

Green and Sustainable Chemistry: Driving Environmental and Industrial Futures

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Abstract

Green and sustainable chemistry is reshaping chemical science and manufacturing by embedding pollution prevention, resource efficiency, and hazard reduction into molecular and process design. In this review, we present the historical foundations and environmental imperatives that motivated green chemistry and outline how its core mechanisms, atom economical syntheses, catalysis, safer solvent systems, renewable feedstocks, and design for degradation are driving industrial transformation. The 12 Principles of green chemistry are summarized with representative examples and practical integration challenges, alongside widely used performance metrics such as atom economy, E factor/PMI, energy intensity, toxicity/safer chemicals indicators, and life cycle assessment. Particular attention is given

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to efficiency oriented principles 6–9, which reduce energy demand, minimize auxiliary substances and unnecessary derivatization, and strengthen operational and end of life safety. Reported environmental benefits include measurable reductions in hazardous waste and pollutant releases, water savings enabled by solvent substitution and process intensification, and greenhouse gas emission cuts achieved through lower temperature routes and renewable carbon inputs, supporting climate mitigation and alignment with the UN Sustainable Development Goals while contributing to ecosystem services and biodiversity protection. Industrial applications are highlighted across pharmaceuticals (streamlined drug synthesis), fine chemicals (biomass to platform molecules), textiles (low impact dyeing and finishing), and the energy sector (biofuels, batteries, and efficiency improvements). Recent advances in precision catalysis, biocatalysis, continuous flow processing, AI assisted optimization, and circular design strategies that valorize waste as a resource indicate clear future trajectories toward resilient, low carbon chemical production.

Keywords: *Sustainable chemical manufacturing; Life-cycle assessment; Biocatalysis; Waste valorization; Flow chemistry; Green chemistry; Atom economy; SDGs*

1. Introduction

Humanity confronts unprecedented environmental crises, with climate change, biodiversity loss, and rampant pollution threatening planetary stability. Global temperatures have risen by approximately 1.2°C since pre-industrial times, fuelling extreme weather events that cost trillions annually, while chemical pollution exacerbated by traditional manufacturing releases over 350,000 synthetic chemicals into ecosystems yearly, many persistent and bioaccumulative [1, 2]. In this context, green and sustainable chemistry emerges as a transformative paradigm, redefining chemical sciences to propel a viable future. This discipline shifts from end-of-pipe remediation to proactive design of processes and products that minimize waste, hazards, and ecological footprints, fostering harmony between industrial innovation and planetary health. By integrating principles of prevention, efficiency, and renewability, it directly tackles global challenges like pollution, climate change, and resource depletion, positioning chemistry as a cornerstone of sustainable development.

The urgency stems from stark realities: industrial activities account for 24% of global greenhouse gas emissions, with chemical production alone generating 5-10% of total energy use and vast hazardous waste [3]. Plastic pollution chokes oceans, microplastics infiltrate food chains, and toxic releases contaminate water for 2.2 billion people lacking safe drinking sources [4]. Conventional chemistry's linear economy extract, produce, discard amplifies these issues, depleting finite resources like rare earths and petroleum at rates exceeding natural replenishment. Green chemistry counters this by embedding sustainability from molecular design,

yielding safer materials, reduced emissions, and circular systems that regenerate value from waste.

2. Historical Foundations

Green chemistry's origins trace to the 1960s-1970s environmental awakening, ignited by Rachel Carson's *Silent Spring*, exposing DDT's ecological devastation and scandals like Minamata mercury poisoning. These catalyzed regulations, such as the U.S. Clean Air Act (1970), but early fixes focused on cleanup, not prevention [5]. The 1990 Pollution Prevention Act marked a watershed, prioritizing source reduction over treatment, birthing green chemistry as an innovation engine. In 1991, the U.S. EPA launched its Green Chemistry Program, followed by Paul Anastas and John Warner's seminal 1998 book, *Green Chemistry: Theory and Practice*, outlining 12 principles that endure as the field's foundation [6].

These principles evolved amid globalization: the 2000s saw the EU's REACH framework mandate safer chemicals, while the UN's 2015 Sustainable Development Goals (SDGs) intertwined green chemistry with SDG 6 (clean water), SDG 12 (sustainable consumption), SDG 13 (climate action), and SDG 14 (oceans) [7]. By 2020s, "sustainable chemistry" broadened the scope, incorporating lifecycle assessments, social equity, and economic viability, as UNEP's 2024 manual outlined 10 objectives for hazard-free, circular processes. This progression reflects chemistry's pivot from polluter to problem-solver.

