STM JOURNALS

Journal of
Modern Chemistry & Chemical Technology

ISSN: 2229-6999 (Online)
ISSN: 2321-5208 (Print)
Volume 17, Issue 1, 2026
January–April
DOI (Journal): 10.37591/JoMCCT

https://journals.stmjournals.com/jomcct

Research JoMCCT

Looking Into New Ideas in Green Chemistry

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Abstract

Green chemistry has become a revolutionary way to change chemical processes such that they have less of an effect on the environment while still being efficient and cost-effective. This article looks at new developments in green chemistry that go beyond small changes and offer completely new ways to build chemicals that are good for the environment. There is a lot of focus on innovative catalytic systems, sustainable feedstocks, reaction pathways that do not use solvents and use less energy and bringing life cycle thinking into molecular creation as early as possible. These improvements show that sustainability can be built into the design process instead of being an afterthought. The article uses case studies from academic and industrial research to show how waste, toxicity, and energy use may be cut down while process performance can be enhanced. The conversation also talks about problems that are happening right now, such as scalability, cost, and regulatory alignment, and it talks about how interdisciplinary collaboration can go forward in the future. The essay contends that green chemistry has transitioned from an alternative methodology to an essential catalyst for innovation, providing novel scientific prospects while addressing pressing environmental and societal demands Moreover, advances in digitalization, artificial intelligence, and process intensification are accelerating the adoption of green chemistry principles by enabling predictive design and real-time optimization. Education, policy support, and industry–academia partnerships will be crucial in translating laboratory-scale innovations into commercially viable, globally sustainable chemical technologies. Such integrated efforts will help standardize metrics, encourage responsible manufacturing practices, and ensure long-term environmental, economic, and social sustainability worldwide

Keywords: Chemical synthesis, circularity, pollution, scalability, thermosets

INTRODUCTION

Chemistry improves our world, yet it also makes it worse. Every day, chemicals affect our lives. They are in the medicines we take, the food we eat, the air we breathe, and the water we drink. They keep us alive, well, and joyful. But many things also kill people, pollute water, mess up the food chain, and harm the air. Most of them are not safe or long-lasting. They will not be able to help with world problems in upcoming decades, like climate change, limited resources, clean air and water, pollution, green energy, biotechnology, and human health [1].

Chemists need to do something. Chemistry must adapt to fulfill human requirements in a timely and sustainable manner. Scientists who study both the sciences and the humanities have said in their ethics standards that "scientists should think ahead and think about how their choices in their research careers and when they come up with new methods might affect the health of the world." Chemists need

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Received Date: January 23, 2026
Accepted Date: January27, 2026
Published Date: March 01, 2026

Citation: V. Basil Hans. Looking Into New Ideas in Green Chemistry. Journal of Modern Chemistry & Chemical Technology. 2026; 17(1): 10–18p.

to change how they make chemicals. They should employ green chemistry, which the US Environmental Protection Agency (EPA) says is the design of chemical goods and processes that cut down on or the production of various dangerous compounds.

PRINCIPLES OF GREEN CHEMISTRY

Green chemistry's goal is to make chemical products and processes that use fewer harmful ingredients and create less waste. The 12 principles of green chemistry are a short list of rules that chemists can use to make their work more environmentally friendly and to check how sustainable it is.

The first principle, waste prevention, says that it is preferable to stop trash from being made in the first place than to deal with it after it has been made. The best ways to do this are to get the most out of each atom or step, make sure the reaction and storage conditions are safe, and create efficient separation methods. The second principle, which is about how dangerous chemical synthesis is, shows how important it is to choose safe materials whenever possible, especially when scaling up from the lab to the pilot plant. The third principle, which is about making synthetic procedures that utilize and make hazardous substances, underlines the need to make chemical syntheses that use fewer solvents, less dangerous solvents, or less volume of solvent.

The fourth principle, developing safer chemicals, shows that it is not enough to find ways to make dangerous compounds that are better for the environment. The compounds that are made should not be dangerous or should be less dangerous than the chemical that is being targeted. The fifth principle, safer solvents and auxiliary chemicals, says that solvents and auxiliary compounds should be avoided or made unnecessary whenever possible. The sixth principle, design for energy efficiency, considers how much energy chemical processes will need as they are being designed. It is best to spend less energy if it does not make the process less safe or useful. The seventh principle, utilization of renewable feedstocks, talks about how important it is to use raw resources that can be used again. For instance, renewable feedstocks are materials that come from renewable sources, including recycled plastics and green chemical feedstocks [2].

