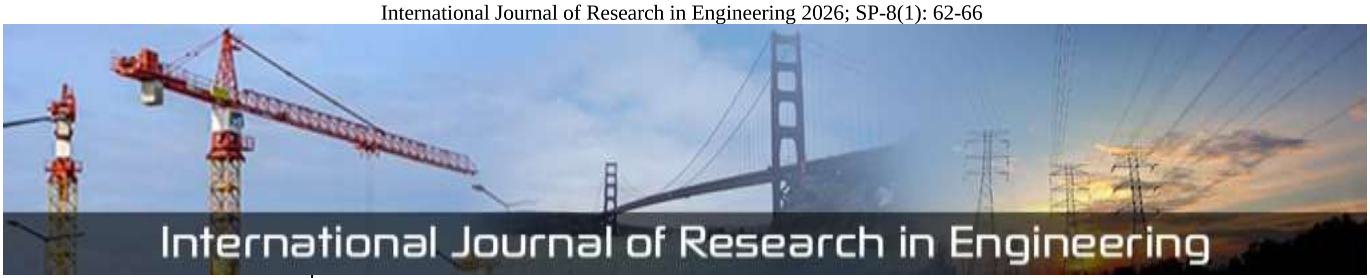

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Green and sustainable chemistry: Educating for environmentally benign scientific practice

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Abstract
To tackle intercontinental environmental obstacles, the incorporation of principles of sustainable chemistry into educational curricula is required. This fusion is mandatory for boosting a new generation of scientists qualified to attain scientific and technological breakthroughs along with maintaining contemporary environmental responsibility and ecological sustainability. In this framework, the methoding methodological blueprint of education of sustainable chemistry and education of green chemistry have evolved as areas of vigorous inspection and functional application, experiencing a remarkable acceleration in growth in modern period. Though, marked inconsistencies remain in extensively realization realizing the historical framework of green chemistry (GC) and sustainable chemistry (SC), their prominent overlap, as well as accomplishment of such knowledge for educational program formation building upon established scheme, persistent, multi-level pedagogical programs are essential for coherent integration of GC and SC into chemical science and associated fields. This incorporation mandates the comprehensive collection and propagation of authenticated practices, along with the establishment of increased cooperative paradigm across global, national, and regional scales. This study will analyze coincident strategy to capacity building and science education metamorphosis towards environmental benign chemical science, highlighting their role in adapting anthropological infrastructural and institutional abilities across sectors. These review paper focus to implement scientific knowledge for formation of environmental green friendly derivatives and processes in an developing intercontinental landscape.

Keywords: Sustainable chemistry, green chemistry, technological breakthroughs, environment friendly derivatives

Introduction
A detailed knowledge of the chronological progression and philosophical understanding of Sustainable Chemistry (SC) and Green Chemistry (GC) is necessary for dealing with their academic dimensions and ramification for specialized chemical practices. Testimony from expertise indicates highlights that a large number of scholars, especially emerging professional technologist, contain limited familiarity to the elementary advancement to these framework or to their wider authority on the design, administration and estimation of processes, services, technologies and products focused at upgrading sustainability within chemistry. Accordingly, a comprehensive description of these theories is represented to construct a shared blueprint for more thorough and informed analysis on this subject. Despite, the paramount characteristics and reactions of substances are managed by fixed physical laws, the persistence of which chemical products and processes are tailed for social implementation includes moral judgments about required functionalities and the feasibility of related risks or unexpected outcome from environmental, economic and ethical perspective. This regulative parameters highlights the requirement for crucial decision making in chemical science, as it affect which methodology, ingredients and apparatus are evolved and opted within industrial practice. Rigorous analysis of these value-laden judgments is important for accelerating the favourable societal impacts of chemical science and for directing its responsible innovation. Education plays a leading role in this process by empowering practitioners to understand engagement of sustainability in chemistry [1].

1.1 Green Chemistry
Green chemistry cultivated in acknowledgement to the influential ecological and population health effect connected with traditional chemical procedures, which became amplifying witnessed in the late 20th century as related to pollution, hazardousness, and resource diminishment gained significance in scientific discussion and policy-framing [2]. As per Pollution Prevention Act reorientation of environmental protocol toward pollution bypassing through upgraded process layout, a collective attempts among government, industry, and academic organizations extended the theory of green chemistry from a legislative regime to an experimentation-driven perspective [3].

