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REVIEW ARTICLE

Recent Developments in the 12 Principles of Green Chemistry: A review of advancements in applications and metrics

Harsh Bhardwaj
Department of Chemistry, Parishkar College of Global Excellence (Autonomous), Rajasthan
Gmail: Harsh.bhardwaj0705@gmail.com

ABSTRACT

Green chemistry is one of the revolutionary changes in the face of chemical process design and execution, where the focus is laid on the minimisation of hazardous products, efficient utilisation of materials, and the creation of sustainable alternatives to other existing methods. Based on the 12 principles of green chemistry, it attempts to reduce waste, energy use and toxicity and increase safety, renewability and efficiency. The review also discusses events in the field recently and also looks at the benefits together with the shortcomings of the application of green chemistry in both industrial and academic arenas. Some examples of the great advantages are the integration of renewable feedstocks, safer solvents, recyclable catalysts, and energy-efficient technologies that have already replaced parts in fields like pharmaceuticals, agriculture, materials and energy. Nevertheless, there are still difficulties associated with high costs of implementation and technical barriers to scalability, as well as the lack of universally harmonised evaluation measures. Environmental performance metrics like atom economy, E-factor, process mass intensity, life cycle assessment and the analytical eco scale are discussed as important means to evaluate environmental performance and inform greener practice but differ in their application by industry. These principles can be efficiently applied to the real world and illustrate the practical importance of these ideas in practice, as well as reveal that it is complicated to make all the things economically feasible and environmentally responsible. A related frontier is green chemistry within the context of broader sustainability and circular economy models and safe-and-sustainable-by-design processes. Education, policies and support will also play a significant part in training scientists and industries to think and develop innovations to overcome sustainability issues through system thinking. In unending times, green chemistry can be positioned as one of the main pillars of sustainable growth, as sustainable chemistry provides both opportunities and challenges as the world shifts to more robust and nature-friendly chemistries.

Keywords: *Green chemistry, sustainability, atom economy, circular economy, life cycle assessment, renewable feedstocks, friendly processes.*

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INTRODUCTION

Green chemistry is a new way of looking at chemistry, aiming to make chemistry safer, cleaner and more sustainable. Green chemistry solves a problem by trying to avoid creating pollutants rather than cleaning up pollution after it occurs. This notion has developed in the last 30 years and has become known as a real solution to the preservation of the environment, human health, and the development industry towards the most efficient and environmentally friendly way [1].

The popularity of the term 'green chemistry' in the late 1990s was driven by programmes directed by the U.S. Environmental Protection Agency in the reduction of chemical waste and pollution. As Krasnodębski [21] states, similar concepts were already being developed on the European continent, as scientists and policymakers were already searching for the techniques of sustainable and safer methodologies of chemicals. This indicates that green chemistry did not have an origin but is a global movement across common concerns of pollution, toxic chemicals and the excessive use of natural resources.

In 1998, Paul Anastas and John Warner developed the 12 Principles of Green Chemistry that made the field more systematic. All these principles are applicable to scientists and industries, and they include aspects like avoiding waste, resources with renewable alternatives, enhanced energy efficiency, safe product design, and less toxic versions of products [2]. Most of these were already in practice in a sense. A good example is that researchers such as Barry Trost and Roger Sheldon had been advocating the atom economy and quantifying waste since well before the principles were codified [31]. The book encouraged integrating these practices into one system and could be taught, developed and used in industries all over the world.

Chemical manufacturing is one of the most resource-intensive industries, and it is also key to clean energy, health care, and environmentally sustainable materials. Green chemistry is one way of filling this gap by giving the means to make chemical production safer and more efficient. As an example, scientists have demonstrated how plant-derived carbohydrates could be converted to useful renewable chemicals through a catalytic process that is low-energy demanding and minimises waste [11]. This shows that various principles can be used concomitantly in achieving more green approaches, such as atom economy, catalysis and renewable feedstocks.
The realities of the impacts of green chemistry are evidenced in numerous ways. In the drug industry, it has contributed to effective and clean drug production [19]. One of the 12 principles was satisfied closely by the mechanochemistry, as it operates with avoidance of harmful solvents [4]. In other areas of interest, techniques such as micellar catalysis are under examination, and although the science remains controversial, it is overall considered a green process [5]. Outside of drugs and chemicals, green chemistry is being implemented into food science and packaging to minimise waste products and increase sustainability on a day-to-day scale [6].
One of the most potential outputs of green chemistry is that it saves the industries money along with ensuring that the environment is not harmed. Companies can save on raw materials, reduce the consumed energy demand, and diminish wastage to both become more profitable and more environmentally friendly [7].
Nevertheless, there are still problems. There are also new technologies such as new catalysts and mechanochemical processes that are yet to overcome the challenges associated with scaling up to an industrial level [8]. It has also been theorised that an increased scope should be incorporated into the field, which is the social and ethical consequences, so that green chemistry does not only resolve technical issues but environmental sustainability issues on a larger scale [9].
This review will comment on the advances achieved in the context of the 12 principles of green chemistry. It will feature new directions in synthesis, catalysis, sustainable materials, and analysis, and ways in which the industry, educators, and policymakers are integrating them. This way the paper renders the potential greenness of the 12 principles of green chemistry despite the fact that they continue to spearhead a greener future in which chemistry is one of the contributors to human life and environmental welfare.