REACTIONS AND SOLVENTS THAT ARE SAFER

Safer Reactions and Solvents

Chemistry has advanced and grown to the point where it takes a lot of work to get the outcomes you want and even more work to meet deeper demands. Waste generation, toxicity, safety, pollution, the risk of chemical use, and many other issues are currently serious difficulties in the field of chemistry. It is now necessary to make the world a safer place and a better place for future generations without interfering with existing chemistry. The techniques and efforts to lessen these issues or lessen their effects were part of the long-overdue "Innovation of Greener Chemistry." To show the slogans and principles of greener chemistry and take a systematic look at the larger field of chemical knowledge and ideas, we will use many examples and scientific data, experimental knowledge, and mechanical orientation from the wider field of chemistry and scientific knowledge to make the process easier. We will do this by addressing the larger area of innovative footprints created by scientific and mechanical approaches with shorter phrases.

Solvents are commonly employed in several chemical reactions to establish a uniform reaction media, attributable to their elevated polarity and solvent-solute binding interactions. There are now chemical reactions that do not need solvents, although solvents are still the most popular choice for synthetic chemistry. People often forget about different technical details when using solvents. A good solvent should be safe for the environment and have a high solubility for the substrates, reactants, intermediates, and products involved in the reaction. This is especially true when the balance of polar and apolar characteristics is right.

Catalysis is a part of all areas of chemistry. The ability to speed up a chemical process without permanently changing the catalyst makes production more selective and chemistry much greener.

ISSN: 2229-6999 (Online), ISSN: 2321-5208 (Print)

Biocatalysis can be used in the lab, in industry, and even in significant green and sustainable chemistry, which saves energy and cuts down on waste. Process intensification is good for green chemistry since it makes things more efficient and saves energy and raw materials. In addition to the building blocks and raw materials that come from renewable resources and recycling trash, producing new active substances from natural systems or synthetic compounds to fight pollution also helps to decrease bottlenecks [3].

Water as a Solvent

Water is generally the solvent of choice in green chemistry reactions. It has a lot of benefits over organic solvents, but there are still some big problems. Some reactions that are rather complicated work well in water. A lot of polymers and other products are made in water at high concentrations since it is cheaper and speeds up the process.

People agree that water is a universal solvent since it is safe, does not evaporate, does not catch fire, is cheap, and comes from renewable sources. You can dissolve a lot of different substances in water by changing the pH, making supportive salts, or adding surfactants. Water is also the best solvent for all industrial biocatalytic processes. Water-as-a-solvent technologies have been effectively utilized for analysis, extractions, materials recycling, and separations in polymers and coatings [4].

Biocatalysis

Enzymes are catalysts that speed up chemical reactions without being used up in the process. The food and detergent industries utilize them a lot. They are quite picky, work well, and work best in mild settings. These traits make enzymes good choices for replacing traditional chemical catalysts. Biocatalytic reactions usually cut down on the demand for protective groups and make fewer by-products. Also, substrates can often be changed in water-based solutions. Biocatalysts are less harmful and easier to break down.

There are some limits on how biocatalytic processes can be designed. Enzymes normally work best when the temperature, pH, or solvent is in a small range. The enzymes that are currently available for sale do not work for many biochemical changes. These obstacles continue to impede the widespread use of biocatalysis. It has been stated that only 20% of the biocatalysis of industrial chemicals involves the use of biocatalysts. Still, today's work in genomes and metagenomics is making biocatalysis more useful. It is possible to find and create strong and new biocatalytic activities in nature.

Biocatalysis can help green chemistry a lot and give us long-lasting options to old chemical methods. Using different solvents could assist reduce toxicity and follow the "less hazardous chemical syntheses" rule, but if the substrate or product is not taken into account, the method might only be a "1.5-grade improvement." The best way to avoid toxic compounds is to not use them at all. Enzymes may change a wide range of frameworks, such as hydrocarbons, heterocycles, and cyclic carbonates, because they have a naturally wide substrate scope.

Biocatalysts are often a more environmentally friendly way to do chemical synthesis [5]. Marine settings exhibit extensive diversity of microorganisms, enzymes, and alternate biocatalytic processes of significance. Using marine metagenomic libraries can quickly increase the chances of finding novel biocatalyst candidates that work well in extreme environments that present biocatalysts cannot handle [6].

