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Green chemistry and Sustainable disease control

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Abstract

Green chemistry has emerged as a cornerstone of sustainable development, offering principles and practices that reduce or eliminate hazardous substances throughout chemical processes. Its application in agriculture and public health highlights a paradigm shift from conventional, chemically intensive methods of disease management toward environmentally responsible and resource-efficient approaches. Traditional disease control strategies, particularly in crop protection and vector management, often rely on synthetic pesticides and pharmaceuticals that contribute to ecological degradation, resistance development, and adverse health effects. By contrast, green chemistry provides a framework for designing interventions that are safer, renewable, and less disruptive to ecosystems. At a broader level, the integration of green chemistry into disease control emphasizes renewable feedstocks, biodegradable formulations, and energy-efficient synthesis. Examples include bio-based pesticides derived from plant secondary metabolites, nanomaterials designed for controlled release with minimal residues, and green solvents used in drug development. These innovations address both human and plant disease burdens while aligning with sustainability goals such as reduced carbon footprints and circular resource use. Narrowing to practical applications, sustainable disease control strategies now incorporate precision delivery systems, integrated pest management (IPM), and the substitution of persistent chemicals with biodegradable alternatives. Collaborative frameworks involving policymakers, scientists, and industry stakeholders are essential to translate laboratory successes into scalable field solutions. Ultimately, the convergence of green chemistry and sustainable disease control not only mitigates environmental and health risks but also ensures resilience against evolving pathogens and pests, reinforcing global food security and public health in the face of climate and ecological challenges.

Keywords: Green Chemistry; Sustainable Disease Control; Biodegradable Pesticides; Integrated Pest Management; Renewable Feedstocks; Environmental Resilience

1. Introduction

1.1. Contextualizing green chemistry in sustainability and global health challenges

Green chemistry has emerged as a pivotal approach in addressing the interconnected challenges of sustainability and global health [1]. At its core, green chemistry seeks to design products and processes that minimize environmental impact while enhancing efficiency and safety. This dual focus responds to urgent concerns such as climate change, biodiversity loss, and pollution, all of which contribute directly or indirectly to human health burdens [4]. For example, the overuse of harmful solvents and pesticides has been linked not only to ecological degradation but also to respiratory diseases, endocrine disruption, and other chronic health outcomes [2].

The global health agenda increasingly acknowledges that chemical practices cannot be separated from sustainability goals. The United Nations Sustainable Development Goals (SDGs) highlight clean water, responsible consumption, and good health as priorities, all of which intersect with the principles of green chemistry [5]. Integrating environmentally

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responsible chemical processes into disease prevention and treatment infrastructures ensures that progress in one area does not undermine another.

Moreover, green chemistry addresses the resource efficiency crisis by promoting renewable feedstocks, energy-efficient reactions, and safer product formulations [3]. These innovations provide a pathway to reduce the dependency on toxic substances while ensuring that essential medicines and public health interventions remain accessible. By aligning industrial practices with sustainability and health outcomes, green chemistry offers a framework that balances innovation with ethical responsibility, ultimately positioning itself as a cornerstone of 21st-century health and environmental strategies [6].

1.2. Historical reliance on conventional chemical controls and their limitations

For decades, conventional chemical controls formed the backbone of strategies to manage pests, infectious diseases, and industrial risks [4]. Widely used pesticides, disinfectants, and industrial reagents were valued for their immediate efficacy in reducing threats to crops, water systems, and human health [1]. This approach, however, was built on an assumption of unlimited resource availability and a tolerance for collateral damage to ecosystems [3].

The limitations of these methods have become increasingly evident. Persistent organic pollutants, for example, accumulate in the environment and enter food chains, resulting in long-term health risks such as cancer and developmental disorders [2]. Similarly, indiscriminate pesticide use has fostered resistance in disease vectors like mosquitoes, undermining the very effectiveness of chemical interventions [6]. Industrial solvents and reagents, though effective in synthesis, have contributed to air and water contamination, raising costs for environmental remediation and public health interventions [5].

These shortcomings underscore the unsustainable nature of conventional practices. While traditional chemistry achieved short-term gains, it often imposed long-term costs that outweighed its benefits. This historical reliance highlights the pressing need for innovative paradigms such as green chemistry that integrate efficacy with environmental stewardship and resilience [4].

1.3. Rationale for integrating green chemistry into disease control

The rationale for embedding green chemistry into disease control lies in its ability to reconcile effectiveness with sustainability [6]. Traditional chemical tools often address immediate risks but create new challenges, such as resistance, pollution, or toxicity [2]. Green chemistry principles such as designing safer molecules, using renewable feedstocks, and improving energy efficiency offer pathways to reduce these trade-offs while maintaining public health outcomes [5].

For example, developing biodegradable insecticides or antimicrobial agents ensures that interventions degrade harmlessly in the environment while targeting pathogens effectively [3]. Similarly, replacing hazardous solvents with benign alternatives minimizes risks to workers and communities engaged in drug production [1].

By emphasizing prevention, sustainability, and safety, green chemistry shifts the focus from reactive measures toward proactive, holistic strategies [4]. Integrating these principles into disease control not only strengthens resilience against emerging health threats but also supports global goals for equity, sustainability, and long-term well-being [6].

2. Principles of green chemistry in the context of disease control

2.1. The 12 principles and their relevance to agriculture and health

The 12 principles of green chemistry, first articulated in the late 1990s, provide a comprehensive framework for designing safer, more sustainable chemical practices [6]. These principles include prevention of waste, atom economy, less hazardous synthesis, design for energy efficiency, and the use of renewable feedstocks, among others [7]. Collectively, they aim to minimize harm to human health and the environment while maximizing resource efficiency [9].

In agriculture, these principles directly address long-standing problems with pesticide overuse and fertilizer dependency [10]. For instance, designing chemicals that degrade into harmless by-products ensures that residues do not accumulate in soil and water systems. By prioritizing atom economy, agricultural inputs can be formulated to minimize excess application, reducing runoff and its contribution to eutrophication [5].

