

Role of Green Chemistry in Air Pollution Control

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Abstract

Air pollution remains a major health and environmental problem despite substantial progress in controlling emissions. Green chemistry addresses pollution at the point of chemical design: it seeks safer substances, efficient reactions, less hazardous solvents, lower energy demand, and monitoring that prevents unwanted by-products. This narrative review examines how these strategies can reduce volatile organic compounds, nitrogen oxides, sulfur dioxide, particulate matter precursors, and toxic releases across manufacturing and product use. It uses published guidance and emissions summaries from the United States Environmental Protection Agency and the World Health Organization. An EPA trend dataset shows large reductions in several U.S. pollutants between 1990 and 2022, but those aggregate reductions cannot be assigned to green chemistry alone. The strongest contribution of green chemistry is a change in the production system itself, especially when safer substitution and process redesign prevent emissions before exhaust treatment becomes necessary. Performance, cost, worker safety, and life cycle impacts must be checked together to avoid shifting pollution to another stage or medium.

Keywords: green chemistry; air pollution; source reduction; volatile organic compounds; catalysis; life cycle assessment

1 Introduction

Ambient air pollution was associated with an estimated 4.2 million premature deaths worldwide in 2019, according to the World Health Organization (WHO, 2024). Fine particles are especially consequential because they can penetrate the respiratory system and contribute to cardiovascular and pulmonary disease. Industrial combustion, transport, agriculture, solvent use, and consumer products each add different contaminants to the atmosphere. Air quality depends on both directly emitted pollutants and secondary products formed through atmospheric reactions. For example, volatile organic compounds (VOCs) and nitrogen oxides (NO_x) can form ground level ozone, while sulfur dioxide (SO₂), NO_x, and ammonia (NH₃)

can contribute to secondary particulate matter. Reducing the harmful chemistry behind these emissions therefore complements conventional air quality regulation.

Conventional control often captures or destroys pollution after it forms: scrubbers remove acidic gases, filters capture particles, and oxidizers destroy VOCs. These technologies remain essential, especially for existing facilities. Green chemistry asks an earlier question: can the chemical, solvent, feedstock, reaction, or product be redesigned so that less pollution forms in the first place? The U.S. Environmental Protection Agency (EPA) defines green chemistry as designing chemical products and processes that reduce or eliminate hazardous substances (EPA, n.d.-a). This paper reviews mechanisms, applications, evidence, limitations, and practical priorities. It treats national emissions trends as context rather than a test of any single intervention.

2 Method and Conceptual Framework

This is a narrative review of primary institutional material, including EPA green chemistry principles, pollution prevention guidance, and national emissions trends, alongside WHO health estimates. The synthesis groups interventions by the stage at which they change emissions: molecular design, production, product use, and measurement. It does not claim to be a systematic review or conduct an original experiment. The numerical table and graph reproduce percentage changes reported by EPA for U.S. emissions from 1990 to 2022; they do not estimate the contribution attributable to green chemistry.

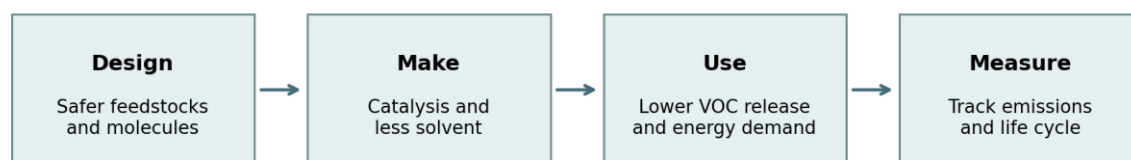


Figure 1. Green chemistry intervention points across a product life cycle. Author constructed schematic.

The twelve principles of green chemistry emphasize waste prevention, atom economy, less hazardous synthesis, safer chemicals and solvents, energy efficiency, renewable feedstocks, catalysis, degradation after use, real time analysis, and accident prevention (EPA, n.d.-b). Several principles overlap in an air pollution problem. A solvent change may reduce evaporation but require additional heat for drying; a

catalyst may lower reaction temperature but introduce a difficult metal recovery problem. A credible claim of improvement therefore compares the whole process with a realistic baseline, accounting for direct releases and upstream energy or material demand.