THE 12 PRINCIPLES OF GREEN CHEMISTRY: DESCRIPTION AND IMPORTANCE

The 12 Principles of Green Chemistry, suggested by Anastas and Warner, offer a guiding approach to designing chemical processes and products so that they create higher environmental sustainability, safety and efficiency. These values reflect a change in the historical approach, in which the primary aim was productivity and a disregard for environmental harmony, to one that aims at being eco-friendly (Zimmerman et al., 2020). All the principles present extremely important and challenging points towards minimising risks, minimising resources, and enhancing sustainability in the chemical sciences.

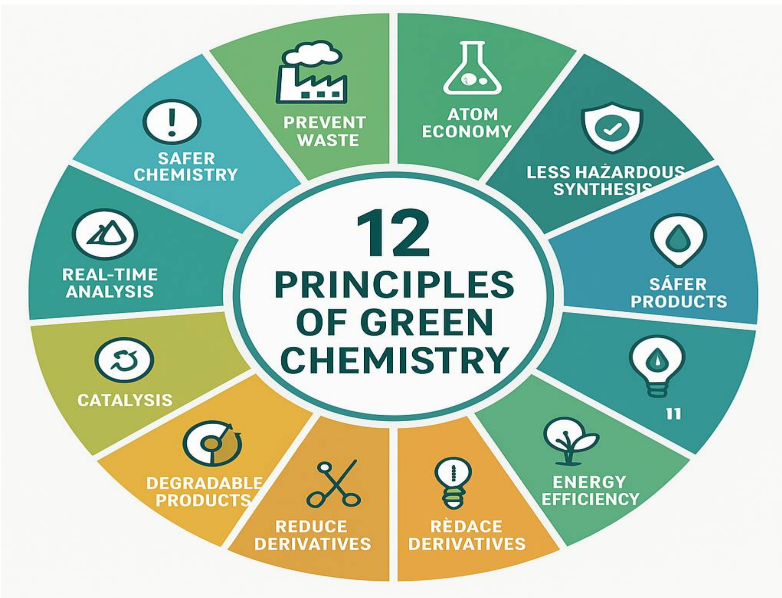

Fig.: The 12 Principles of Green Chemistry

THE 12 PRINCIPLES AND THEIR APPLICATIONS

The prevention principle means that it would be more appropriate to prevent the formation of waste rather than to clean it after its formation. Industries can minimise waste generation and subsequent environmental pollution as well as the high expenses spent on managing waste [10].

Another aspect of atom economy that can be used is to motivate the synthesis of methods where the vast majority (if not all) of starting materials are built into the final product. This is particularly pertinent in pharmaceutical and fine chemical sectors, where it is crucial to be resource efficient in the production sphere of the sector [11].

Less hazardous synthetic methods Less hazardous chemical processes encourage the adoption of innovations in an endeavour to introduce procedures that cause little or no harm to the human and the environment due to toxicity. This minimises not only the risks faced by industrial workers but also their consumers and the ecosystems to which such chemical products are exposed [12].

Designing safer chemicals refers to the production of goods that do not pose significant hazards to the people even when used. This notion is also extended to the formulation of pharmaceuticals and agrochemicals, where the need to have high efficacy must be balanced by having decreased side effects and environmental persistence [13].

Say heavier solvents and auxiliaries underscore the reason to consider reducing or excluding solvents and other auxiliary materials. Because solvents are an important part of industrial waste and dangers, other environmentally friendlier approaches, including the use of water, supercritical fluids, or bio-based solvents, are gaining increasing popularity [19].

The principle of design to enhance energy efficiency focuses on ensuring that it is comprised of reducing energy consumption through performing reactions at ambient temperature and pressure where possible. This is in line with the drive to reduce carbon emissions and manufacturing costs of large-scale industries elsewhere in the world [14].

Use of renewable feedstocks promotes the use of raw materials of renewable origin instead of the depletion of fossils. The move into biomass-derived chemicals is one of the ways in which an industry can accommodate the principles of the circular economy and at the same time liberate itself somewhat from non-renewable resources [15].

The avoidance of unnecessary manipulation steps, i.e., protect and deprotect, through the rule of reduce derivatives saves steps that create waste and are otherwise cumbersome in terms of reagents, etc. The intensity (compressed synthetic production) will decrease, and environmental effects (reduced) will be introduced [16].

Catalysis promotes the use of selective catalytic reagents as opposed to stoichiometric reagents. Reusable catalysts positively affect efficiency and selectivity and minimise by-products; thus, this principle is extremely influential in the industrial chemical reactions [17].

The principle of designing degradation also emphasises the principle of having chemical products break into non-harmful substances after being consumed. This will prevent such a compounding effect in the surroundings and eliminate the problem of persistent pollutants [18].

Real-time analysis and pollution prevention explain how advanced analysis techniques can help monitor the way chemicals are proceeding as they occur. Real-time makes it possible to take actions in real-time and minimises the chances of chemical releases due to mistakes and enhances process safety [20].

Lastly, inherently safer chemistry as a means of preventing accidents encourages the selection of quantities and conditions that will produce minimal possibilities of accidents like explosion, fire or release of chemicals. This norm is particularly critical in a large-scale industrial facility where accidents may result in disastrous effects [21].

IMPORTANCE IN MODERN ENVIRONMENTAL AND INDUSTRIAL CHALLENGES

All the 12 principles will offer successful measures to address critical issues like the hazardous waste production, consumption of resources, energy use, and the threat to human health. With the example, the atom economy with catalysis enables efficient industry production with fewer waste products, whereas renewable carbon and energy efficiency technologies and practices help mitigate the climate crisis by reducing industrial emissions and minimising the use of resources [5, 18]. These principles are also present in the creation of safer drugs and polymers, the development of which is motivated by the desire to offer drugs and polymers that may directly influence the well-being of humans [19].

