pathways of chemicals [31]. Well-known databases like **BIODEG** and **MITI-I** provide essential data for these AI systems [32]. In **drug discovery and design**, AI combined with green chemistry principles is revolutionizing the search for affordable, effective, and sustainable medicines. AI supports tasks like data analysis, predicting molecular interactions, optimizing drug structures, and identifying promising drug candidates — all while ensuring eco-friendly production methods [33-35].

7. Green Environment-Related Laws and Constitutional Provisions in India

India has developed a strong legal and constitutional framework aimed at safeguarding the environment and promoting sustainable development. These laws and provisions are designed to conserve natural resources, prevent pollution, and protect biodiversity (Government of India, *Environment (Protection) Act*, 1986).

Key Green Environment Laws

- **Environment (Protection) Act, 1986:** A comprehensive laws empowering the central government to protect and improve environmental quality and control of the pollution.
- **Forest (Conservation) Act, 1980:** Regulates deforestation and ensures land of the forest is not diverted for non-forest purposes without central approval.
- **Wildlife (Protection) Act, 1972:** Act protecting the wildlife and their habitats by establishing national parks, sanctuaries, etc.
- **Water (Prevention and Control of Pollution) Act, 1974:** This is to prevent and control water pollution through Pollution Control Boards.
- **Air (Prevention and Control of Pollution) Act, 1981:** Aims to reduce and prevent air pollution from various sources.
- **Biological Diversity Act, 2002:** Promotes conservation of biodiversity and protects traditional knowledge.
- **National Green Tribunal (NGT) Act, 2010:** Provides for speedy resolution of environmental disputes.[36,37]

Constitutional Provisions

Article 48A (Directive Principles of State Policy)
"The State shall endeavour to protect and improve the environment and to safeguard the forests and wildlife of the country."
Article 51A(g) (Fundamental Duties)*"It shall be the duty of every citizen of India to protect and improve the natural environment including forests, lakes, rivers and wildlife, and to have compassion for living creatures."* [36,37] India's legal framework, supported by constitutional provisions like

Articles 48A and 51A(g), reflects the nation's commitment to environmental protection. Together, these ensure both the government and citizens play active roles in conserving nature for future generations.

Conclusion

Green chemistry stands as a crucial scientific response to the environmental and physiological challenges posed by traditional chemical industries and modern technological growth. By prioritizing the design of safer chemicals, renewable feedstocks, and energy-efficient processes, green chemistry protects human health from harmful exposures and fosters a cleaner, more sustainable environment. Its applications—from biodegradable plastics to eco-friendly pharmaceuticals and green solvents—demonstrate tangible benefits for both people and the planet. The integration of artificial intelligence and green nanotechnology offers new pathways for innovation, enabling smarter, more effective solutions to pressing environmental and health concerns. As we advance toward sustainable development, adopting green chemistry principles is not just a scientific necessity but a moral imperative to safeguard human physiology and ensure the well-being of future generations.

References

1. Anastas P, Williamson T., *Green chemistry-designing chemistry for the environment*, American Chemical Society (1996).
2. Horváth IT, Anastas PT, *New Haven*, CT, USA: ACS Publications (2007).
3. Carpenter, K., *ACS Sustainable Chem. Eng.*, **9**, 12729 (2021).
4. Gour A. & Jaim. K.N., *Artificial Cells, Nanomedicine, and Biotechnology*, **47**, 844 (2019).
5. Hardian R., Liang Z, Zhang X. & Szekely G., *Green Chemistry*, **22**, 7521(2020).
6. Anastas P, Eghbali N., *Chem Soc Rev.*, **39**, 12 (2010).
7. Brunnermeie S. B. & Cohen M. A., *Journal of Environmental Economics and Management*, **45**, 278 (2003).
8. Scott R Milliman S. R. & Prince R., *Journal of Environmental Economics and Management*, 17, 247 (1989).
9. Konar S. & Cohen m. A., *Journal of Environmental Economics and Management*, **32**, 109 (1997).
10. Jorgenson D. W. & Wilcoxen P.J., *RAND Journal of Economics*, 21, 314 (1990).
11. Manigandan P et al., *Resources Policy*, **90** (2024).
12. Gupta S., Kumar R. & Kumar A., *International Journal of Hydrogen Energy*, **50**, 226 (2024).
13. Kapoor K. et al., *Renewable and Sustainable Energy Reviews*, **40**, 475 (2014).
14. Falcone P. M. & Hiete M., *Current Opinion in Green and Sustainable Chemistry*, **19**, 66 (2019).
15. Yang J. et al., *Science of The Total Environment*, **830**, 154787 (2022).
16. Flury M. & Narayan R., *Current Opinion in Green and Sustainable Chemistry*, **30**, 100490 (2021).
17. Jairoun A. A. et al., *Exploratory Research in Clinical and Social Pharmacy*, **17**, 100576 (2025).
18. Nanda B. et al., *Materialstoday Proceedings*, **47**, 1234 (2021).
19. Raveendran P., Fu J. & Wallen S. L., *J Am Chem Soc.*, **125**, 1 (2003).
20. Banerjee A., Das D., Andler R. & Bandopadhyay R., *J Polym Environ.*, **29**, 1 (2021).
21. Ghobashy M. M. & Mohamed T. M., *J Inorg Organomet Polym Mater*, **28**, 2297 (2018).
22. Feng X. et al., *J of Colloid Interface Sci.*, **607**, 22 (2022).
23. Heidari H & Karbalaee M., *Appl Organomet Chem.*, **33**, e5070 (2019).
24. Phan T.T. V. et al., *Carbohydr Polym.*, **205**, 52 (2019).

25. A. van Wynsberghe, *AI Ethics*, **1**, 213 (2021).
26. M. Liao, K. Lan, Y. Yao, *J. Ind. Ecol.*, **26**, 164 (2021).
27. Nourani V., Elkiran G., Water Science & Technology, **78**, 2064 (2018).
28. Malviya A & Jaspal D., *Environmental Technology Reviews*, **10**, 177 (2021).
29. Roberts J., Bursten J. R. & Risko C., *Chem. Mater*., **33**, 6589 (2021).
30. Howard, P.H., *Environ. Toxicol., Chem,.* **19**, 527 (2000).
31. Cowan, C. E., Federle T. W., Larson, R. J. & Feijtel, T. C. J., *SAR QSAR Environ. Res*., **5**, 37 (1996).
32. Howard, P.H et al., *Environ. Toxicol. Chem*., **5**, 977 (1986).
33. Blanco-González A. et al., *Pharmaceuticals*, **16**, 891 (2023).
34. Hasselgren C. & Oprea T. I., *Annual Review of Pharmacology And Toxicology*, 64, 527 (2024).
35. Bentwich I., *Pharma's bio-AI revolution. Drug Discov. Today.*, **28**:5103515 (2023).
36. Government of India. (1986). The Environment (Protection) Act, 1986.
37. Government of India. The Constitution of India.