Health applications are equally significant. The principle of safer solvents, for example, reduces occupational exposure risks in pharmaceutical manufacturing, where traditional reagents can be toxic or carcinogenic [12]. Similarly, designing drugs to degrade after therapeutic action prevents environmental contamination with persistent pharmaceutical residues [8].

Perhaps most importantly, the principle of prevention aligns directly with public health objectives. Reducing hazardous waste generation lessens the burden on healthcare systems dealing with pollution-related illnesses [11]. Thus, the 12 principles are not abstract ideals but actionable guidelines that link chemistry with sustainable agriculture and health outcomes, enabling a holistic approach to managing global challenges [9].

2.2. Designing safer chemicals for reduced toxicity and persistence

A cornerstone of green chemistry is the intentional design of safer chemicals, with the goal of reducing both toxicity and environmental persistence [5]. Traditional approaches often emphasized efficacy alone, leading to products that controlled pests or pathogens effectively but caused unintended ecological and health damage [7]. Green chemistry reframes this by embedding safety as a design criterion from the outset [10].

In agriculture, safer pesticide design has become increasingly urgent. Conventional pesticides frequently accumulate in ecosystems, harming pollinators, contaminating groundwater, and entering food chains [11]. By applying green chemistry, novel compounds can be engineered for targeted action and rapid biodegradation, ensuring effectiveness without long-term residues [6]. Similarly, designing fertilizers with controlled-release mechanisms reduces nutrient leaching and minimizes greenhouse gas emissions associated with conventional inputs [12].

In healthcare, persistent chemicals are a growing concern. Pharmaceuticals such as antibiotics often remain in the environment long after use, contributing to antimicrobial resistance [9]. Safer drug design emphasizes structures that metabolize efficiently in the body and degrade into non-toxic by-products in the environment [8]. This approach reduces both patient risk and ecological impact.

Advances in computational modeling and molecular biology further support safer design. Predictive toxicology tools allow chemists to anticipate potential harms before synthesis, aligning discovery processes with sustainability objectives [10]. By emphasizing hazard reduction alongside functionality, the design of safer chemicals exemplifies how green chemistry can simultaneously protect ecosystems, safeguard human health, and sustain agricultural productivity [7].

2.3. Renewable feedstocks and energy-efficient processes in disease control

Another vital principle of green chemistry is the use of renewable feedstocks and energy-efficient processes, which directly supports disease control strategies [11]. Traditional chemical manufacturing often relies on non-renewable fossil fuels and energy-intensive reactions, contributing significantly to carbon emissions and environmental degradation [6]. Transitioning to renewable inputs reduces dependence on finite resources and aligns with climate mitigation goals [9].

In agriculture, bio-based pesticides and fertilizers derived from plant extracts, microbial metabolites, or waste biomass exemplify this principle [12]. These alternatives not only reduce reliance on petrochemicals but also promote circular economies, where agricultural residues are repurposed into inputs for future production [8]. Energy-efficient synthesis of such compounds further enhances their sustainability, lowering costs while minimizing environmental footprints [5].

In healthcare, renewable feedstocks are increasingly being applied in the production of essential medicines and vaccines [7]. For example, plant-based bioreactors and microbial fermentation systems provide scalable, low-cost, and environmentally friendly pathways for manufacturing biologics [10]. Integrating energy-efficient processes into these systems ensures that large-scale disease control programs remain both effective and sustainable [9].

Furthermore, reducing energy demands lowers barriers for implementation in low-resource settings, where energy infrastructure may be limited [11]. By prioritizing renewable feedstocks and efficiency, green chemistry not only strengthens disease control but also enhances resilience, ensuring equitable access to interventions across diverse global contexts [12].

3. Conventional vs. Sustainable disease control approaches

3.1. Conventional pesticides, fungicides, and pharmaceuticals: benefits and drawbacks

Conventional pesticides, fungicides, and pharmaceuticals have historically delivered significant benefits by controlling pests, preventing crop losses, and managing infectious diseases [11]. Their development marked a turning point in agriculture and public health, offering reliable, scalable solutions to global challenges such as food security and epidemic outbreaks [13]. For example, synthetic fungicides have proven effective in combating crop pathogens, reducing spoilage and ensuring higher yields, while pharmaceutical antibiotics revolutionized disease treatment and extended life expectancy [15].

Despite these achievements, drawbacks have become increasingly evident. Pesticides, while effective against pests, often require repeated applications and contribute to resistance in target species, necessitating higher doses or stronger formulations over time [12]. This not only undermines efficacy but also increases economic burdens for farmers and public health systems [16].

Pharmaceutical overuse presents parallel challenges. The widespread application of antibiotics has accelerated the emergence of antimicrobial resistance, now considered one of the most pressing global health threats [14]. Additionally, reliance on synthetic chemicals often overlooks long-term ecological impacts, focusing narrowly on immediate outcomes.

Thus, while conventional solutions remain indispensable in many contexts, their limitations highlight the need for innovative, sustainable approaches. These alternatives must balance efficacy with reduced ecological disruption and long-term resilience, bridging the gap between short-term control and sustainable disease management [11].

3.2. Ecological and health risks of conventional practices

The ecological and health risks associated with conventional pesticides, fungicides, and pharmaceuticals are profound and well documented [15]. Persistent residues from these chemicals contaminate soil, water, and air, disrupting ecological balance and threatening biodiversity [13]. For example, neonicotinoid pesticides, widely applied in crop protection, have been linked to declines in pollinator populations, jeopardizing agricultural productivity and food systems [12].

Human health risks are equally concerning. Chronic exposure to pesticide residues has been associated with endocrine disruption, cancers, and neurological disorders [14]. Communities living near intensive agricultural zones face disproportionate risks due to cumulative exposure, reflecting broader inequities in environmental health [11]. Pharmaceuticals contribute to risks in different ways. Drug residues excreted into wastewater systems persist in the environment, where they accumulate and contribute to antimicrobial resistance [16]. Such resistance diminishes the effectiveness of frontline therapies, posing systemic threats to global health security.