EFFICIENCY OF RESOURCES AND ENERGY

Increasingly, chemistry depends on procedures that use a lot of energy. More than 90% of all reactions happen at high temperatures nowadays, and heating facilities can cost up to 40% of capital expenses. A lot of starting materials become by-products, which are things that happen that you do not want [1]. Catalysis enables processes to selectively circumvent the generation of by-products, hence enhancing atom economy and resource efficiency. However, it is still possible for chemical technologies to substitute feedstock. There are still problems that need to be solved To improve the conduction of parts of sustainable development.

Studies show that catalysts are crucial in many chemical industries and that 80% of chemical processes depend on them. You can use a catalyst again and again with the same reagent or toxic organic compounds, but it still needs a lot of energy or another waste stream at room temperature. Condensation of two molecules into a more complex product happens in a "dischargeable" way. This means that the bond formation between the simple starting materials CO_2 and water is turned into a tenuous graft-chain. The one-pot process combined a simple feedstock with a catalyst-free process that worked at room temperature to satisfy four steps and 100% of atom economy. There is a lot of heat recovery, with up to 69% and up to 51% of water only.

Process Intensification and Catalysis

Catalysis speeds up reactions, which means that equipment can be smaller and use less energy. Process intensification uses a mix of techniques to make production smaller, easier, and safer. Modular flow platforms use this idea to make materials and energy more flexible. Reactors combine microporous membranes with catalysts that are not the same. These kinds of setups make reactions safer at ambient temperature and atmospheric pressure, which is not possible with standard methods. Continuous production makes it easier to deal with by-products. The system can even handle chemicals that are hazardous, corrosive, or flammable.

A microwave-assisted process for making three high-value chemicals shows how these benefits work. First, a two-step process that turns glucose into 5-hydroxymethylfurfural happens without changing the solvent and at room temperature, and it takes ten times less time than batch approaches. Second, a one-pot glucose-to-coumarin sequence uses phosphoric acid as both a catalyst and a solvent, leaving behind only by-products that can be separated by crystallization [7]. The system can even work with catalysts that are sensitive to changes in conversion and selectivity [8].

Solar and Heat from Waste

Forests take in a lot of solar energy in grassland and wooded areas since there are few clouds and wet air that obstruct solar radiation. To help photosynthesis, green plants put down roots and store the energy they get from the sun as carbs or lignin. Pyrolysis or carbonization of biomass or trash at high temperatures produces oil or CO_2. When processed garbage is put through hydrothermal conditions, it turns either edible oil or useful chemical raw material [9]. In industrial manufacturing processes, a lot of waste heat rises over 100 °C, which makes it hard to recycle with regular heat exchangers. During the winter, solar energy that was stored in the summer becomes available. Waste heat can only be recovered from a small number of streams [10].

FEEDSTOCKS THAT CAN BE USED AGAIN

Bio-based materials can be made from organic raw materials that come from natural processes, such plants, animals, or microbes. These materials can completely or partially replace traditional petroleum-based materials [11]. Bio-based materials are good for the environment in many ways. They have a smaller ecological impact, lower greenhouse gas emissions, and less reliance on fossil fuels.

Bioconversion of raw biomass feedstocks results in the production of universal building block saccharides (such as those from plants, sugar cane, sugar beetroot, and resonance systems like hemicellulose), fatty acid C-rich compounds (from micro-algae, plant oil, and animal fat), complex polymeric biopolymers, and straight-C building block biomaterials. These serve as alternative sources to C_1, C_2, or C_3 materials obtained from fossil or petrochemical origins [12]. The economic feasibility of biomass bioconversion is contingent upon the generation of intermediate materials (thermo-chemical or catalytic) that facilitate the commercial development of bio-industrial or bio-refinery enterprises in China.

There are many ways to use CO_2 to make organic molecules, such as cyclo-carbonation, carboxylation, renalysis, and amidation. There are hundreds of ways that CO_2-based carboxylic acids, which are derivatives of alkenes or alcohols, esters, or urethane and amide linkers in polymers, might be used in business. There are also hundreds of other business opportunities for CO_2-based one-carbon homologues and acyclic systems that use C–C coupling. CO_2 is safe to store and does not harm people or the environment, which makes it more marketable.

Materials Made from Living Things

Bio-based materials come from resources that can be used again and again. Plastics and fibers are two examples of polymers that can be used as these materials. They also have tiny molecules that can be used as colorants, additives, lubricants, and solvents. The bio-material industry is a new field where pine trees and cellulose can be turned into chemicals and materials that are based on living things [13]. Using renewable resources lessens our dependence on fossil fuels, cuts down on greenhouse gas emissions, and helps the environment stay healthy [14]. To make bio-based products, you need to do enough inspections to make sure they are sustainable.