The chemistry of secondary pollution explains why precursor prevention matters. In sunlight, nitrogen dioxide photolyzes to generate reactive oxygen, which combines with molecular oxygen to make ozone. VOC oxidation produces peroxy radicals that convert nitric oxide to nitrogen dioxide without consuming ozone, allowing ozone to accumulate. Oxidation of SO₂ and NO_x produces sulfuric and nitric acids that can react with ammonia to form fine sulfate and nitrate aerosols. The atmosphere contains competing reactions and variable meteorology, so a kilogram reduction in one precursor does not imply a fixed reduction in ozone or PM_{2.5}. Nevertheless, preventing precursor release removes reactants from these pathways and often reduces direct exposure as well.

3 Pathways for Air Pollution Prevention

3.1 Safer solvents and low emission formulations

Organic solvents evaporate during synthesis, cleaning, coating, printing, and application. Depending on their composition, released VOCs can contribute to ozone formation and expose workers or nearby residents to hazardous compounds. Waterborne formulations, high solids coatings, solvent free reactions, and carefully selected low volatility media can reduce releases at their source. The main benefit arises when the redesigned product actually replaces evaporative solvent without increasing toxicity or causing major losses in performance. “Solvent free” also requires scrutiny: a concentrated formulation may still depend on solvent intensive raw material manufacture or energy intensive washing after use.

Solvent substitution must distinguish several goals. Low vapor pressure can lower direct evaporation, but it does not by itself guarantee low toxicity, rapid environmental breakdown, or low climate impact. A water based coating can avoid much of the organic solvent load while potentially demanding more drying energy. Facilities should measure the mass of solvent purchased, recovered, and emitted per unit of finished product, along with occupational exposure and product quality. This material balance makes the prevention claim testable rather than relying on a label such as “green.”

The relevant physicochemical properties include vapor pressure, boiling point, water miscibility, flash point, atmospheric reactivity, and toxicity. A low boiling solvent can be convenient to remove from a reaction mixture but readily escapes from open equipment. A higher boiling replacement can reduce fugitive loss yet require more heat for evaporation and leave residues in the product. Solvent guides

therefore need to be applied to the specific reaction, recovery equipment, and use setting. For a coating, curing chemistry and film performance determine whether eliminating solvent actually decreases the total material and energy used over the service life.

3.2 Catalysis and reaction efficiency

A selective catalyst can improve yield, reduce by-products, and allow milder reaction conditions. In chemical manufacture, higher selectivity means less unwanted material requiring separation, incineration, or disposal. Lower temperature and pressure may reduce fuel combustion and its associated NO_x, SO₂, and particulate emissions, depending on the energy source. Catalysis also supports exhaust treatment, including oxidation of carbon monoxide and hydrocarbons and reduction of nitrogen oxides. However, catalytic removal from exhaust is primarily an end of pipe measure; the green chemistry contribution is clearest when catalysis redesigns the underlying synthesis or energy use.

Industrial implementation is constrained by catalyst cost, poisoning, stability, and recovery. Precious metals and certain transition metals carry upstream impacts that can offset some operating benefits. Engineers should compare catalyst lifetime, selectivity, regeneration requirements, energy consumption, and emissions per tonne of saleable product. A laboratory reaction that performs well in a clean flask may behave differently with variable industrial feedstocks. Pilot scale testing is therefore an important bridge between attractive chemistry and measurable atmospheric benefit.

Chemists can quantify reaction improvement with atom economy, reaction mass efficiency, and the E factor, defined as mass of waste divided by mass of product. Atom economy follows a balanced reaction equation and indicates how much reagent mass can theoretically appear in the desired molecule; it does not include solvent or purification losses. Reaction mass efficiency incorporates actual yield and reagent excess. The E factor captures waste more broadly but depends on whether water and recovered solvent are counted. None of these metrics alone measures airborne toxicity. Pairing them with a measured VOC emission factor and process energy intensity gives a better picture of air quality consequences.

3.3 Feedstocks, product design, and degradation

Renewable or recycled feedstocks can displace fossil derived inputs when their cultivation, collection, and processing create fewer overall impacts. The route matters more than the label: biomass grown with fertilizer, transported long distances, or processed with large quantities of heat can generate NH₃, NO_x, or particulate precursor emissions. Similarly, redesigning a molecule to perform its function at lower dose can reduce raw material handling and waste. Designing products to degrade into innocuous substances after use

can limit persistent contamination, although rapid degradation is not always desirable during storage or service.