Besides, the principles are shaping education and policy. They are also more frequently introduced in the chemistry curricula to equip the following generations in the scientific world with the sustainability mindset [22]. Governments and industries are also incorporating green chemistry approaches in order to meet international agendas that are similar to the United Nations Sustainable Development Goals.

Incorporating these ideals into academic and industrial work, chemistry is redefining more than a means of innovation; chemistry is redefining itself as a fundamental representation of environmental stewardship.

RECENT ADVANCEMENTS IN APPLICATION THE 12 PRINCIPLES OF GREEN CHEMISTRY

The 12 principles of green chemistry have been steadily transferred into practice the past years, becoming a guide to research and innovation in the analytical sciences, synthetic chemistry, materials development and pharmaceutical manufacturing. These principles – waste minimisation, atom economy, cleaner solvents, safer solvents, and design towards energy-efficient processes, among others – are pillars that can help to lessen the environmental and health-associated challenges of chemical processes. This discussion will highlight some of the recent applications and developments of these principles, based on the use of case studies and elaborations reported in the literature and without leaving behind some of the current limitations that still require to be met.

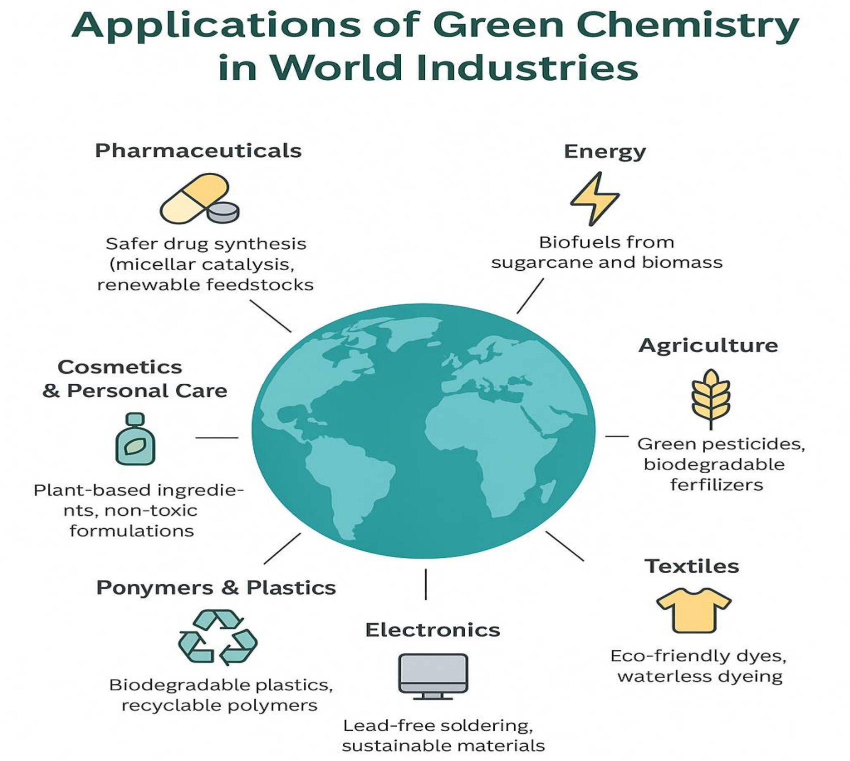

Fig.: Applications of Green Chemistry in Industrial World

GREEN ANALYTICAL CHEMISTRY: MINIATURIZATION, SOLVENTLESS ANALYSIS AND METRICS

Analytical chemistry has experienced a radical transformation due to the impacts of green chemistry, especially due to the innovation of greener approaches in the sample preparation and informing schemes. Conventional analytical methods have frequently used hazardous solvents and energy-demanding procedures, yet the recent past has seen the integration of techniques including microextraction, supercritical fluid extraction and the use of ionic liquids and biobased solvents. The strategies diminish solvent use of toxic solvents, decrease waste quantities, and enhance the developer and operator safety and efficiency [23].

Perhaps one of the most dramatic advances is the creation and use of green metrics, which are the quantitative tools to assess the environmental impact of analysis techniques. Green analytical procedure (GAPI) and analytical greenness (AGREE) measures support and enable the assessment and comparison of methodological strategies; they also allow calibre across processes and approaches on the basis of the aspect of greenness [24]. For example, AGREE provides a comprehensive measure of analytical workflows where the 12 principles of green chemistry are incorporated into a scoring system to assist in the discovery of less hazardous solutions.

New technologies have adopted the use of water, supercritical CO_2 and ionic liquids as green solvents coupled with energy-saving processes, e.g., microwave- and ultrasound-assisted extractions [26]. Further, miniaturisation has become an efficient instrument in green analysis chemistry. These portable and automated devices allow carrying out analysis in the field, and this decreases the use of resources, as well as the large laboratory infrastructure requirements [25]. Nevertheless, there are some difficulties in ensuring enhancement in analytical sensitivity and selectivity without causing environmental degradation. Also, there exist no uniform standards of sustainability evaluation, thus making it difficult to compare studies in cross-sections, further indicating that unification in the implementation of green analytical procedures is required on a global level [25].