2.1. Core Principles and Mechanisms

Anastas and Warner's 12 principles form green chemistry's blueprint, urging prevention over remediation. Principle 1 mandates waste prevention; Principle 2, atom economy, ensures maximal reactant incorporation into products, often achieving >95% yields versus traditional 40-60%. Principles 3-5 promote safer syntheses, chemicals, and solvents (e.g., water or supercritical CO₂ over toluene), while 6-7 stress energy efficiency and renewable sources like biomass over petrochemicals. Catalysis (Principle 9) and real-time analysis (Principle 11) enable precise control, reducing inputs by orders of magnitude [8]. Principle 12 designs for safer use, degradation, and accident prevention. These dismantle linear models, fostering cycles where outputs become inputs, slashing entropy and aligning with circular economy tenets [9]. Metrics like Sheldon's E-factor (waste kg/product kg) quantify success: pharma dropped from 25-100 to <5 via green routes.

2.2. Environmental Imperative

Traditional chemistry's toll is immense: it produces 90% of industrial toxins, with U.S. facilities historically releasing billions of pounds yearly. Green innovations averted 830 million pounds of hazards and saved 21 billion gallons of water via

EPA Presidential Challenges [10]. By curbing effluents, they protect aquifers and soils, advancing SDG 6/14 amid 80% of wastewater being untreated globally [11]. Energy thrift cuts GHGs, catalytic processes at room temperature slash fossil use by 90% while bio-feedstocks preserve biodiversity [12]. In hotspots like India's Ganges or China's rivers, these prevent persistent pollutants, enabling ecosystem regeneration.

2.3. Industrial Transformations and Future Trajectories

Markets validate impact: green chemicals surged from \$122 billion in 2025 toward \$272 billion by 2033, led by bio-polymers and solvents [13]. Pharma's Pfizer slashed sildenafil waste 90%; Novozymes' enzymes greened detergents. Ahead, AI designs catalysts, biomimicry yields self-healing materials, and 2026 conferences spotlight waste-to-value. Challenges like scale-up persist, but policies propel net-zero futures. Green and sustainable chemistry thus bridges ingenuity and stewardship, driving industry-planet synergy. This review unpacks strategies, cases, and horizons for stakeholders.

3. Core Principles and Metrics

Green chemistry's foundational framework rests on the 12 principles articulated by Paul Anastas and John Warner in 1998, which guide the design of chemical products and processes to reduce or eliminate hazardous substances from their inception. These principles prioritize prevention, efficiency, and safety, transforming traditional synthesis into sustainable practices that minimize environmental and health risks. Far from abstract ideals, they integrate quantifiable metrics like atom economy and E-factors, enabling chemists to measure and optimize sustainability across molecular design, synthesis, and lifecycle stages.

The principles cluster into themes of waste reduction, safety, efficiency, and renewability, with practical examples drawn from pharmaceuticals, materials, and manufacturing. Principle 1 stresses prevention, advocating waste avoidance over treatment; for instance, solvent-free polyester synthesis eliminates cleanup needs. Principle 2, atom economy, maximizes reactant incorporation into products Pfizer's green sildenafil process achieved 91% atom economy versus 37% in traditional routes, slashing byproducts [14].

Principle 3 (less hazardous synthesis) favours routes generating benign substances, as in ibuprofen production via acetic anhydride instead of toxic hydrogen fluoride. Principle 4 (designing safer chemicals) ensures functionality without toxicity, exemplified by non-bioaccumulative fluorinated alternatives in refrigerants. Principle 5 (safer solvents/auxiliaries) promotes water or supercritical CO₂ over volatile organics; ethyl lactate from renewables replaces toluene in extractions [14].

Principle 6 (energy efficiency) targets ambient conditions, microwave-assisted reactions cut energy by 85%. Principle 7 (renewable feedstocks) shifts to biomass; bio-based adipic acid from glucose supplants petroleum-derived versions [14]. Principle 8 (reduce derivatives) minimizes protection steps, as in one-pot enzymatic peptide synthesis. Principle 9 (catalysis) prefers selective catalysts over stoichiometric reagents; Novozymes' enzymes in detergents amplify yields under mild conditions [14].