Product design can also reduce emissions during consumer use. Low emission adhesives, cleaning products, inks, and building materials may lower VOC release in occupied spaces and outdoors. Design teams must consider both the compound emitted and its ozone formation potential, toxicity, and exposure pattern. For example, replacing one strong solvent with several less volatile ingredients could lower measured VOC mass yet introduce a different health concern. Independent safety assessment and transparent ingredient information improve confidence in substitution decisions.

3.4 Energy efficiency and continuous processing

Heating, cooling, distillation, and repeated batch cleaning consume energy. Reactions that proceed at ambient conditions, use fewer separation steps, or operate continuously can reduce fuel consumption per unit of output. Continuous processing can also improve control of temperature and reagent addition, limiting runaway reactions and off specification batches. In electricity intensive processes, air quality gains depend on the electricity mix and the time at which power is used. An efficient process is not automatically cleaner if it causes a large increase in total production or relies on a more polluting energy supply.

Real time analytical monitoring detects impurities, incomplete conversion, solvent leaks, or changing catalyst performance before they create avoidable waste. Leak detection and repair are especially useful when volatile materials are transferred through many fittings and storage tanks. Monitoring should connect process indicators to actual stack, fugitive, and workplace measurements. This makes it possible to distinguish theoretical emission potential from observed emission reductions under normal operating conditions.

4 Quantitative Context and Interpretation

The EPA reports substantial changes in national U.S. emissions from 1990 to 2022. Table 1 and Figure 2 present selected percentage reductions from its Our Nation's Air 2023 summary (EPA, 2023). The pollutants are not equally harmful per tonne, and percentage changes do not convey absolute mass, local exposure, or differences among source sectors. They are useful as a broad indication of the scale of air pollution control achieved across many policies and technologies.

Table 1. Reported reductions in U.S. pollutant emissions, 1990 to 2022

Pollutant	Reduction (%)	Relevant green chemistry pathway
Sulfur dioxide (SO ₂)	92	Lower sulfur feedstocks; reduced fuel demand
Nitrogen oxides (NO _x)	71	Lower temperature processing; reduced fuel demand
Carbon monoxide (CO)	70	Efficient combustion and process design
Volatile organic compounds (VOCs)	48	Safer solvents and low emission products
Direct fine particles (PM _{2.5})	27	Cleaner processes and lower combustion
Ammonia (NH ₃)	20	Improved chemical and fertilizer handling

Source: EPA (2023). Percentages compare estimated 2022 national emissions with 1990 levels. Pathways in the final column are illustrative mechanisms, not causal estimates.

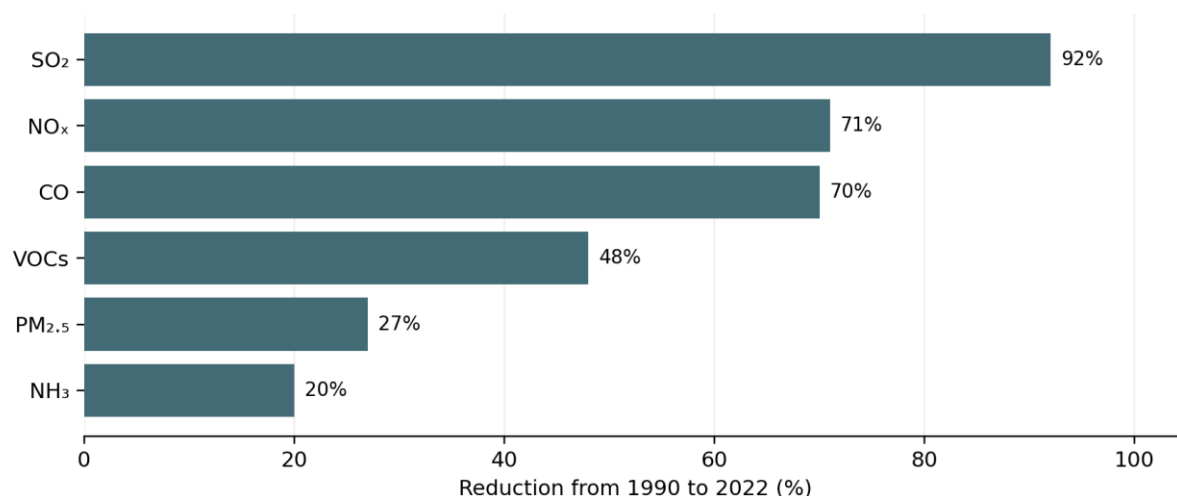


Figure 2. Percentage reduction in selected U.S. pollutant emissions, 1990 to 2022. Author graph from EPA (2023).