MECHANOCHEMISTRY AND SOLVENT-FREE CHEMISTRY

One of the most promising areas to which to positively ascribe the green chemistry we can refer to is mechanochemistry, or the process by which chemical reactions can be accelerated by mechanical energy instead of using a solvent. Such a solution minimises the use of volatile organic solvents and considerably decreases hazardous waste, also decreasing the energy demands. The field of mechanochemical synthesis is gaining traction in the preparation of pharmaceuticals and nanomaterials, as well as polymers, where there is an increasingly clear demonstration that mechanochemical methods are more atom-economical and have reduced environmental impacts compared to more traditional solvent-based approaches [26].

In one of the applications, the field of advanced materials is one area that has attracted considerable attention in the light of mechanochemistry research, which is in metal-organic frameworks (MOFs). Ball milling and twin-screw extrusion have been explored as mechanochemical processes with the advantage of being solvent-free or solvent-limited, with high yields and reproducibilities [2]. These materials have a large surface area, and their porosity can be tuned, making the materials essential in carbon capture, catalysis and energy storage. Meanwhile, despite the significant benefits of mechanochemical synthesis, constraints are set by scaling up and the extreme machines needed, which can thus hamper further industrial adoption [27].

GREEN SYNTHESIS OF MATERIALS: MOFS AND LIGNIN-BASED POLYMERS

The sustainability of material synthesis has emerged as a prime area to apply the 12 principles of green chemistry in the development of safer, renewable and degradable alternatives. MOFs have also followed this trend, with current studies being on greener methodologies that utilise water-based media, supercritical fluids and biocompatible linkers. Not only do these developments decrease the use of harmful solvents but also ensure the phenomenon of synthesis is energy-saving and cost-efficient [28]. Moreover, such green MOFs are becoming used in environmental remediation, gas separation, and water purification, which provides solutions to problems in environmental protection on a global scale [1].

Similar to MOFs, efforts to valorise the products of biomass, such as lignin, have received impetus. Lignin, a pulp and paper industry by-product, has long been under-exploited, but a recently muscled-up research effort aims to convert the brittle wood-derived compound to renewable polymers. Other developments, like lignin-based green solvents and a lignin-based biodegradable polymer that has been utilised in food packaging and biomedical devices, as well as the development of sustainable electronics, have contributed. Lignin-derived polymers can provide the green chemistry principle of renewable feedstocks in addition to helping solve the plastic waste problem.

GREEN CATALYSIS AND ENVIRONMENTALLY FRIENDLY REACTION MEDIA

Catalysis, as the guts of green chemistry, has received new impetus on how the foundations of green chemistry can be anchored into catalysis strategies. Micellar catalysis, or micellar-catalysed reaction, in particular, has become important. Catalytic reactions can then be performed in water, through the generation of a micellar environment via the addition of surfactants, and can significantly improve selectivity and efficacy compared with nonmicellar environments to reduce the requirement of harmful organic solvents [29]. This invention has been found particularly useful in pharmaceutical and fine chemical synthesis in which waterborne reactions are both safe and environmentally desirable.

C(sp)-H activation reactions have also seen further development, which increases atom efficiency through the use of direct functionalisation of the C(sp)-H bond, without initial prefunctionalisation of the C(sp)-H. Such a methodology reduces reagents used and produces less waste, which leads to manufacturing processes of increasingly narrow optimisation and improved environmental friendliness [30]. There is also the trend in the direction of green reaction media in terms of alternative solvents such as supercritical fluids, ionic liquids, and bio-based solvents. These solvents are also disadvantaged by their toxicity and volatility even when they have reduced toxicity and volatility as compared to the solvents that they replace, meaning that they are still challenged by value and recyclability and even toxicity [31].

APPLICATIONS IN PHARMACEUTICAL MANUFACTURING

Green chemistry principles have taken root in the pharmaceutical sector, and there are obvious incentives to make this sector of the economy more sustainable through green chemistry. The comprehensive design

of active pharmaceutical ingredient (API) synthesis with a focus on waste minimisation, atom economy, and renewable or safer reagents is one of the developments. The relevance of continuous flow chemistry has increased specifically due to the capability to intensify the processes, monitor in real time, and carry out reactions under safer conditions, as well as to minimise waste and energy requirements [32].
Green solvents and green catalysts also have been remarkable in helping pharmaceutical processes be more viable for the environment. As another example, water and supercritical CO_2 have been successfully used in drug synthesis and formulation, and this example shows how solvent conversion can also be conducted on a safety and efficiency basis [16]. Simultaneously, in-line process monitoring and automation also favour greener production since the conditions of processes will be better controlled, and that will mean fewer deviations, side products, and waste forms.
Although these have been achieved, issues still exist in harmonising regulatory requirements with new innovations in green chemistry. Such industries like the pharmaceutical industry demand strict quality and safety measures and therefore have some difficulties migrating to new solvents and catalysts or process architecture. However, with the rising trend of the necessity of books that use sustainable pharmaceutics, the idea of green chemistry in pharmaceutical design and production is also becoming more widespread, which makes such environmentally conscious approaches even clearer in one of the most resource-demanding fields [33].

METRICS OF GREEN CHEMISTRY AND THEIR APPLICATIONS, BENEFITS AND LIMITATIONS

It is worth mentioning that green chemistry metrics have gained prevalence as important tools in the contemporary chemical sciences, as they enable researchers, industry experts, and regulators to determine the extent to which a process is indeed environmentally friendly. Rather than rely on assumptions or subjective evaluation, such measures offer systematic and repeatable measures to evaluate the extent to which an analytical, or synthetic, process is green-chemistry aligned. In so doing, they help in steering scientists in a safer, cleaner, and more environment-friendly direction. Research on their development has been increasing in the past decade and presents numerous, relatively easy-to-apply as well as highly sophisticated, yet audience-specific evaluation tools [34, 35].