There are three types of bio-based polymers: i) a polymer made entirely from bio-based monomers, ii) a polymer made from fossil resources but containing a bio-based additive or plasticizer, and iii) a polymer that has been changed a lot but does not come from fossil resources. A bio-based polymer is polyethylene (PE) made from bio-based ethanol made from sugar cane. Bio-based materials include engineering plastics, thermosets, fibers, elastomers, and blends. Researchers are still looking into making new polymers from biomass or derivatives of fossil polymers. Strategies aim to establish new ways for polymers to polymerize, come up with new polymers, and add biomass to current polymers to solve the problem of plastic sustainability.

Using CO_2

Not only may carbon dioxide be a greenhouse gas, but it can also be a raw material. One interesting notion in green chemistry is to use carbon dioxide to make useful chemical compounds. There have been many suggestions for how to use it, such as utilizing methanol as a protic or aprotic polar solvent, using Fischer-Tropsch synthesis to make hydrocarbons, and using hydro-formylation procedures to selectively get aldehydes [15]. Also, carbon dioxide may be turned into carbon monoxide, which is a useful carbon source for making cyanide intermediates that can be used to make pharmaceuticals and agrochemicals [16].

CUTTING DOWN ON WASTE AND MAKING THINGS LAST LONGER

Waste is not waste. It is a useful resource. Less waste means more stable economies. Circularity makes sure that materials can be reused over and over again without causing any damage.

Atom economy tells you how well feedstock resources are turned into the product you want. It is the molecular weight of the product you want divided by the molecular weights of all the reactants. Maximizing atom economy boosts product yield, cuts down on waste, and encourages more environmentally friendly operations. The calculation for 3-pheyl-2-propanone shows that the atom economy is 98.2%. A second way that uses acetophenone has an atom economy of only 40.3% [17].

Life cycle thinking looks at a substance's whole life cycle, from getting the basic materials to getting rid of it. Cradle-to-grave looks at the process in a straight line, from cradle to grave. Cradle-to-cradle, on the other hand, looks at the possibility of reusing materials that have been recovered, like turning a bottle into another bottle. Life cycle analysis works best when there is specialization, good modeling skills, and a consistent way of doing things. Simple indicators are generally better for making decisions and getting a lot of people interested than for sending across complicated concepts.

Economy of Atoms

Atom economy tells you how well the atoms in the reactants are used in the end product. A perfect reaction makes a product that uses all of the beginning atoms and does not waste any. A process with

100% atom economy does not create any waste, hence making by-products with low molecular weight, such CO_2 and H_2O, is not encouraged. Reducing the quantity of by-products will also improve the atom economy and raise the yield of the targeted goods. For instance, making phenols or salicylate esters from acid chlorides produces a lot of chlorobenzenes as waste, which means that the atom economy is low. In short:

1. Using DMSO as an effective alternative solvent, phenols can be made from acid chlorides. Salicylate esters can be made from phenolic compounds and acid chlorides with $CeCl_3 \cdot 7H_2O$ as a catalyst in water as a solvent. This process produces a lot of trash.
2. The synthesis of benzhydrol derivatives from benzhydrylic ketones utilizing $BF_3 \cdot Et_2O$ or Amberlite IR-120 as catalysts in an aqueous solution, resulting in no waste by-products [18].

By utilizing particular solvents or converting the reaction medium into water, the enhanced atom economy facilitates the development of more cost-effective synthetic pathways for phenol derivatives, while simultaneously rendering the activated, high-energy chlorobenzene by-product, which necessitates additional processing prior to disposal, insignificant [19].

Thinking About the Life Cycle

Changing the way we think about a product from "cradle to grave" to "cradle to cradle" gives us a better understanding of its environmental impact across its whole life cycle. It also makes it easier to use life cycle thinking in new ideas. Indicators like the Eco-Indicator and LCA (Life Cycle Assessment) help keep an eye on how a new product will affect the environment by assessing how it will affect human health, the quality of ecosystems, and the availability of resources. The embedded carbon, or the net CO_2 emissions generated during the guiding, consumption, synthesis, maintenance, and final disposal of the product, is a straightforward way to quantify environmental pressure.

STUDIES OF CASES

Green Pharmaceuticals

Pharmaceutical products present significant health, safety, and environmental risks. In the making of drugs, dangerous chemicals are used in reactions, solvents, and isolation steps. These agents are still used in many important synthetic procedures in industry, which creates a lot of waste. There are worries about how safe many common solvents are. Because of pressure for "greener" behaviors, people are looking for safer options or routes that are naturally safer to avoid accidents and lessen their effect on the environment.