Moreover, overreliance on conventional chemicals fosters dependency and leaves few incentives for innovation. The ecological costs such as loss of biodiversity and soil degradation—combine with health risks to create a cycle of vulnerability that undermines long-term sustainability [13]. Recognizing these risks underscores the urgency of integrating safer, green chemistry-driven interventions into disease control strategies [15].

3.3. Comparative evaluation of sustainable, green-based interventions

Sustainable interventions rooted in green chemistry offer compelling alternatives to conventional practices, addressing many of their ecological and health shortcomings [12]. These approaches prioritize biodegradability, reduced toxicity, and efficiency, ensuring that interventions are both effective and environmentally responsible [14]. For instance, bio-based pesticides derived from plant extracts or microbial metabolites degrade naturally, leaving minimal residues and reducing ecological disruption [11].

Green-based fungicides similarly emphasize targeted mechanisms that prevent broad-spectrum ecological damage. Some formulations exploit naturally occurring compounds to disrupt pathogen life cycles, lowering the risk of resistance compared with synthetic chemicals [15]. In healthcare, green chemistry has driven the development of pharmaceuticals that degrade after use, preventing contamination of waterways and reducing antimicrobial resistance pressures [13].

Economic feasibility also supports green-based approaches. Though initial investments in research and infrastructure may be higher, long-term benefits include lower remediation costs, reduced resistance, and enhanced ecosystem resilience [16]. These advantages align with sustainability goals while safeguarding public health.

Table 1 provides a comparative matrix of conventional versus green chemistry approaches in disease control. The table highlights distinctions in toxicity, persistence, ecological impact, and long-term effectiveness, illustrating how sustainable solutions address the shortcomings of traditional models [14]. Such evidence demonstrates that green chemistry is not only an ethical imperative but also a practical, scalable framework for transforming disease management across agriculture and health systems [12].

Table 1 Comparative matrix of conventional versus green chemistry approaches in disease control

Criteria	Conventional Approaches (Pesticides, Fungicides, Pharmaceuticals)	Green Chemistry Approaches (Bio-based, Eco-friendly, Sustainable)
Toxicity	Often high; impacts non-target organisms including pollinators, aquatic life, and humans.	Designed to minimize toxicity; targeted action reduces risks to non-target organisms.
Persistence	Persistent residues remain in soil, water, and food chains; long-term contamination risks.	Biodegradable compounds degrade quickly, leaving minimal residues in the environment.
Ecological Impact	Disrupts ecosystems, reduces biodiversity, and fosters resistance in pests and pathogens.	Promotes ecological balance by preserving biodiversity and reducing selective pressure.
Long-term Effectiveness	Diminishes over time due to resistance; requires higher doses or stronger chemicals.	Maintains effectiveness with reduced risk of resistance; compatible with integrated management systems.
Economic Costs	Lower upfront cost but high remediation and health costs over time.	Higher initial investment but lower long-term costs due to sustainability and reduced remediation.
Public Acceptance	Increasingly contested due to health and environmental risks.	Broad acceptance due to eco-friendly reputation and consumer demand for safer solutions.

4. Technological innovations in green chemistry for disease control

4.1. Bio-based pesticides and botanicals: eco-friendly alternatives

Bio-based pesticides and botanicals have gained attention as eco-friendly alternatives to conventional synthetic pesticides [16]. Derived from natural sources such as plant extracts, essential oils, and microbial metabolites, these products degrade more rapidly in the environment, leaving fewer residues in soil and water [18]. This property addresses one of the major shortcomings of conventional pesticides long-term persistence and ecological harm [15].

Botanicals such as neem, pyrethrum, and citronella exemplify how natural compounds can disrupt insect growth, feeding, or reproduction without causing widespread damage to non-target organisms [19]. Similarly, microbial-based pesticides, including those derived from *Bacillus thuringiensis*, provide targeted action against pests while reducing risks to pollinators and other beneficial species [21].

These eco-friendly solutions are increasingly being integrated into agricultural systems that emphasize sustainability, such as organic farming [20]. They not only reduce environmental risks but also support market demands for chemical-free produce, adding value for both farmers and consumers [17]. However, challenges remain in ensuring consistent efficacy under varying environmental conditions and scaling production to meet global demand [15].

Despite these hurdles, bio-based pesticides and botanicals represent a key pillar in the transition to sustainable pest management, offering practical alternatives that align agricultural productivity with ecological stewardship [18].

4.2. Nanotechnology and smart delivery systems for controlled release

Nanotechnology has revolutionized the design of controlled release systems for agricultural and health applications [19]. By manipulating materials at the nanoscale, researchers have developed formulations that enhance solubility, stability, and bioavailability of active ingredients [16]. This precision ensures that smaller amounts of pesticides or drugs can achieve greater efficacy, reducing both waste and unintended environmental impacts [20].

Smart delivery systems based on nanoparticles, liposomes, or polymeric carriers allow chemicals to be released gradually or in response to specific environmental triggers such as pH or moisture levels [17]. This controlled release minimizes leaching into groundwater and reduces the frequency of applications, addressing both environmental and economic concerns [21].

In disease control, nanotechnology also enables improved targeting of pathogens or vectors. For example, nanoparticle-based larvicides can concentrate in mosquito breeding grounds, enhancing vector management while lowering collateral ecological damage [15]. Similarly, nanocarriers in pharmaceuticals improve drug delivery to infected tissues, enhancing therapeutic outcomes while reducing toxicity [18].

Despite promising advances, nanotechnology raises regulatory and safety considerations, particularly regarding the long-term fate of nanoparticles in ecosystems [19]. Addressing these issues requires balanced oversight that fosters innovation while safeguarding health and the environment [20]. Nonetheless, nanotechnology-driven delivery systems remain one of the most transformative innovations in modern green chemistry and sustainable disease management [16].