3.1. Closing principles ensure end-of-life and operational safety

Principle 10 (design for degradation) creates biodegradable polymers like polylactic acid from corn starch. Principle 11 (real-time pollution prevention) employs in-line monitoring, such as process analytical technology (PAT) in pharma for instant adjustments. Principle 12 (inherently safer processes) minimizes accident risks, as in continuous flow reactors, replacing batch explosions. **Table/ 1** reveals examples of the 12 principles of green chemistry, highlighting practical processes and their sustainability gains, such as waste reduction, energy savings, safer reagents, and improved material efficiency.

Table 1: Examples illustrating the principles of green chemistry with sustainability gains

Principle	Key Focus	Example	Sustainability Gain bchgreenlabs+1	Ref
Prevention	Avoid waste generation	Solvent-free polymerizations	100% waste reduction	[15, 16]
Economy	Maximize material use	Sildenafil synthesis (Pfizer)	91% vs. 37% incorporation	[17, 18]
Less Hazardous Synthesis	Benign reagents/products	Acetic anhydride for ibuprofen	No HF corrosion	[15, 18]
Safer Chemicals	Function without toxicity	Safer refrigerants	Reduced ozone depletion	[19]
Safer Solvents	Innocuous auxiliaries	Supercritical CO ₂ extraction	No VOC emissions	[20]
Energy Efficiency	Ambient conditions	Microwave synthesis	85% energy savings	[21]
Renewables	Biomass feedstocks	Bio-adipic acid	Cuts fossil use by 60%	[22]
Reduce Derivatives	Fewer steps	One-pot enzymatics	Halves reagents	[23]
Catalysis	Selective over stoichiometric	Enzyme detergents	10x yield boost	[24]
Degradation	Biodegradable products	PLA plastics	Full composability	[25]
Real-Time Analysis	In-process monitoring	PAT in reactors	99% yield control	[26]
Safer Processes	Accident prevention	Flow chemistry	No explosion risk	[27]

3.2. Key Assessment Metrics

Metrics operationalize these principles, providing data-driven benchmarks for greenness. Atom economy, calculated as $\frac{\text{molecular weight of product}}{\sum \text{molecular weights of reactants}} \times 100$ quantifies efficiency; ideal reactions approach 100%, as in Diels-Alder cycloadditions. For complex syntheses, stereoselectivity and yield refine this, with catalytic processes often exceeding 95% [6, 28]. The E-factor (environmental factor), introduced by Roger Sheldon, measures waste: $E = \frac{\text{kg waste}}{\text{kg product}}$. Oil refining boasts $E=0.1$, but pharma averages 25-100, dropping to <5 via green routes like BHC's shikimic acid process (E from 210 to 0.6). Process Mass Intensity (PMI) extends this: $PMI = \frac{\text{total mass in}}{\text{mass product}}$, capturing solvents (often 80-90% of mass). Life Cycle Assessment (LCA) holistically evaluates cradle-to-grave impacts using ISO 14040 standards, scoring energy, emissions, and toxicity via tools like SimaPro or GaBi. LCA reveals trade-offs; bio-based solvents may raise land use but cut GHGs by 50-70% [28]. Complementary tools include Green Aspiration Level (GAL) for Score** for multi-metric scoring and DOZN™ for hazard profiling.

3.3. Integration and Challenges

These principles and metrics synergize: high atom economy lowers E-factors, while LCA validates scalability. Software like IBM RXN integrates AI for principle-compliant retrosynthesis. Challenges include quantifying principle 4's "toxicity," relying on predictive toxicology and balancing metrics amid economic pressures [29]. Yet, the EPA Green Chemistry Awards document cumulative impacts: 830M lbs hazards averted. In practice, principles guide innovation, as in UNEP's 10 sustainable chemistry objectives emphasizing circularity. This section equips readers to apply them systematically, fostering metrics-driven progress toward sustainable futures.

4. Environmental Impacts and Benefits

Traditional chemical processes inflict profound environmental damage, generating vast hazardous wastes, greenhouse gases (GHGs), and pollutants that compromise air, water, and soil integrity. Globally, the chemical sector emits over 1.5 gigatons of CO₂ equivalents annually, while U.S. facilities historically released billions of pounds of toxins yearly, contributing to 24% of industrial GHGs [30]. Green chemistry reverses this trajectory by preventing pollution at the source, yielding measurable benefits in waste diversion, resource conservation, and ecosystem restoration. EPA-recognized technologies alone have eliminated nearly 1 billion pounds of hazardous chemicals, such as solvents, underscoring the field's scalable impact.