The best way to make things more sustainable is to stop them from happening in the first place. Direct hazard indicators, which are identified in the fields of toxicology, fire, the environment, and exposure, can help with the adverse effects of solvents. A specific choice can help you evaluate other options in a green way. Replacing dangerous solvents with safer ones, using water instead, or using non-toxic process intensification, and reducing the amount of solvent needed by using more selective reactions or getting rid of solubilization all have benefits for industry. Clean, safe technological channels bring built-in sustainability without the need for a lot of risk evaluation. The use of water in making drugs is a powerful medium that needs safety checks and is generally thought of as green. The evaluations look at current industry processes and find places where water can still be used instead of dangerous solvents, based on research on "inherently safer design" [20].

Zero pollution strategies address toxicity, persistence, bioaccumulation, and endocrine disruption by alterations in reagent selection. A thorough analysis of the basic materials uncovers elements that increase toxicity beyond the synthesized result. All current modification options that reduce environmental effect while maintaining functionality.

Plastics That Are Safer and Better for the Environment

We still rely on fossil-based raw resources, even for "green" polymers made from bio-sources. The goal of these approaches is to move from fossil-based feedstock to renewable feedstock, get raw materials from trash, and make recycling possible. Polylactic acid from non-edible biomaterials, BioPET, and BioPE from renewable sources, polyamino acid from amino acid feedstocks, and polycaprolactone from CO_2, waste gas, or biomass are all examples of commercial goods. The incentive to harmonize petroleum and renewable raw materials through bio-material recycling promotes diminished hazardous impacts—plastic presents significant toxicity risk via migration. Applications come from the analogy of raw material feedstock, which makes it easier to add economic additives. A simplified toxicity evaluation shows that pure PLA polymers could be safer than regular polyolefins by 66%.

Green Drugs

The pharmaceutical sector knows how important it is to go green and how much of an impact it has. Sustainable green pharmaceuticals include safer ways to make and mix drugs, greener solvents, cleaner ways to make drugs, and less toxic finished products [21]. When dangerous reagents are replaced with safer ones or when fewer steps are needed, as employing one-pot synthesis instead of multi-step synthesis, synthesis can be safer [22]. When necessary, separating products may also use greener methods, such as homogeneous catalysis instead of column separation. Different design and selection techniques can help find greener options and sort compounds into green or nongreen categories. This helps make medication discovery and design more environmentally friendly [23].

Plastics That Are Safer

Plastics change crude oil into things that are useful. But crude oil, gas, and coal are not renewable resources. Condensation and polymerization change plant oils or sugars into plastic polymers that have the same chemical structures and properties. For sustainable material development, recycling needs to be easy, cheap, and effective. Oligomerization of vegetable oils stops polymerization, making recycling easier without the need for chemical changes. It is important to keep an eye on additives because plasticizers, flame retardants, and fillers move about as they are being used. Coated chipboards do not let things through, although the inside layers often have additions from the outer layer. A novel strategy is needed to recover or regenerate plastic additives after they have been processed several times since the chemicals that are utilized most often are still harmful. The goal is to make sure that new materials have little or no toxicity by screening and monitoring them.

PROBLEMS AND CHANCES

Green Chemistry has done a lot of great things. It has made effective fire-extinguishing agents that get rid of halon and drugs without making any poisonous waste. Yttrium has taken the place of lead in higher-performance car coatings, and arsenic has been taken out of wood preservatives. People are using bio-based polymers to package food. Liquid carbon dioxide has taken the place of ultra-pure water in the making of chips. Pesticides kill pests, but they break down in a way that is good for the environment. But the advances are disruptive, and there are several institutional, cultural, and infrastructural impediments that make it hard for them to be widely used [20]. To encourage more use of Green Chemistry in the future, it is important to understand these problems. Understanding the problems helps create plans for making lasting improvements in product and process design. These frameworks help society and the economy reach their long-term goals for sustainability [24].

CONCLUSION

A few new ideas have made chemical processes much safer and more reliable. Researchers are frequently making exciting new discoveries and advances. There is also great potential currently within the field using simple improvements to basic procedures.

Green chemistry is still a good way to deal with problems that come up nowadays. But putting it into practice on a large scale is still hard, especially when it comes to dealing with the toxicity, reactivity, and destiny of chemicals.

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