4.3. Green solvents and synthesis pathways in drug development

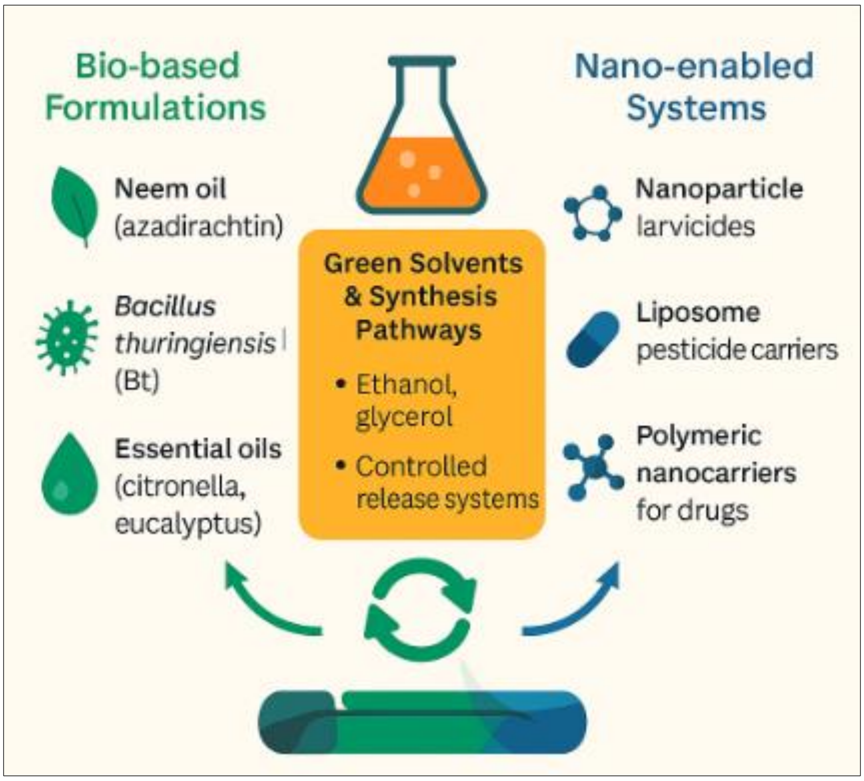

Figure 1 Illustrates examples of bio-based and nano-enabled formulations for plant and vector disease control, highlighting how innovations in solvents and delivery mechanisms converge to support sustainable health interventions [20]. Together, these approaches showcase the role of green chemistry in redefining drug development as both an industrial and ecological priority [18]

Green solvents and sustainable synthesis pathways are reshaping pharmaceutical research by reducing reliance on hazardous chemicals [17]. Traditional solvents such as chlorinated hydrocarbons are efficient but toxic and environmentally persistent [15]. Replacing them with bio-derived solvents like ethanol, glycerol, and ionic liquids minimizes risks to both workers and ecosystems [20].

These innovations align with broader green chemistry goals by ensuring that drug production processes are safer, cleaner, and more resource-efficient [18]. For example, enzymatic catalysis offers a renewable and low-energy alternative to conventional chemical synthesis, significantly reducing waste generation [21]. Similarly, solvent-free or aqueous-based reactions eliminate toxic emissions and reduce water contamination [19].

The adoption of green solvents also enhances scalability. As pharmaceutical companies face mounting pressure to meet sustainability targets, these methods demonstrate how profitability can be aligned with environmental responsibility [16]. Moreover, integrating green solvents reduces downstream costs for waste treatment and regulatory compliance, strengthening their appeal across industries [17].

4.4. Integration with precision agriculture and IPM

The integration of green chemistry innovations with precision agriculture and integrated pest management (IPM) frameworks provides a comprehensive strategy for sustainable disease control [15]. Precision agriculture leverages technologies such as drones, sensors, and geographic information systems to monitor field conditions and apply interventions with pinpoint accuracy [19]. This ensures that bio-based or nano-enabled pesticides are delivered only where needed, reducing waste and exposure [21].

IPM complements these advances by combining biological, cultural, and chemical methods in a coordinated framework [17]. For instance, green chemistry-based products can be used alongside crop rotation, habitat management, and biological control agents to achieve effective pest suppression while preserving ecosystem balance [20]. Such integration reduces reliance on conventional synthetic chemicals and strengthens resilience against pest resistance [16].

The economic benefits are also significant. Farmers adopting precision-guided IPM practices often report reduced input costs and higher yields due to improved efficiency and ecological stability [18]. These systems additionally support consumer demand for sustainable food production, enhancing competitiveness in global markets [19].

By embedding green chemistry innovations within precision agriculture and IPM, stakeholders create a synergistic model that optimizes productivity, minimizes risks, and promotes long-term sustainability [17]. This integration demonstrates how technological and ecological strategies can be harmonized to advance disease management in ways that benefit both producers and the environment [21].

5. Environmental and socioeconomic impacts

5.1. Environmental resilience: reducing pollution and preserving biodiversity

Green chemistry enhances environmental resilience by reducing pollution, conserving resources, and supporting biodiversity [22]. Conventional pesticides and industrial reagents often persist in ecosystems, contaminating soil, groundwater, and air [21]. These residues disrupt ecological balance, threatening species that provide essential ecosystem services, such as pollinators and natural pest regulators [25].

In contrast, bio-based pesticides and eco-friendly formulations degrade rapidly, preventing long-term accumulation [23]. For example, essential-oil-based insecticides have demonstrated efficacy while leaving minimal environmental residues [20]. This characteristic ensures that biodiversity is preserved, as non-target organisms are less likely to be harmed [26].

Energy-efficient synthesis pathways also play a role in environmental resilience by lowering greenhouse gas emissions associated with chemical manufacturing [24]. Similarly, renewable feedstocks reduce dependency on fossil resources, aligning green chemistry with climate change mitigation strategies [21]. These measures directly protect ecosystems vulnerable to pollution and resource exploitation.

Beyond environmental protection, resilience is strengthened by improving the adaptability of systems. By maintaining biodiversity and reducing chemical pressures, ecosystems are better equipped to recover from shocks such as pest outbreaks or climate stress [25]. Thus, green chemistry not only reduces harm but actively contributes to long-term ecological stability, positioning itself as a sustainable foundation for disease control [22].