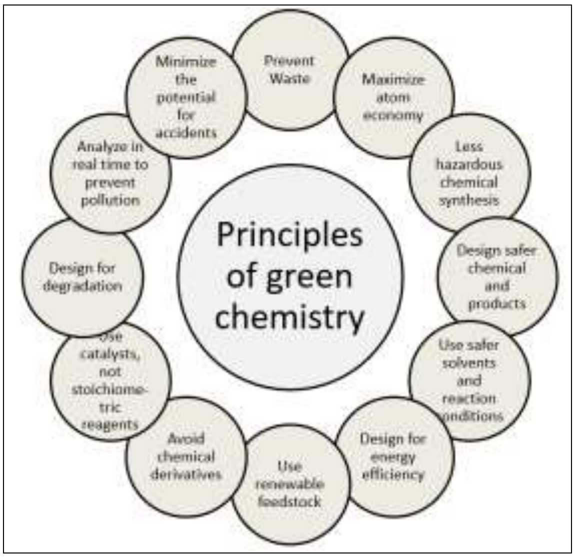

Fig 1: Principles of green chemistry

Figure 1 shows the 12 principles of green chemistry which promote safer, eco-friendly chemical practices by reducing waste and minimizing environmental impact. They encourage the use of renewable resources, energy-efficient methods and safer materials in chemical processes.
The Twelve Principles of Green Chemical sciences provide a systematic blueprint for the design of chemical products and mechanisms that diminish environmental consequences while optimizing safety and productivity. These principles emphasize the safeguarding of trash generation rather than its succeeding treatment and recommend for amplifying atom economy to ensure efficient integration of reactants into the terminal product. They accentuate the selection of less hazardous reagents and the synthesis of fundamentally safer and reduced-toxicity compounds. The paradigm further motivates trimming the use of hazardous dissolving agents and supplementary substances and upgrading energy efficacy by performing reactions under optimum temperature and pressure whenever required. It boosts the utilization of renewable precursors and undermines unnecessary adjustment steps to constraint waste generation. The deployment of catalyst-driven reactions is prescribed due to their capability to enhance reaction competence and diminish reagent demand. Furthermore, chemical products should be designed to endure degradation into chemical free, environmentally synergistic substances after their planned use. The consolidation of real-time analytical and supervising methods is crucial to prevent pollutant creation during synthesis. Broadly, the principles highlights the integration of essential safety measures in chemical processes to reduce risks associated with blowouts, fires, and the emission of hazardous materials [4].

1.2 Sustainable Chemistry
Sustainable chemistry (SC) emerged in the 1990s as an extensive theory than green chemistry (GC), targeting not only on decontaminating chemical manufacturing but also on the whole development stages of products and their responsibility in society. While GC aspires to design chemicals and processes that mitigate pollution, SC integrates chemistry with broader ecological, financial and social sustainability goals. Enterprises like OECD and UNEP have funded environmental chemistry as part of planetary efforts such as the sustainable chemistry goals and sound chemicals supervision [5, 6]. Eco-friendly chemistry prioritizes avoiding precarious substances, using regenerative resources, reducing environmental impacts and supporting advancement and economic advantages. However, regardless these initiatives, globalized pollution and resource use continue to flourish, showing that green chemistry and sustainable chemistry alone are not sufficient. Renewable chemistry therefore requires a more comprehensive, systems-based approach that considers morality, new business prototypes and total product flows. Although clean chemistry is an essential component of environment benign chemistry, it does not cover dilemmas such as replenishable resource trade-offs, social outcomes or long-term environmental stewardship. As a result, green and sustainable chemistry are often integrated today, but eco-friendly chemistry remains the broader, more detailed blueprint for guiding chemistry toward responsible development [7-9].

Fig 2: Major technical focus areas of sustainable chemistry (OECD)

Fig 2 states that sustainable chemistry concentrates on using recyclable and biodegradable materials, choosing safer solvents and reaction parameters, and fabricating processes that harness less energy and generate diminished waste. It also encompasses creating chemicals that are minor toxic to mankind and the atmosphere while still working productively [10].