4.1. Quantified Pollution Reduction

Green innovations have slashed toxic releases dramatically. EPA Green Chemistry Challenge winners averted 830 million pounds of hazards annually through redesigned syntheses, alongside eliminating emissions equivalent to 8 billion pounds of CO₂. Pharmaceutical firms, notorious for high waste (E-factors up to 100), halved TRI-reported releases from 2004-2013 via greener solvents and catalysts, reducing methanol and toluene by 75%, not due to outsourcing but inherent process improvements [31]. Overall, TRI data shows a 7% drop in chemical waste to land, air, and water over the decade, with hydrochloric acid and trichloroethylene declining >60%. In manufacturing, enzyme-based detergents from Novozymes biodegrade fully, preventing aquatic toxicity versus persistent phosphates. Bio-pesticides and biodegradable fertilizers cut soil/water contamination from agrochemicals, reducing non-point source pollution. These reductions mitigate bioaccumulation, where toxins like PCBs concentrate up food chains, harming wildlife and humans.

4.2. Water Savings and Resource Conservation

Water scarcity amplifies green chemistry's value: awardees conserved over 20 billion gallons annually by minimizing usage in reactions and cleanups. Optimized wastewater treatment via green coagulants and advanced oxidation achieves 189% eco-efficiency gains, curbing freshwater withdrawal (industry uses 20% globally) [32]. Supercritical CO₂ extractions eliminate aqueous solvents, as in decaffeination, saving millions of gallons. Renewable feedstocks like biomass-derived monomers preserve aquifers strained by petrochemical extraction, aligning with circularity to regenerate resources.

4.3. GHG Emission Cuts and Climate Mitigation

Green processes deliver substantial GHG reductions: catalytic routes at ambient temperatures slash energy by 85-90%, equivalent to billions of pounds of CO₂ avoided. Bio-based plastics from corn/sugarcane cut fossil emissions by 60-70% over petroleum polymers [33]. Lifecycle analyses confirm: green batteries and solar cells lower clean energy footprints. Collectively, these combat climate change, with chemical innovations offsetting 1-2% of industrial emissions yearly.

Alignment with UN Sustainable Development Goals

Green chemistry propels multiple SDGs, providing targeted solutions:

- *SDG 6 (Clean Water and Sanitation)*: Reduced effluents protect 2.2 billion without safe water; safer coagulants purify without residues.
- *SDG 12 (Responsible Consumption/Production)*: Circular designs minimize waste; Dow's catalysts boost efficiency, cutting residues in supply chains.

- *SDG 13 (Climate Action)*: GHG cuts via renewables; aligns with Paris Agreement through low-carbon processes.
- *SDG 14 (Life Below Water)*: Biodegradable products prevent ocean plastics (14M tons/year); enzyme detergents safeguard marine life.

4.4. Ecosystem Services and Biodiversity Preservation

Beyond metrics, green chemistry restores ecosystem services valued at trillions: clean water filtration, pollination, and carbon sequestration. Curbing persistent pollutants, it prevents eutrophication dead zones from nutrient runoff and endocrine disruption in fish. Bio-based alternatives mitigate habitat loss from mining (e.g., rare earths for catalysts), preserving 30% of biodiversity hotspots. In agriculture, biopesticides foster soil microbiomes, enhancing fertility without erosion. **Table/ 2** summarizes the health co-benefits of green chemical practices, including reduced fenceline exposures in marginalized communities, thereby supporting environmental justice.

Table 2: Health co-benefits include fewer fenceline exposures in marginalized communities, advancing environmental justice [34].

Impact Area	Green Chemistry Benefit	Quantified Example epa+1
Hazardous Waste	Source prevention	1B lbs chemicals/year avoided
Water Use	Efficient processes	20B+ gallons/year saved
GHG Emissions	Low-energy catalysis	8B lbs CO ₂ equiv./year cut
SDG 6/14	Reduced aquatic toxins	Biodegradable outputs
Biodiversity	Renewable feedstocks	60% lower habitat impact

4.5. Broader Implications and Validation

These benefits compound: lower pollution burdens ecosystems, enabling resilience against climate stressors. EPA analyses confirm green practices drive reductions, not economics. Recent 2025 nominations highlight bio-proteins from waste, extending gains. Challenges remain in verifying long-term degradation, but metrics like LCA ensure rigour. Green chemistry thus quantifiably safeguards environments, aligning industrial futures with planetary health.