5.2. Addressing resistance in pathogens and pests

Resistance is a growing challenge in both agriculture and healthcare. Overuse of conventional pesticides and pharmaceuticals exerts selective pressure on pests and pathogens, accelerating the evolution of resistant strains [23]. This phenomenon reduces the effectiveness of frontline interventions, forcing reliance on stronger, more toxic alternatives [21].

Green chemistry offers tools to address this problem by designing compounds that degrade quickly and act through multiple mechanisms [24]. For instance, plant-derived pesticides often contain complex mixtures of active compounds, making it more difficult for pests to develop resistance [20]. In healthcare, green-driven drug development emphasizes molecules that are metabolized efficiently and leave fewer residues in the environment, reducing opportunities for resistance to emerge [26].

Integration with practices like integrated pest management further reduces reliance on single interventions, slowing resistance evolution [22]. By diversifying strategies and minimizing ecological disruption, green chemistry provides a proactive approach that safeguards the long-term efficacy of disease control systems [25].

5.3. Socioeconomic benefits: affordability, accessibility, and public acceptance

The socioeconomic benefits of green chemistry approaches extend beyond environmental gains to affordability, accessibility, and public trust [20]. Although the initial investment in research and infrastructure can be higher, long-term costs are typically lower due to reduced remediation needs, decreased health impacts, and improved resource efficiency [23]. For farmers, using biodegradable pesticides often translates into lower application rates and fewer treatment cycles, ultimately reducing expenses [22].

Table 2 Socioeconomic and environmental benefits of green vs. conventional approaches

Criteria	Conventional Approaches (Pesticides, Fungicides, Pharmaceuticals)	Green Chemistry Approaches (Bio-based, Eco-friendly, Sustainable)
Cost Savings (Long-term)	Lower upfront purchase price but higher long-term costs due to remediation, health care, and resistance management.	Higher initial RandD and production costs but significant long-term savings from reduced remediation, fewer health risks, and lower resistance management costs.
Accessibility	Dependent on imports and centralized production; limited access in low-resource regions.	Often derived from locally available feedstocks; enhances accessibility for smallholder farmers and low-income healthcare systems.
Societal Acceptance	Growing skepticism due to toxicity, persistence, and environmental hazards.	Strong public trust and acceptance as eco-friendly and health-conscious alternatives gain consumer support.
Equity and Inclusion	Benefits often concentrated among industrial producers; smallholders and vulnerable groups face higher risks.	Promotes equitable participation by enabling safe, locally adapted, and inclusive solutions.
Environmental Benefits	Significant ecological disruption, biodiversity loss, and pollution.	Reduced ecological harm, preservation of biodiversity, and contribution to climate resilience.
Health Impacts	Chronic exposure risks for workers and communities; linked to endocrine disruption, cancers, and resistance.	Lower occupational and community health risks; supports preventive and sustainable health outcomes.

Accessibility is also improved. Green chemistry-based interventions are often derived from locally available feedstocks, reducing dependency on imported chemicals and fostering regional self-reliance [25]. For low-resource settings, this can significantly lower barriers to adoption and support equitable access to sustainable solutions [21].

Public acceptance is another key factor. Communities are increasingly aware of the health and environmental risks associated with conventional chemicals, and demand for safer, sustainable alternatives continues to grow [24]. Green products marketed as eco-friendly often enjoy a higher level of consumer trust, further driving adoption.

Table 2 presents a comparative analysis of the socioeconomic and environmental benefits of green versus conventional approaches. It highlights not only cost savings but also improvements in accessibility and societal acceptance, underscoring the holistic value of sustainable interventions [26].

5.4. Policy frameworks for adoption of green solutions

Policy frameworks are essential to scaling up the adoption of green chemistry solutions [21]. Regulations can incentivize innovation through subsidies, tax benefits, or funding for research and development [23]. For example, policies that phase out harmful pesticides or mandate safer alternatives create clear market signals that accelerate transition [24].

International agreements also play a role. Global frameworks such as the Stockholm Convention on Persistent Organic Pollutants demonstrate how coordinated policies can eliminate harmful chemicals and encourage sustainable replacements [20]. National strategies must similarly integrate green chemistry into agricultural and healthcare planning, ensuring that policies address both ecological and social dimensions [25].

Effective policy frameworks combine regulation with capacity-building, supporting education, training, and public awareness [22]. By aligning incentives and enforcement, governments can create enabling environments that foster widespread adoption of safer, greener solutions [26].

6. Case studies of green chemistry in action

6.1. Agricultural case: Biopesticides in crop disease management

Biopesticides represent one of the most prominent agricultural applications of green chemistry, offering sustainable alternatives to conventional chemical pesticides [25]. Derived from natural materials such as microorganisms, plant extracts, or minerals, they provide targeted action against pests and pathogens while minimizing ecological damage [27]. Unlike synthetic pesticides, which often persist in the environment, biopesticides degrade quickly, reducing contamination of soil and water [29].

Case studies highlight their effectiveness in managing fungal and bacterial crop diseases. For example, *Bacillus subtilis*-based formulations are used globally to suppress fungal pathogens while simultaneously promoting plant growth [26]. Similarly, neem oil, rich in azadirachtin, disrupts insect feeding and reproduction with minimal impact on beneficial species such as pollinators [30]. These eco-friendly features enhance biodiversity and long-term resilience in farming systems [28].

Economic benefits are also significant. Biopesticides often require lower input volumes and fewer applications, reducing costs for smallholder farmers [31]. Additionally, their compatibility with organic certification provides access to premium markets, creating financial incentives for adoption [27].

Despite challenges such as shorter shelf life and sensitivity to environmental conditions, ongoing research and improved formulations are addressing these limitations [25]. Overall, biopesticides demonstrate how green chemistry principles can be successfully applied in agriculture to achieve both productivity and sustainability [29].