SO₂ shows the largest decline among these categories, while direct PM_{2.5} and NH₃ show smaller percentage declines. These figures must not be presented as the measured effect of green chemistry. The national pattern reflects regulation, fuel switching, changes in economic activity, cleaner vehicles, exhaust controls, industrial practices, and other factors. Furthermore, a national percentage can conceal areas with persistent exposure. A facility level evaluation of green chemistry should instead compare the same product and functional output before and after substitution, ideally accounting for changes in throughput, energy source, and pollution transferred to water or solid waste.

5 Application in Major Sectors

In coatings and printing, the most direct opportunity is reducing solvent evaporation by switching to suitable waterborne, powder, ultraviolet cured, or high solids formulations. The formulation must still meet durability and application requirements, because premature failure can increase replacement frequency and total emissions. Chemical manufacturing can use selective catalysis, continuous flow synthesis, and solvent recovery alongside safer reagents. Pharmaceutical synthesis is a particularly useful setting for tracking solvent intensity and reaction mass efficiency because multistep production can consume large volumes of auxiliary material.

Agriculture links green chemistry with air pollution through fertilizers and pesticides. Improved fertilizer formulations and application technologies may lower ammonia losses, although field outcomes depend heavily on weather, soil, and management. Less volatile pesticide formulations can reduce drift and inhalation exposure. Transport and energy production require broader system changes beyond chemistry alone, but cleaner fuels, batteries, catalytic materials, and process efficiency can play supporting roles. In all sectors, source prevention works best when paired with standards, measurement, maintenance, and worker training.

6 Challenges and Research Priorities

The first challenge is avoiding regrettable substitution. Replacing a familiar hazardous compound with a poorly studied alternative may exchange visible emissions for persistent or toxic residues. Screening should consider human health, atmospheric reactions, breakdown products, flammability, and the feasibility of recovery. A second challenge is scale: a laboratory method may depend on expensive reagents or work only for pure inputs. Industrial trials need to evaluate yield, solvent balance, catalyst life, water demand,

downtime, and waste management. A third challenge is uneven access to capital and technical expertise, especially for smaller firms that cannot readily reformulate established products.

Life cycle assessment can reveal whether lower on site VOC emissions coincide with higher upstream emissions from raw material production or electricity generation. Results depend on boundaries, data quality, and the function being compared. For reliable decisions, report both an operational indicator, such as kilograms of VOC emitted per tonne of finished material, and wider impacts per equivalent product function. Emission estimates should be accompanied by uncertainty and, when possible, verified through monitoring. Researchers should also investigate how green chemistry affects local exposure, since a modest reduction near a densely populated facility can matter more for health than a larger reduction at a remote site.

Public policy can encourage prevention by rewarding demonstrable reductions in hazardous substance use and emissions, supporting pilot facilities, and promoting access to chemical hazard data. Procurement specifications can favor performance based safer materials without prescribing a particular chemistry. Reporting systems should distinguish direct releases, precursor emissions, energy related emissions, and avoided waste. Such separation helps prevent the mistake of equating all forms of “green” improvement with improved ambient air quality.

A practical research design would select two production routes yielding the same chemical at the same purity. Investigators would record reagent inputs, product yield, solvent recovery, measured stack and fugitive VOC mass, electricity and fuel use, and catalyst replacement over repeated batches. The primary endpoint could be kilograms of pollutant emitted per kilogram of purified product. Secondary endpoints could include E factor, worker exposure, greenhouse gas emissions, and cost. Replicated measurements under representative operating conditions would allow uncertainty intervals and a meaningful comparison. This design would connect molecular innovation to verified air pollution control more directly than a national trend chart can.

7 Conclusion

Green chemistry provides a practical route to air pollution control by changing chemical choices and production conditions before pollutants are generated. Safer solvents and formulations target VOC releases; selective catalysts and efficient processing can reduce by-products and combustion demand; better feedstock and product design can limit emissions during production and use. The U.S. trends presented here show the scale of broader air quality progress, not the share caused by green chemistry. A defensible project

evaluates emissions per functional unit, exposure, safety, performance, and life cycle tradeoffs against a clearly defined baseline. Green chemistry is most effective as part of an integrated strategy with monitoring, regulation, and conventional controls where residual emissions remain.

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