5. Industrial Applications and Case Studies

Green chemistry permeates diverse industries, delivering economic and environmental gains through redesigned processes that embody the 12 principles. From pharmaceuticals to energy, applications reduce waste, energy, and costs while enhancing scalability. This section reviews the sector-specific implementations and spotlights successes.

5.1. Pharmaceuticals: Streamlining Drug Synthesis

Pharma leads in green adoption, tackling high E-factors (25-100 kg waste/

kg product). Pfizer's sildenafil citrate (Viagra) exemplifies: the original 8-step process used toxic solvents (e.g., dichloromethane) and reagents, yielding E-factor ~80 [35]. Redesigned to 5 steps with safer chemistry convergent synthesis, no extractive workups, and efficient solvents, it achieved E-factor 6 [Figure 1], atom economy 91% (vs. 37%), and 90% waste cut. No chromium or cyanide; solvent recovery hit 90%. This earned the 2003 UK Green Chemical Technology Award and scaled to tons/year. BASF's artemisinin antimalarial used plant extraction and semi-synthesis, slashing energy by 70% and solvents. Enzymatic resolutions boost stereoselectivity, reducing racemic waste.

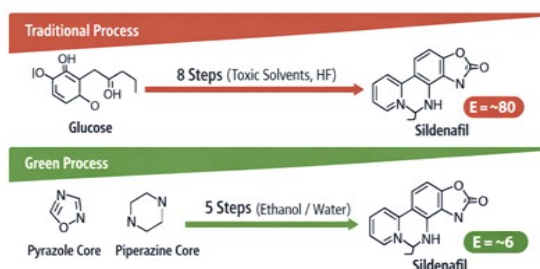


Figure 1: Simplified process flow for sildenafil synthesis comparing traditional and green routes [35].

5.2. Fine Chemicals: Biomass to Platform Molecules

Fine chemicals shift to renewables, exemplified by adipic acid (nylon precursor, 3M tons/year). Conventional nitric oxidation of cyclohexane emits 5-8 tons NO_x/ton product and relies on petroleum. Green routes oxidize biomass-derived glucose to glucaric acid (Pt/CNT catalyst, 90% yield), then deoxygenate via ReO_x-Pd/C (99% adipic acid yield). This bifunctional catalysis removes four OH groups efficiently, cutting GHGs by 60% and NO_x to zero [36]. The pathway of adipic acid is depicted in Figure 2. Rennovia (now UOP) commercialized this, with pilots producing tons sustainably.

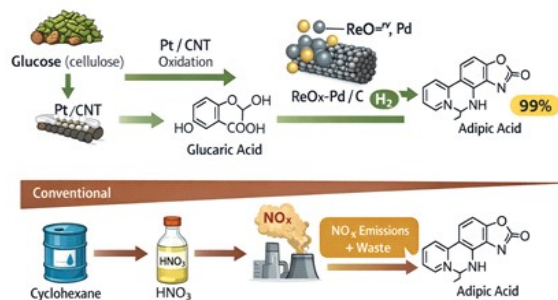


Figure 2: Biomass adipic acid production pathway [36]

5.3. Textiles: Low-Impact Dyeing and Finishing

Textiles consume 93B m³ water/year and 10% industrial energy, discharging azo dyes and salts. Green shifts: enzymatic scouring replaces NaOH (saves 50% water/energy); plasma/UV pretreatment boosts dye uptake 30%, eliminating carriers. Inditex/Zara uses reducing sugars over Na₂S for sulfur dyeing, non-toxic, biodegradable, cutting H₂S emissions 100%. Bio-based dyes from microbes/algae reduce metal mordants; supercritical CO₂ dyeing (Nikolaus Sonneborn) is waterless, solvent-recyclable (95%), slashing effluent [37].

Figure 3 illustrates a comparison between traditional fabric dyeing processes and sustainable dyeing approaches, highlighting differences in water usage, chemical consumption, energy demand, and environmental impact. These yield zero-liquid discharge, aligning with ZDHC standards.