2. Firms Opting Green and Sustainable Chemistry
Hill *et al*. (2013) features that chemical organizations are sophisticated systems with many integrated sustainability attributes. Estimating whether a mechanism is "green" is difficult because the principles of green chemistry deprive clear weighting and breakpoints, and even processes that meet them may not be sustainable—chemical conflict agents being a incendiary example. While green chemistry concentrates mainly on output, sustainable chemistry accommodates atmosphere, social, and financial factors, requiring multidisciplinary evaluation. This put forward broader question, such as whether biomass consumption for chemicals and biofuels is legitimately sustainable, whether carbon dioxide reductions from composite-based cars surpass the impacts of creating and recycling these substances, and how resource flows for renewable energy

foundations can be redesigned to refine efficiency and bypass new resource tussle [11-13].

Fig 3: Structure of chemical enterprise towards sustainability

Figure 3 depicts the distinctive parts of a chemical association that affect sustainability. It pinnacles how chemicals are crafted, utilized, and handled, including products, mechanism, and raw materials. It also includes significant consideration like security, waste discarding, and reducing or reusing substances. Environmental areas such as energy consumption, water utilization, and overall sustainability impact are illustrated as well. Education and research promote all these efforts to develop chemical industries safer and further environmentally benign [14].

3. From traditional chemistry to green chemistry education, finally to sustainable chemistry education

Chemistry education accustomed to pay minimal consideration to toxicology or ecological protection, but this modified in the final decades of 20th century as pollution and chemical liabilities became more precise. New fields like atmospheric chemistry and environmental risk assessment appeared, and many countries started modifying their chemistry academic progress. By 1997, the first research degree programs in green chemistry was initiated, and in the early 2000s clean chemistry ideas disperse widely, especially in the United States. Today, many organizations teach aspects of green chemical sciences, supported by enterprises, governments, and voluntary organizations. Freshly, some universities have augmented the idea into sustainable chemistry education, which goes beyond the 12 principles of clean chemical sciences. However, environmental benign chemistry is less common than green chemistry, and terms like sustainable green chemical sciences are often used without defining these methodologies. Understanding their unique histories can help show how sustainable chemistry education offers a wider view that incorporates various aspects of sustainability [15, 16].

3.1 Green and sustainable chemical science in a broader aspect of educational enterprises curricula

The consolidation of Green and Sustainable Chemistry into education is amplifying across senior high school, university, and certification program. Many research organizations recently opt Green Chemistry Education and Sustainable Chemistry development to assist this shift. New tutoring tools and resources are being established to help showcase clean, eco-friendly chemistry and basic toxicology even at premature grade strata. This development reflects a escalating global obligation to sustainability-directed science mentoring. The UNESCO Decade of Education for Sustainable Development further intensified the development of innovative and environmental chemistry based learning materials for pursuer of knowledge [17].

3.2 Educational breakthroughs progressing unevenly globally

Academic fascination in Green Chemistry Education and Ecological Chemistry Education is gradually expanding, supported by intercontinental conferences and new customized journals. These agendas are being incorporated into university tutoring through committed courses, summer schools, and organized contents added to conventional subjects such as organic synthesis. Some firms now offer full Green chemistry-focused research trajectories and Master's programs, often developed in collaboration with industry. A remarkable example is a clean chemistry-based organic experimentation centre course from Germany that has been greatly adopted. Pioneering progress was focused in developed countries, but collaboration is now growing in developing and growing economies such as China, Brazil, Indonesia, and India. Since 1998, the literature on Green and Sustainable chemical science tutoring has expanded to greater than 520 publications. These studies investigate curriculum innovation, judgement of student learning, and the utilization of multidimensional sustainability benchmarks [18].

3.3 Varied strategies and continual reforms in sustainable chemistry education

Education in Green Chemistry and Sustainable Chemistry varies across organizations; with diverge mentoring methods and resources used to articulate key ideas. These efforts are commencement to influence behaviours within associations, universities, and educator certification program. As a result, there is growing interest in reframing these curricula to accommodate societal perspectives and promote systems referring for sophisticated sustainability challenges [19].

