Indian Journal of Pharmaceutical Chemistry and Analytical Techniques (IJPCAT)
ISSN: 3049-3765 | Vol. 01, Issue-06, Nov-Dec, 2025, pp. 01-20
https://ijpcat.com/1

Green Pharmaceutical Manufacturing: A Focus on Sustainable Approaches to Drug Formulation Development, Production & Case Studies

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ABSTRACT

Pharmaceutical manufacturing is a cornerstone of modern medicine but it's also one of the most resource-intensive and environmentally burdensome industrial sectors. Traditional synthesis and formulation processes consume massive amounts of energy, water, and toxic solvents, generating significant waste and greenhouse emissions. The concept of green pharmaceutical manufacturing has emerged as a transformative framework that integrates sustainability principles into every stage of the drug lifecycle as from raw material sourcing and process development to formulation and packaging. This review discusses the major sustainable approaches in pharmaceutical production, including green chemistry, solvent substitution, biocatalysis, continuous manufacturing, renewable feedstocks and eco-friendly formulation technologies. It also explores Life Cycle Assessment (LCA), regulatory initiatives and industrial case studies which demonstrates shift toward cleaner, safer and more efficient drug production systems.

Key Words:

Green Chemistry, Sustainable Manufacturing, Pharmaceutical Formulation, Eco-Design, Biocatalysis, Solvent-Free Synthesis, Continuous Processing, Life Cycle Assessment.Article History:

Received on Sep 21, 2025

Revised on Oct 14, 2025

Accepted on Nov 29, 2025

Published on Dec 31, 2025

DOI: https://doi.org/10.64062/IJPCAT.Vol1.Issue6.1

1. INTRODUCTION

The pharmaceutical industry, for all its life-saving breakthroughs, has carried a not-so-pretty environmental footprint for decades. Traditional batch manufacturing methods rely heavily on organic solvents, high-temperature reactions, and energy-intensive purification steps. This

approach doesn't just consume massive resources, it leaves behind mountains of hazardous waste. In fact, for every single kilogram of active pharmaceutical ingredient (API) produced, an estimated 100–500 kilograms of waste can be generated [1]. Much of this waste contains toxic chemicals, residual solvents, and by-products that pose serious risks to ecosystems and public health if not properly managed. And it doesn't stop there, the carbon footprint skyrockets further with the energy demands of manufacturing facilities, transportation logistics, packaging materials, and the disposal of unused drugs [2]. In an era where environmental accountability is no longer optional, the pharmaceutical sector is under increasing pressure from regulators, consumers, and global sustainability goals to clean up its act. In the last decade, "going green" has evolved from a trendy catchphrase into a strategic industry-wide movement [3]. The principles of green chemistry, first articulated by Anastas and Warner, have become foundational pillars for modern pharmaceutical R&D. These principles encourage reducing or eliminating hazardous substances at the source, improving efficiency, and using more environmentally benign processes. Major players like Pfizer, GSK, and Novartis have introduced green scorecards quantitative systems for evaluating the environmental performance of their processes [4]. These scorecards assess key metrics like E-factor (mass of waste per mass of product), atom economy (efficiency of material use), and carbon intensity (total greenhouse gas emissions). As a result, green manufacturing isn't just about reducing harm but also about driving innovation, cutting costs, and future-proofing the industry against tightening regulations [5]. The ultimate aim of sustainable pharmaceutical manufacturing goes far beyond basic compliance. It's about designing sustainability into every step of the process, from molecule to market. This includes minimizing or eliminating hazardous substances, improving energy and water efficiency, shifting toward renewable feedstocks instead of petroleum-based sources, and promoting material recyclability wherever possible [6]. Many companies are now embedding circular economy principles into their operations, ensuring that by-products are not simply discarded but repurposed or reintegrated into the production cycle. This approach not only lowers the environmental burden but also enhances economic resilience. As the pharmaceutical landscape evolves, green manufacturing isn't just a "nice-to-have" anymore becoming a core pillar of responsible and competitive pharma sector [7].