Figure 3: Sustainable vs. Traditional fabric dyeing processes [37]

5.4. Energy Sector: Biofuels, Batteries, and Efficiency

Energy leverages catalysis for low-carbon fuels/materials. Novozymes dominates with enzymes: 700+ products avert 76M metric tons CO₂/year across bioenergy [38]. In biofuels, cellulases hydrolyze biomass to sugars (yield >90%), enabling ethanol from corn stover to cut fossil fuels by 86% vs. gasoline. Detergents use lipases/proteases, replacing phosphates (lakes eutrophication avoided) and boosting cold-water efficacy (20% energy savings/wash). Lithium-ion batteries employ green electrolytes (ionic liquids over flammables); solar PV uses bio-sourced encapsulants. Hydrogen peroxide via the anthraquinone process is greened electrochemically, eliminating solvents. As shown in Figure 4, enzyme-enabled pathways integrate biomass processing and household sustainability by facilitating efficient bioconversion of organic waste into value-added products while reducing energy consumption and

environmental impact. Life cycle assessments of enzyme applications highlight sustainability benefits in bioethanol and household detergent applications.

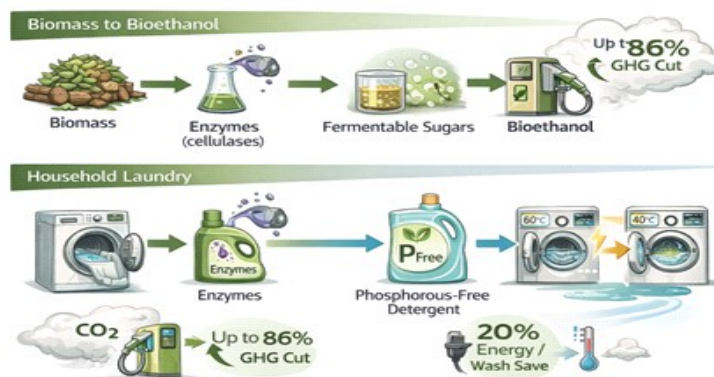


Figure 4: Enzyme-enabled biomass and household sustainability pathways [38]

6. Technological Advances and Innovations

Green chemistry thrives on cutting-edge technologies that operationalize its principles, from advanced catalysis to digital tools, enabling unprecedented efficiency and sustainability. Innovations in biocatalysis, flow chemistry, AI optimization, renewable feedstocks, and circular designs address waste and resource limits, propelling the sector's growth from USD 122 billion in 2025 to USD 272 billion by 2033 at a 10.5% CAGR, driven by bio-based chemicals and regulations [39]. These advances minimize environmental footprints while boosting yields, with scaling challenges increasingly met through hybrid systems and policy support.

Catalysis (Principle 9) evolves with heterogeneous and organocatalysts replacing stoichiometric reagents. Single-atom catalysts (SACs), like Pt on graphene, achieve 99% selectivity in CO₂ electroreduction to methanol, slashing energy 50% vs. traditional routes. Photocatalysis harnesses sunlight for H₂ production or pollutant degradation. TiO₂ variants mineralize dyes 95% efficiently. These cut GHGs and enable ambient conditions (Principle 6), as in Rusal's aluminium electrolysis with inert anodes, reducing CO₂ 80%.

Enzymes and whole-cell biocatalysts excel in mild, selective transformations. Directed evolution yields variants tolerant to organics; Codexis' enzymes produce sitagliptin (Januvia) with 99% ee and 19% yield boost, E-factor <2. Novozymes' 700+ products avert 76M tons CO₂/year in biofuels/detergents [40]. Immobilized enzymes enable reuse (100+ cycles), as in lipases for biodiesel from waste oils (95% conversion). Hybrid chemo-enzymatic cascades streamline multi-steps, cutting waste by 70%. Figure 5 reveals that a substrate undergoes an initial oxidation step catalysed

by Enzyme 1, followed directly (without intermediate isolation) by a reduction step catalysed by Enzyme 2 in a single reaction vessel (one-pot cascade), delivering the desired product in high overall yield (typically >90 %). Cascade biocatalysis enables combined redox transformations under mild conditions with reduced waste and solvent use relative to separate stepwise reactions. Inspired by industrial biocatalysis workflows such as those developed by Codexis [41].