6.2. Public health case: Eco-friendly vector control in malaria and dengue

Vector control is essential for managing mosquito-borne diseases such as malaria and dengue, which remain significant public health burdens worldwide [28]. Conventional insecticides, while effective, often lead to resistance in mosquito populations and impose ecological risks [26]. Green chemistry offers eco-friendly alternatives that reduce these drawbacks while maintaining disease control effectiveness [30].

One successful example is the use of microbial larvicides such as *Bacillus thuringiensis israelensis* (Bti). These biopesticides specifically target mosquito larvae without harming fish, amphibians, or other non-target species [27]. Field studies have demonstrated their capacity to suppress mosquito populations in endemic regions, lowering transmission rates for malaria and dengue [25].

Plant-derived repellents also illustrate green approaches. Citronella, eucalyptus, and neem-based formulations provide effective personal protection against mosquito bites, reducing reliance on synthetic chemical repellents [29]. Importantly, these botanicals degrade rapidly, avoiding long-term environmental persistence [31].

Beyond ecological benefits, eco-friendly vector control strengthens community trust and acceptance [28]. Programs that emphasize safety and sustainability often encounter less resistance from local populations compared with conventional spraying campaigns [30]. By combining efficacy with ecological stewardship, green chemistry-based interventions in vector control demonstrate their potential to transform public health strategies for mosquito-borne diseases [26].

6.3. Pharmaceutical case: Green chemistry in drug design for antimicrobial resistance

Pharmaceutical innovation grounded in green chemistry plays a critical role in addressing the global crisis of antimicrobial resistance (AMR) [30]. Conventional drug development has often prioritized efficacy without considering environmental persistence, leading to widespread contamination of waterways with active pharmaceutical residues [27]. These residues contribute to the selection pressure driving resistance in microbial populations [25].

Green chemistry offers solutions by embedding sustainability into drug design. One strategy involves creating molecules that metabolize efficiently in the human body and degrade into harmless by-products after therapeutic use [29]. Such drugs reduce both patient exposure to toxicity and environmental contamination [26].

Advances in computational chemistry and predictive toxicology enable researchers to design drug candidates with minimized ecological impact from the earliest stages of discovery [28]. For example, next-generation antibiotics are being modeled not only for potency but also for biodegradability, ensuring that they leave limited residues in ecosystems [31].

Green solvents and catalytic pathways also reduce waste during drug synthesis, lowering the carbon footprint of pharmaceutical production [30]. Biocatalysis, in particular, uses enzymes to create efficient, selective reactions that avoid hazardous intermediates [27]. These innovations illustrate how production methods and product design can jointly contribute to sustainability goals.

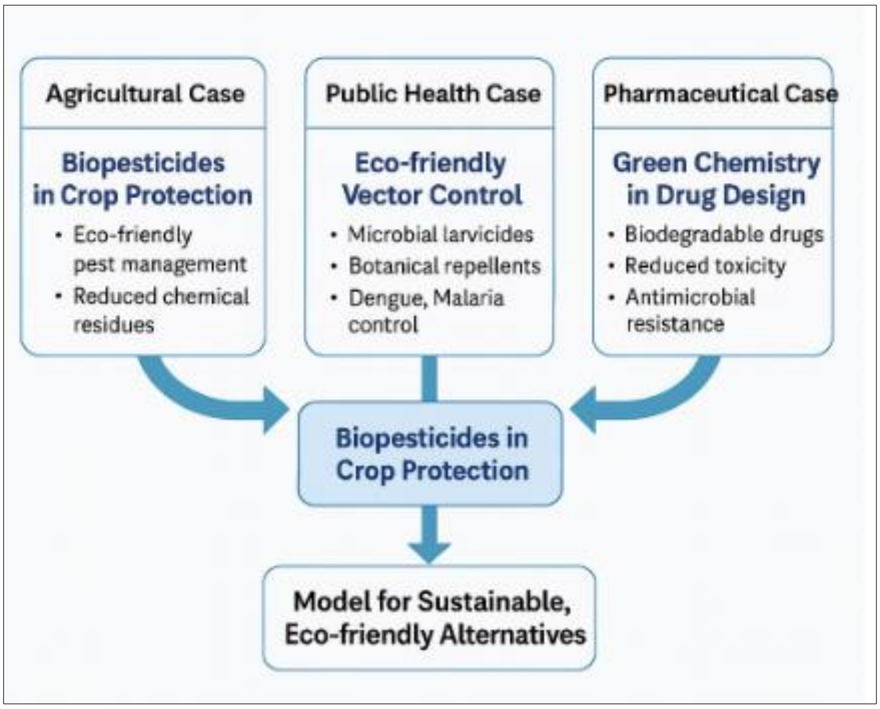

Figure 2 Provides a diagram of case studies, illustrating the success of biopesticides in crop protection while emphasizing their role as a model for pharmaceutical applications [25]. This comparative view underscores that sustainability lessons from agriculture can inform healthcare, making green chemistry a unifying framework across sectors [29].

7. Integration with broader sustainability agendas

7.1. Alignment with UN SDGs and One Health approaches

Green chemistry aligns strongly with the United Nations Sustainable Development Goals (SDGs), providing an operational pathway for sustainable disease control and environmental stewardship [31]. Several principles of green chemistry directly support SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), and SDG 12 (Responsible Consumption and Production) [34]. By designing safer chemicals and minimizing waste, green chemistry simultaneously addresses human health needs and environmental priorities.

The One Health approach, which emphasizes the interconnectedness of human, animal, and ecosystem health, is particularly compatible with green chemistry frameworks [32]. For instance, the reduction of pesticide residues in agricultural runoff not only protects biodiversity but also reduces exposure risks for humans and livestock [35]. Similarly, the development of biodegradable pharmaceuticals lowers contamination in water systems, thereby decreasing antimicrobial resistance in both clinical and environmental settings [33].

By embedding sustainability into disease control, green chemistry offers a unifying mechanism to operationalize these international frameworks [36]. It ensures that chemical innovations contribute positively to health outcomes while also strengthening ecological resilience. This dual focus positions green chemistry as a critical enabler of global strategies that link health, sustainability, and environmental justice, reflecting a holistic vision for 21st-century challenges [31].