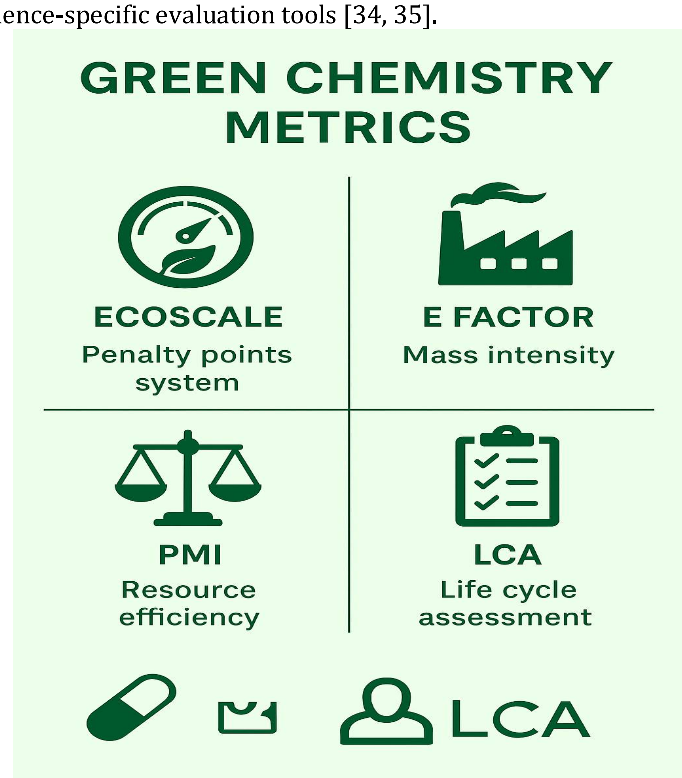

Fig.: Metrics in Green Chemistry

APPLICATIONS OF GREEN CHEMISTRY METRICS

Green chemistry metrics are intended to measure the greenness of processes in terms of toxicity, the amount of waste they generate, how they use energy, and their safety hazards. Some of the widely applied instruments reveal the extent to which such approaches can differ.
One of the first measures is the National Environmental Methods Index (NEMI), which is a pictogram-condensed scale. It also verifies four main aspects: that a process must be free of toxic materials, have

limited waste products, have non-hazardous reagents, and also be non-corrosive. The best part of it is that it is very simple to use, making it appropriate in quick screenings. But there is also the weakness of the approach to not deliver more specific information [32].

The Analytical Eco-Scale takes a more quantitative approach since a score of 100 is assigned to the method, and the score is then lowered by penalty points, each assigned to environmentally damaging factors in the method, including toxic reagents, energy- or waste-intensive procedures, etc. The method is either categorised as being green, acceptable, or not green, based on the final score. This can encourage easy comparison between various methods and hence provides a higher level of information when compared to NEMI, yet it can be easy to use [36].

A popular tool, however, is the Green Analytical Procedure Index (GAPI). It is an illustration of a coloured pictogram indicating the greenness of each singular step of an analytical tool, starting with the sample preparation procedure and ending with detection. It differs in comparison with NEMI or Eco-Scale, which gives its overview since it is systemic in its representation. However, due to the lack of a single overall score, it has been less convenient when the need arises to compare a number of procedures [27].

The Analytical GREEnness Metric (AGREE) is one of the most thorough tools of today. It combines all 12 principles of green analytical chemistry to form a unified 0-1 score and circular picture, which provides an evaluation (of whether the principles are followed or not) in a numerical form and in a visual form. It is user-friendly, which is attractive to both research and teaching environments; additionally, it is an open-source solution. Because of its customisability, GREE can be easily customised to fit a particular set of objectives, a fact that has made it very versatile and accommodating [37].

Other more sophisticated tools have also been developed in the recent years, including ComplexGAPI, MoGSA, RGB models, and AGREEprep. They overcome some of the constraints of previous tools either by introducing more flexibility or new and additional assessment considerations or by concentrating on particular issues such as that of sample preparation. These new inventions are indications of the increase in the demand towards precise and thorough sustainability assessments [38].

Together, the metrics have found use in a range of applications spanning environmental surveillance, food safety, pharmaceutical analysis, regulatory decision-making, and plant and process design.

THE BENEFITS OF GREEN CHEMISTRY METRICS

The presence of green chemistry metrics has come with a lot of benefits. To start with, they allow an objective and replicable measure of sustainability. As opposed to relying on individual opinions, researchers can resort to clear criteria to assess techniques, which increases scientific transparency [31].

The other strength is the relative power of such tools. Other methods include the introduction of metrics like the Eco-Scale or AGREE, through which chemists can compare two methods and decide which is less harmful to the ecology. This fosters creativity because one has a clear road to betterment [38].

Another advantage is ease of use by the user. Several tools, such as AGREE and MoGSA, are open-source and are user-friendly, which reduces the entry cost threshold of adoption both academically and industrially. NEMI and GAPI can also visually display even the most complicated sustainability topics in the form of pictograms, which can be invaluable when presenting findings to non-experts or to regulatory authorities [39].