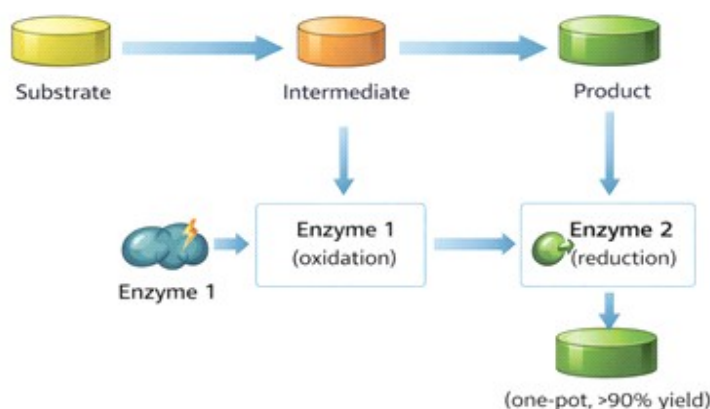


Figure 5. Biocatalytic cascade example [41]

Microfluidic flow reactors embody Principle 12 (safer processes), enabling precise control and hazardous handling. Coriolis' pharma platforms run nitrations/explosives continuously, yield up to 99%, waste <1%. Vaportec systems scale from mg to kg, reducing solvents by 90%. Photoflow integrates light for green photochemistry, producing APIs 10x faster.

AI revolutionizes retrosynthesis and optimization. IBM RXN predicts green routes with 90% accuracy; AlphaFold3 designs novel enzymes for plastic degradation. Machine learning tunes catalysts, Google DeepMind's GNoME discovered 2.2M stable materials, accelerating renewables. These tools embody Principle 11 (real-time analysis), minimizing trials by 80%. Principle 7 drives biomass valorization: lignocellulose to platform chemicals via hydrothermal liquefaction (yields 50% bio-crude). CO₂ utilization electroreduction to ethylene (Cu catalysts, 70% FE) closes carbon loops. Waste plastics depolymerize enzymatically (Cabrios' PETase recycles 90%).

Circularity integrates degradation (Principle 10) with recycling: self-healing polymers via dynamic bonds repair 90%; covalent adaptable networks (CANs) reprocess indefinitely. Chemical recycling of mixed plastics via pyrolysis/catalysis yields monomers 85%. These foster "upcycling," turning waste into high-value

products. The green chemicals market expands rapidly: bio-based segment (40% share) grows 11.5% CAGR, fuelled by EU Green Deal and US IRA incentives. Projections: USD 121.9B (2025) to 271.5B (2033), with biofuels/polymers leading. Asia-Pacific dominates 45%, driven by China/India mandates.

Scaling hurdles persist: biocatalysts deactivate industrially (cost >\$10/kg); flow systems clog at tons. Solutions: immobilization, genetic engineering, and modular reactors. CAPEX for bio-plants rivals Petrochem (20-30% higher), but OPEX drops 40% long-term. Policy aids: subsidies cut payback to 3-5 years. Pilots succeed Rennovia's adipic acid nears commercial.

7. Conclusions

Green and sustainable chemistry stands as a pivotal force in reconciling industrial progress with environmental imperatives, as evidenced across its foundational principles, quantified impacts, and innovative applications. From the historical shift sparked by Anastas and Warner's 12 principles emphasizing prevention, atom economy, and safer designs, the field has evolved into a metrics-driven discipline, wielding tools like E-factors, LCA, and atom economy calculations to benchmark true sustainability. Its environmental benefits are profound: averting billions of pounds of hazardous waste, conserving 20+ billion gallons of water yearly, and slashing GHGs through catalytic efficiencies, all while advancing UN SDGs 6, 12, 13, and 14.

Industrial case studies in pharmaceuticals (Pfizer's sildenafil), chemicals (biomass adipic acid), textiles (enzyme dyeing), and energy (Novozymes biofuels) demonstrate scalable triumphs, reducing E-factors from 80+ to under 6 and unlocking economic gains amid a market surging from USD 122 billion in 2025 to 272 billion by 2033. Technological frontiers, such as biocatalysis, flow chemistry, AI retrosynthesis, and circular feedstocks, further amplify this, overcoming linear "take-make-waste" paradigms with regenerative systems that prioritize renewability and safety. Ultimately, green chemistry transcends incremental fixes, driving transformative futures where chemical innovation fosters planetary health. By embedding sustainability at the molecular level, it equips industries, policymakers, and researchers to navigate resource scarcity and climate crises, ensuring prosperity without ecological compromise. This review underscores its proven trajectory: from principles to practice, green chemistry not only mitigates harm but actively builds resilient, circular economies for generations ahead.

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