7.2. Bridging gaps between science, industry, and policy

A persistent barrier to mainstreaming green chemistry is the disconnect between scientific innovation, industrial adoption, and policy frameworks [32]. Academic research continues to deliver eco-friendly solutions such as bio-based pesticides, safer solvents, and renewable feedstocks, yet these advances often remain confined to laboratories [34]. Without mechanisms to facilitate technology transfer, industries face difficulties in scaling and commercializing sustainable innovations [31].

Policy plays a critical bridging role. Incentives such as subsidies, tax credits, and preferential procurement can reduce the costs associated with adopting green technologies [36]. At the same time, regulatory frameworks that restrict harmful chemicals and mandate eco-friendly alternatives create strong market signals for industry adoption [33]. For example, national bans on certain persistent pesticides have accelerated the shift toward biopesticides in several regions, showing how regulation and innovation can reinforce each other [35].

Industry also holds responsibility for bridging gaps by investing in sustainable infrastructure and aligning business models with long-term environmental goals [32]. Partnerships between corporations, universities, and policymakers are particularly valuable in accelerating innovation cycles and reducing fragmentation [34].

Ultimately, the alignment of science, industry, and policy is essential for embedding green chemistry into mainstream disease control strategies. Without this integration, the transformative potential of green innovations risks being diluted or delayed, limiting their impact on global health and sustainability [31].

7.3. Future research and global collaboration opportunities

Future research in green chemistry should focus on enhancing scalability, affordability, and accessibility of eco-friendly interventions [35]. For instance, developing robust formulations of biopesticides that remain stable under diverse climatic conditions can expand their applicability in global agriculture [33]. Similarly, designing pharmaceuticals that balance efficacy with biodegradability requires continued interdisciplinary collaboration across chemistry, biology, and engineering [31].

Global collaboration is equally critical. Disease control challenges transcend borders, and solutions must be adapted to diverse social, ecological, and economic contexts [36]. International research networks, knowledge-sharing platforms, and cross-sectoral partnerships can accelerate the diffusion of green innovations, ensuring that low- and middle-income countries also benefit from advancements [32].

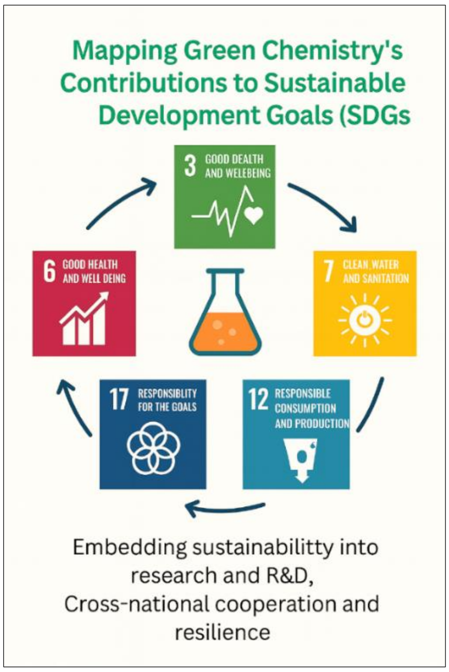

Figure 3 Maps how green chemistry contributes to multiple SDGs, emphasizing its integrative role across health, environment, and development goals [34]. By embedding sustainability into research and fostering collaboration across nations, green chemistry strengthens collective resilience. Such global efforts will be vital for ensuring that sustainable disease control becomes not an exception but the standard for future health and environmental strategies [35]

8. Challenges, limitations, and ethical considerations

8.1. Technical and financial barriers to adoption

Despite its promise, the adoption of green chemistry faces significant technical and financial challenges [36]. Many bio-based and eco-friendly alternatives lack the stability and shelf life of conventional chemicals, limiting their scalability in diverse agricultural and clinical settings [37]. Similarly, production processes for renewable feedstocks or biodegradable drugs often require specialized infrastructure, which is expensive to establish and maintain [39].

Financially, high upfront costs deter smallholder farmers, local healthcare systems, and emerging economies from adopting green solutions [35]. While long-term benefits include reduced remediation costs and improved health outcomes, short-term affordability remains a barrier [38]. Limited investment in research and development further slows innovation, creating dependency on traditional, cheaper chemicals [40]. Addressing these barriers requires targeted subsidies, international funding, and technology-sharing initiatives to ensure equitable access across sectors and geographies [37].

8.2. Ethical issues: access, equity, and unintended consequences

The ethical dimensions of green chemistry adoption are equally critical [35]. Access and equity remain central concerns, as high costs or limited availability risk excluding vulnerable populations [38]. For instance, eco-friendly pesticides may be more common in developed markets, while farmers in low-income regions continue to depend on toxic alternatives [39]. This inequity undermines the universal promise of sustainability and perpetuates health disparities [36].

Unintended consequences also raise ethical dilemmas. For example, rapid replacement of conventional chemicals without thorough testing may introduce unforeseen ecological effects, such as disruption of non-target organisms [37]. Additionally, shifting to bio-based feedstocks could place pressure on land use, competing with food production and raising social justice concerns [40]. Ensuring that green chemistry aligns with ethical standards requires transparent governance, inclusive stakeholder engagement, and careful monitoring of unintended outcomes [39].

8.3. Balancing innovation with precautionary principles

Balancing innovation with precaution is a recurring challenge in green chemistry [36]. While innovation is vital to address urgent issues like antimicrobial resistance and pesticide overuse, premature deployment without rigorous testing risks ecological or health harms [38]. The precautionary principle emphasizes minimizing uncertainty by requiring evidence of safety before widespread adoption [35]. Yet excessive caution can stifle progress, delaying solutions urgently needed for sustainability [40].

A balanced framework integrates both agility and caution, enabling innovation to flourish while embedding safeguards [37]. This approach ensures that green chemistry contributes responsibly to sustainable disease control [39].