These tools eliminate the hesitation between ease of use and rigour of science and so facilitate greater adoption of sustainability across disciplines.

LIMITATIONS OF GREEN CHEMISTRY METRICS

Even though it appears clear that green chemistry metrics are important, they are not without blemishes. One of the greatest problems is simplifications. As tools such as NEMI and GAPI tend to be based on narrow or binary observational criteria, they can fail to capture the grey zones in the intrinsic complex processes involved. As an example, they may label a reagent as satisfactory or unsatisfactory without taking into consideration the variations of concentrations and of contexts [40].

The other shortcoming is subjectivity. Others involve human judgement to score or assign colours, and this may induce bias. Such subjectivity can provide uneven results with application across a variety of users [6].

Another issue is that most metrics emphasise only the environmental impact, ignoring at best the others, e.g., the performance of the analysis method, its economic feasibility, and social consequences. Such limited applicability might reduce the usefulness of those industries where cost-effectiveness and performance are as essential as environmental responsibility [3, 8].

Lastly, none of the tools are universal. Both have advantages and disadvantages, which precondition that the measure selection greatly depends on a context and the purpose of the conducted research. To conduct comprehensive assessments, it is frequently required to apply several tools simultaneously, which makes the process more time-consuming and complicated [19].

GREEN CHEMISTRY IN POLICY AND EDUCATION: HOW, WHY AND WHAT NEXT?

Already known, and one of the most important ways of ensuring sustainability in the chemical sciences and other industries, is the integration of green chemistry into the aspects of education and the establishment of policy frameworks. It is in this pursuit of establishing environmentally responsible and socially conscious scientists and professionals that the 12 principles of green chemistry have been put in curricula and various systems of governance to ensure that, by inculcating these principles, researchers, educators and policymakers will be able to raise environmentally responsible and socially conscious scientists and professionals. Although there has been a marked improvement in awareness in building awareness in developing education globally, there is still a long way to go in terms of scale, accessibility and the match between education policies and the objectives pursued by educational systems. Bright examples are given both in the real world and with empirical studies to demonstrate both the successes and gaps in this continual transformation.

GREEN CHEMISTRY IN EDUCATION: PROGRESS AND DEVELOPMENT

Inquiry-based and problem-based learning approaches to introducing green chemistry at the school level have been designed to relate abstract chemistry to concrete real-life issues of sustainability. This transition has been successful in increasing the interaction and learning of the students. Specifically, Koulougliotis et al. [9] reported that secondary students exposed to chemistry activities on environmental problems – i.e., plastic waste reduction and water quality – showed better conceptual understanding and a greater level of motivation in comparison to students under instruction with classic methods. These results stress the socially relevant and relatable nature of green chemistry-related activities.

Higher education Universities across the world are working towards integrating green chemistry into their curriculum in exams, in new courses and in research. In several institutions in Europe and North America, green chemistry courses have been developed separately, and in other institutions sustainability-focused modules are integrated into existing organic, analytical, and industrial chemistry curricula. The most remarkable one, in my opinion, is the case of Brazil when the University of São Paulo adapted their courses to directly compare the 12 principles of green chemistry and the United Nations Sustainable Development Goals [41]. On the same note, Day et al. [8] gave an idea of the installations of the green labs at US institutions where the students are exposed to the green practices through the handwork of replying to the use of the trivials and disposal of waste materials.

In Indonesia, Mitarlis *et al.* [30] investigated the influence that green chemistry had on the local setting with regard to the teaching needs and approaches to teaching through contextual teaching practices, including the pollution analysis of local industries. The reason why these practices were introduced is to show how curricula should be modified to represent the local environmental issues; thus, green chemistry becomes very local to local people. Yet, not every context will have equal resources and trained faculty. In the Philippines, Jovero and Picardal [17] observed that although the interest exists in integrating green chemistry into the curricula, the lack of faculty training and the scarcity of institutional support are the leading challenges of this initiative. Such disparities indicate that the international spread of the green chemistry education system is not uniform, and specific efforts must be made with the aim of addressing the resource gap.

INTERNATIONAL AND REGIONAL EFFORTS IN THE DEVELOPMENT OF POLICY SUPPORT FOR GREEN CHEMISTRY

In response to the education endeavours, the policy agenda has also noted the importance of green chemistry in attaining environmental sustainability goals on local and global scales. In reference to Europe, the European Green Deal has prioritised the focus on sustainable production and circular economy practices, and hence this has been the impetus behind the considerations of green chemistry being instilled in the research and innovation systems [18]. As will also be discussed in the present paper, the Southern European region managed to attach much significance to regional research policy as a key tool to promote green chemistry in the shape of the establishment of bio-based products and renewable energy sources. Not only were these policies environmentally friendly, but they were also able to be framed as regional economic development policies, which means the two drivers of sustainability and competitiveness can coincide with each other when it has the appropriate level of government regulation and funding.

Chen et al. [5] put an emphasis on how green chemistry and circular economy overlap at the global level in terms of reducing waste and enhancing resource efficiency. Their report presented real-life examples of green chemistry implementation in China that lowered environmental footprints in the large-scale production area in tandem with cutbacks in production cost, a factor that demonstrated how green chemistry practised in pursuit of a policy could achieve the two-fold targets of sustainability and financial profitability. The above illustration proves especially effective in breaking the stereotype according to which sustainability is always cost-ineffective.