3.4 Capacity of current clean chemical sciences networks

Consolidating the global leverage of Green Chemistry Education and Sustainable Chemistry Education requires coordinated, cross-national, and multi-sector collaboration supported by shared goals and effective tutoring practices. This involves capitalizing existing networks at country-wide, provincial, and universal levels and bringing together key visionaries and entrepreneurs in the field. Building strong collaborations and educator infrastructure is essential for integrating these phenomenons into mainstream education internationally [20].

4. Overcoming Barriers: Key Determinants For Effective Educational Reform

4.1Advancing instructional practices in green sciences

Many progressing countries struggle to embrace Green Chemistry Education because current coursework give little attention to sustainability. This limits students' understanding of chemical life span and environmental consequences. A major challenge is the inadequacy of professionals trained in green and sustainable chemistry. Academic systems also give precedence publishing research over refining teaching programs. Language barriers make it difficult to acquire global scientific supplies. Fortifying training in chemical synthesis and using Green Chemistry principles from the start is critically needed to reduce environmental detriment [21].

4.2 Convergence of policy, science and industry
Blending Green and Sustainable Chemistry across all educational and professional levels is essential to connect chemistry, product layout, and eco-friendliness. Training mentors and lecturers is especially important because they affect future professionals. Embedding these concepts across fields such as law, business, engineering, and public governance can shape strategy and financial decisions. Some programs promote green management, but they often lack strong associations to chemical principles. Strengthening this link is indispensable to fully assist sustainable practices [22, 23].

4.3 Rising industrial demand for chemists
Broadening Green and Sustainable Chemistry education across all levels of knowledge acquisition is essential for connecting chemical expertise with product design and sustainability goals. Training teachers and professors is especially significant because they shape the skills and realization of future professionals. Integrating these concepts into fields exceeding science can strengthen strategy and financial decisions. Some specialist programs already accentuate green management, but they often lack a connection to the fundamental chemistry. Bridging this gap is crucial for fully incorporating sustainability into material and product advancement [24].

4.4 Addressing systemic resistance
Ubiquitous acceptance of Green and Sustainable Chemistry requires educating all community-based stakeholders, from manufacturer to end-user and advocacy groups. Passionate educators alone are not enough; curriculum development needs support from external collaborators. These groups can provide case studies, pedagogical resources, and other essential resources. Professional organizations already offer precious materials to aid execution. Encouragements are crucial to ensure continued adoption and prolonged sustainability of clean and ecological science schemes [25].

4.5 Productive scientific outlooks
A more comprehensive form of Green Chemistry education is needed to incorporate chemistry with anthropology and economics, giving students a more lucid understanding of chemistry's social and commercial roles. This strategy recognizes that chemistry must transform to support sustainability and that students need both scientific knowledge and consciousness of socio-environmental consequences. Starting with extensive questions such as whether a material is sincerely more sustainable—helps introduce historical, principled, and social dimensions alongside scientific material. Certain case studies, demonstrate these connections. Courses that include circular resources, policy, and systems thinking enable students to move beyond linear viewpoint. Such programs teach learners to evaluate products and processes using clear sustainability indicators. This situational and critical model enables future chemists to judge chemical and non-chemical substitute effectively [26, 27].

5. Conclusion
Sustainable Chemistry Education is important for multinational sustainable development, yet it is still not highlighted enough in schools and institutions. It can reinforce capacity building by blending Green Chemistry and Sustainable Chemistry concepts across all tiers of education. Programs should demonstrate regional conditions, including culture, available resources, and technological needs, and show both the benefits and obstacles of chemical products. Coaching for teachers and persistent professional development are essential, as are links with disciplines like economics, law, social sciences, and the humanities. Eco friendly science education also depends on multinational cooperation, sharing successful practices, and synchronizing with global initiatives such as UNESCO's Education for Sustainable Development. Collaboration among industry, research, and civil society can support the inclusion of GC and SC in education and specialist training. Recognizing the value of education in sustainable chemistry and creating incentives for these efforts will help construct more sustainable societies [28].

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