9. Future directions and strategic recommendations

9.1. Strengthening interdisciplinary collaboration

Interdisciplinary collaboration is essential for embedding green chemistry into sustainable disease control [40]. Chemists, biologists, environmental scientists, and clinicians each contribute unique expertise, but their efforts are often siloed [41]. Breaking down disciplinary barriers enables holistic approaches that integrate molecular design, ecological risk assessment, and public health delivery [39].

Collaboration extends beyond academia. Industry partners provide insights into scalability and commercialization, while policymakers ensure that innovations are aligned with societal priorities [42]. For instance, partnerships between agricultural scientists and pharmaceutical developers have produced dual-use biopesticides with applications in both crop protection and vector control [43].

Global research networks further enhance collaboration by pooling resources and sharing data across borders [44]. This collective effort accelerates discovery while addressing challenges such as antimicrobial resistance and pesticide resistance, which no single discipline can resolve in isolation [41]. By fostering interdisciplinary engagement, green chemistry can more effectively advance global sustainability goals [45].

9.2. Incentivizing innovation through policy and funding

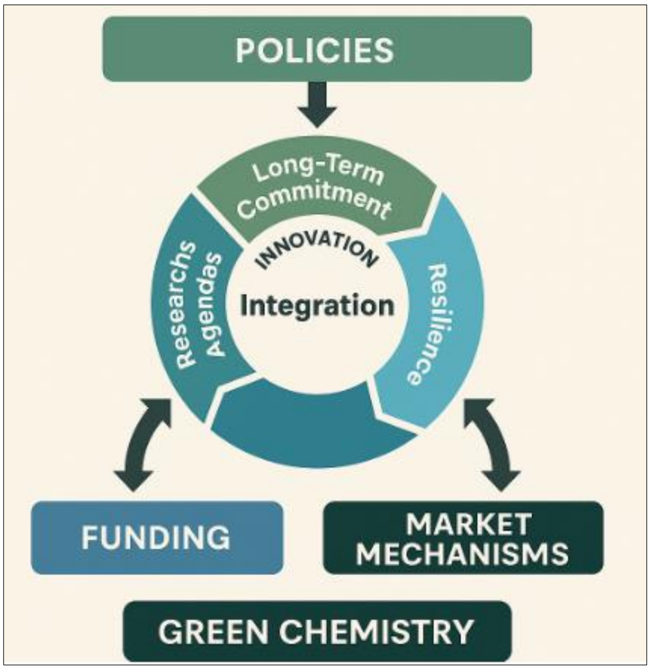

Figure 4 Illustrates a conceptual framework for incentivizing innovation, emphasizing how policies, funding, and market mechanisms align to accelerate integration [43]. Embedding green chemistry into national research agendas ensures long-term commitment and resilience [45]. Ultimately, policy-driven incentives not only reduce barriers but also catalyze sustainable transitions across health and agriculture [39]

Policy and funding are critical drivers of green chemistry adoption [39]. Governments can stimulate innovation by offering targeted grants, subsidies, and tax incentives for companies investing in sustainable products [42]. At the same time, regulatory frameworks that restrict toxic chemicals create strong market signals for green alternatives [40].

Public–private partnerships also play a role, enabling shared risk and investment in infrastructure necessary for scaling bio-based solutions [44]. International development agencies have successfully financed pilot projects in low-income regions, demonstrating the feasibility of eco-friendly disease control strategies [41].

9.3. Building resilience against emerging global health threats

Emerging global health threats demand resilient systems that anticipate and respond to crises [42]. Green chemistry strengthens resilience by reducing dependency on hazardous chemicals, fostering safer alternatives, and ensuring supply chains grounded in renewable feedstocks [44]. For example, eco-friendly formulations can be rapidly adapted to address evolving pathogens or pest pressures [41].

By embedding sustainability into disease control, societies gain tools that are both effective and adaptable [40]. International collaboration further enhances resilience, ensuring equitable access to solutions during crises [43]. Green chemistry thus becomes not only an innovation pathway but also a safeguard against future global health challenges [45].

10. Conclusion

10.1. Recap of green chemistry's role in reshaping disease control

Green chemistry has demonstrated its transformative potential in reshaping disease control by replacing conventional, high-risk chemicals with safer, eco-friendly alternatives. Through principles emphasizing prevention, renewable feedstocks, safer molecular design, and energy efficiency, it addresses the shortcomings of traditional pesticides, fungicides, and pharmaceuticals. Case studies across agriculture, public health, and pharmaceuticals illustrate how biopesticides, microbial larvicides, and biodegradable drugs can protect crops, combat vector-borne diseases, and mitigate antimicrobial resistance. By prioritizing safety and sustainability, green chemistry offers a unifying framework that simultaneously enhances human health, protects ecosystems, and ensures more resilient and equitable approaches to managing global disease burdens.

10.2. Reinforcing sustainability and resilience outcomes

Sustainability and resilience outcomes are at the heart of green chemistry-driven disease control. By reducing pollution, preserving biodiversity, and limiting the spread of resistance in pathogens and pests, these practices strengthen ecological systems while safeguarding public health. Socioeconomic benefits further reinforce resilience, as affordability, accessibility, and consumer acceptance make eco-friendly solutions viable for diverse populations. Integrated with precision agriculture, policy frameworks, and One Health principles, green chemistry ensures that innovations contribute to long-term stability rather than short-lived gains. In doing so, it supports global sustainability goals while fostering robust systems capable of adapting to emerging threats and crises.

10.3. Call to action for global, cross-sectoral adoption

Realizing the full promise of green chemistry requires a unified global effort that spans science, industry, and policy. Governments must incentivize innovation, researchers must drive interdisciplinary collaboration, and industries must commit to scaling eco-friendly solutions. Communities, too, must be engaged to ensure equitable access and trust in sustainable practices. Adoption should not be viewed as optional but as an urgent necessity to safeguard health and the environment. A collective commitment to green chemistry ensures disease control strategies that are not only effective but also ethical, resilient, and sustainable, securing healthier futures for both people and the planet.

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