ADVANTAGES OF INTEGRATING GREEN CHEMISTRY IN EDUCATION AND POLICY

The advantages of institutionalisation of green chemistry within education and policies are multiple. First, learning initiatives created graduates that are environmentally conscious at the same level with the skills that the industry requires in the present time. To give an example, US-based universities featuring green chemistry laboratories have testified that students who have been able to experience sustainable practices during their studies would be more appealing to employees during the recruitment process in relation to their pharmaceuticals and materials science-related industries (Day et al., 2024). This demonstrates that the clear career advantage of students is that educational reformation will not only support sustainability interests, but it also directly benefits students.

Second, the introduction of green chemistry into policy frameworks creates an incentive and a framework for moving industries towards greener processes. In the case studies of Southern Europe, it is shown that favourable policy tools, like taxes and subsidies on green research, as well as support in catalysis, can speed up the innovation process in sustainable materials [12]. Likewise, in Asia, the circular economy approaches demonstrate that government-driven regulations result in quantifiable waste and emissions reductions [5]. These show that policy integration is not merely a pipe dream with a few concrete results.

IN EDUCATION AND POLICY, ITS PROBLEMS AND OBSTACLES

Despite all of these achievements, there are issues to reckon with. The lack of expertise of a faculty can perhaps also be seen as one of the most lasting barriers on the educational side. The fact is that most teachers cannot teach the topic because they do not possess expertise in performing the practical aspects of green chemistry [12]. The same can be stated by characterising scaling these initiatives, particularly in scarce resource-dense contexts mentioned by Mitarlis et al. [30]. Until there is certain institutional support for the green chemistry movement, there is a risk of the movement becoming a series of isolated pilot projects rather than a part of sustained organisational chemistry teaching.

There also exist scope and alignment issues of policy frameworks. They all concentrate on the technical matters and environmental concerns without paying attention to the ethical/social and economic factors of the programmes. Amoneit et al. [3] also suggest that frameworks should be complemented by the promising responsible research and innovation (RRI), whereby policies should consider the social implication of the chemical technology. This is consistent with what Mehlich [28] has articulated when he notes that the European Green Deal is not purely technical or specialist-envisioned and needed by chemists, but it is a happy profession that can also interact and engage with ethical discourse and values. Without the greater vision, environmental gains can be achieved with the policies whilst leaving more ground-seated issues of systems problems to sustainability.

The other tension that has continued to exist is the conflict between market-based short-term policies and long-term objectives of green chemistry. According to Alhazmi and Almashhour [2], the influences of market logics in teaching institutions tend to limit the inclusion of sustainability programmes since curricular reforms need a lot of investment without the short-term returns. This contradiction demonstrates the necessity of sound policy inductions and structural changes that can acknowledge the prospect of green chemistry as a sustainable facsimile in the international environment.

PROSPECTS IN THE FUTURE AND IN REAL LIFE

The harmonisation of green chemistry into education and policy will need to be enhanced in the future to provide the possibility of fulfilling global sustainability objectives. Among the educational priorities are faculty education, interdisciplinary collaboration and institutional investments. The alignment of the University of Sao Paulo with the UN SDGs [41] is an effective example that can be adapted to a particular environment. On the same note, we see problem-based learning programmes in secondary schools [17] that can influence future scientists in their values and career paths at such a young age.

In terms of policy, what is going on in Europe and in Asia is highly instructive and informative. The European Green Deal can serve as the model of how a variety of policies can be employed to align research, industry, and education to the comparable green goals [28]. In Asia, the inefficiencies of utilising solvents in terms of environmental and economic aspects have spurred solvent-replacing measures backed by a circular economy notion of green use of chemistry, with cost- and environment-saving implications [5].

These examples show that well-designed policies positively affect adoption as well as introduce feedback loops: competitiveness and innovation stakeholders have to be environmentally responsible.
The ultimate application potential of green chemistry can be achieved through the closing of the educational, policy and industrial gaps. Through such efforts towards collaboration in all these areas, green chemistry should develop into a central component in the practice of science globally.

CHALLENGES AND FUTURE DIRECTIONS FOR GREEN CHEMISTRY IMPLEMENTATION

Scaling up of green chemistry in the industries in large proportions hasn't yet been able to successfully get rid of the problem of unavoidable challenges despite the evident environmental and economical inferences that this venture holds. Although a significant sustainability potential of laboratory-scale innovations can be observed, making the process of transition to an industrial level is usually hampered by a combination of financial, technical and policy-related challenges. Meanwhile, the prospects in the future are potential interdisciplinary connections to be established, new metrics to be standardised and cross-accepted, and integrating green chemistry both into the sphere of a circular economy and overall sustainability strategies.

OBSTACLES TO FULL ADOPTION IN INDUSTRY

Among the most well-known reasons why the achievement of large-scale adoption of green chemistry in industrial practices has not been able to take place is the steep price and technological problems related to the switch of chemical processes in industry to greener variants. Numerous green technologies necessitate the need for new infrastructure, specialised equipment or a change to an existing process, and that too requires substantial investment. Industries with narrow profit commitments tend to be reluctant to take such steps unless they are duly supported by a regulatory organisation or long-term incitation of necessities in terms of economics [8]. Also, when green methods are technically possible, their scale-up is a serious issue. Experimental tests that are conducted in a laboratory setting and deal with relatively small volumes can be scaled up to industrial applications that need more energy, larger amounts of renewable feedstocks, and more elaborate strategies of waste disposal [7].
There is also the problem of renewable feedstock availability. The main constraints of green chemistry innovations may be associated not with the use of bio-based materials and alternative solvents but with agricultural needs, land-use regulations, and competition with food systems. This makes green raw materials in short supply, limiting industries in their ability to source these materials reliably at scale [21]. Furthermore, certain processes continue to rely on either reagents or catalysts that, although less energy- and toxicity-intensive than traditional ones, remain not quite devoid of warning flags in these regards. E.g., in the case of ionic liquids as a solvent, their recyclability is also advocated, but toxicity and biodegradability issues remain unclear [16].
The industries are also questioned about the performance of products and uncertainty of regulation. The fear of many companies is that the alternative greener products will affect the quality, lifespan or shelf life of their products. In the absence of clear and harmonised regulation and policy incentives, there is minimal incentive for the firms to adopt the risks attached to implementing new green technologies [38]. All these issues are complicated by the absence of cross-sectoral cooperation between academics, government and industry, which means that green chemistry breakthroughs have a hard time scaling and commercialising their Western partners [25].

NEED FOR INTERDISCIPLINARY APPROACHES AND STANDARDIZED METRICS

The implementation of green chemistry can only be realised in the future depending on the uptake of interdisciplinary strategies that connect chemistry, engineering, environmental science and policy. Simple industrial systems that can be altered by chemistry alone; they need the ability to integrate systems thinking, consider lasting design, and technological innovation across disciplines (Zimmerman et al., 2020). In another example, an engineer will be very important in the redesigning of the equipment to fit the greener processes, whereas a policymaker will need to come up with the regulatory policies that are conducive to entrenching innovation without killing adversity.
One of the significant areas of concern which needs to be addressed on an urgent basis is the development and adoption of standardised metrics. Various tools, including atom economy, E-factor, process mass intensity and life cycle assessment (LCA), have been proposed; however, their use is difficult because some of them lack consistency [13]. The missing universally accepted standards imply that there are, in several instances, cases where processes and industry comparisons are not affected reliably. To give an example, when using the term "green efficiency", the two different companies may reckon differently and thereby fail to accommodate accountability. Dalton et al. [7] note that it is highly necessary to work out standardised and transparent metrics to benchmark progress, inform regulatory decisions and set research priorities. In

the absence of these, green chemistry becomes a hypothetical figment as opposed to an actual quantification.

INTEGRATION WITH CIRCULAR ECONOMY AND SUSTAINABILITY GOALS

The second significant future orientation is the interface between green chemistry and the circular economy and the wider sustainability strategies. The circular economy concept draws attention to the resource effectiveness, recycling, and waste minimisation that are related closely to the achievements of green chemistry [32]. As an example, green chemistry practices aiming at using agricultural residues or CO_2 as the raw material fit into the circular economy strategy of using waste as raw material and lessening the use of fossil sources. Likewise, safe-and-sustainable-by-design principles, the development of materials and products that are designed to be non-toxic and recyclable, overlap with green chemistry goals greatly [33].

The realisation of green chemistry in the setting of sustainability also calls out joint policy reinforcement. Another general rule is the influence that governments and international organisations have on the transition to greener practices in any industry, encouraging them to provide incentives and other benefits in the form of subsidies or tax benefits to the companies that switch to renewable feedstocks or low-waste procedures [7]. Meanwhile, fresh business models will have to develop as they not only focus on mere profitability but also lay an emphasis on sustainability. To illustrate the point, one can mention companies that introduce circular production cycles when their by-products become a basis of other industries [25].

Lastly, by integrating green chemistry into any circular economy, one will be able to respond to consumer demands. There is an awareness that is growing about the environment, and this has seen an increased need to have products with a lower carbon footprint and with less environmental impact. Not only do the companies undertaking green chemistry ensure that they do not attract penalties in the future due to new regulations, but they also improve on their brand reputation and competitiveness in the world markets [38].

CONCLUSION

Green chemistry has emerged as an important tenet in sustainable development by providing roadmaps towards reduction or elimination of hazardous materials and modelling products and processes which are ecologically friendly and safer to humans. Formally concerned with the area of hazard reduction, the field has evolved to the system-based approach with the life cycle analysis, interdisciplinary cooperation, and sustainability integration expanded into the discipline. These developmental priorities represent the evolution of green chemistry as a comprehensive, sustaining driver of sustainable transformation, which bridges the scientific aspects to the environmental affairs of the planet.

A major future direction is to harmonise the principles of green chemistry with those of the circular economy. The circular economy follows closed-loop systems, where the resources are not discarded but used over again and where waste products are reduced to a minimum. Green chemistry brings the technological expertise to this transition via the use of renewable feedstocks and/or biodegradable products and catalysts that can be recycled.

Training and education are also the key ingredients of green chemistry in the future. By embedding its beliefs in curricula, the academy can hope to raise a generation of chemists and engineers working with the mindset required to produce ever-more-sustainable processes. Increasing these programmes around the world would enhance the ability of the human resource to develop this area.

Green chemistry will be key in the attainment of United Nations Sustainable Development Goals (SDGs) in the future. Innovations in the digital technologies, artificial intelligence-based optimisation of processes and biocatalysis would allow speeding up the process of designing safer and more efficient chemical systems. These facts suggest that green chemistry should be combined with the safe-and-sustainable-by-design concepts to bring about the change that would be transformational rather than incremental. Green chemistry contributes to the next generation of the chemical industry through resilience, economic viability and environmental compatibility by integrating both the principles of the circular economy, standardised metrics and education.

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