2. Green Chemistry Principles in Drug Synthesis

Sustainable drug synthesis isn't just about swapping out a few nasty chemicals it's about rethinking the entire process from the molecular level up. Green chemistry provides a strategic roadmap to achieve this transformation [8]. By emphasizing atom economy, safer solvents, and catalytic efficiency, the pharmaceutical industry can minimize waste, lower energy consumption, and create cleaner, more responsible manufacturing pathways. Let's break it down a bit. Atom economy is basically the "efficiency scorecard" of a chemical reaction [9]. It calculates how much of the starting materials actually end up in the final product rather than going down the drain as by-products. Reactions with high atom economy like catalytic hydrogenations or click chemistry to maximize resource utilization and drastically reduce the volume of unwanted waste. Unlike traditional stoichiometric processes, these methods aim to keep nearly every atom in play, making the production of APIs cleaner, leaner, and cheaper. This shift doesn't just save money; it also lightens the environmental burden, cutting down the need for downstream purification and disposal. Solvents are the unsung villains of

pharmaceutical manufacturing. While they make reactions smoother, they also account for most of the waste and toxicity generated [10]. Conventional solvents such as dichloromethane, toluene, and acetonitrile are volatile, hazardous, and environmentally persistent. Green chemistry flips this script by encouraging safer, more sustainable options:

- **Water: It** is being embraced as a reaction medium for many organic transformations, and in some cases, solvent-free systems are proving even more efficient.
- **Supercritical CO_2: It** is used for eco-friendly extractions and particle engineering, offering recyclability and minimal toxicity.
- **Ionic liquids and deep eutectic solvents: Use** act as biodegradable and tunable alternatives to conventional solvents.
- **Bio-based solvents**: Such as, ethyl lactate and glycerol derivatives, derived from renewable resources, further shrink the carbon footprint. By reengineering solvent use, the pharma sector can significantly slash emissions and improve worker and environmental safety.

Catalysis is the beating heart of green synthesis. By lowering activation energies and enhancing reaction selectivity, catalysts minimize side products and energy demands [11-12]. Enzyme-catalyzed processes using lipases, oxidoreductases, and transaminases that are now replacing many harsh chemical steps, making synthesis gentler and more sustainable. Meanwhile, **metal-organic frameworks (MOFs)** are gaining attention as reusable heterogeneous catalysts, reducing the need for excess reagents and simplifying purification. These innovations not only streamline the production pipeline but also push the pharmaceutical industry toward truly **circular chemistry,** where efficiency and responsibility go hand in hand [13].

Table 1. Comparative Overview of Traditional vs. Green Synthetic Approaches.

Parameters	Traditional Synthesis	Green Synthesis	References
Solvent Use	Chlorinated Solvents	Water, ethanol & Ionic liquids	14
Waste Generation	100–500 Kg/Kg API	<50 Kg/Kg API	15
Energy Consumption	High (Thermal)	Moderate to Low (Enzymatic, Microwave)	16
Safety	Toxic Reagents	Non-toxic, Biodegradable inputs	17

3. Rationale to Develop Sustainable for Choosing Green Formulation

As we know, within the world steadily moving towards sustainability, even the pharmaceutical industry is required to develop formulations that are safe, effective and sustainable in nature. Here, green chemistry principles, biodegradable excipients, minimization of waste and biocompatibility are the basic aspects that contribute in making sustainable and green formulations of choice for the development as follows [18]:

- Reduce Environmental Impact: The primary reason for opting for green formulation is to reduce the environmental effect. Traditional pharmaceutical manufacturing processes routinely employ toxic chemicals, solvents and packaging materials that promote pollution and the depletion of resources [19].
- Enhanced Regulatory Pressure: The increasing pressure from governments and regulatory bodies across the globe, includes pharmaceuticals, for transition greener processes in the wake of climate change and environmental degradation. Many countries have adopted or are transitioning to stricter environmental regulations. Both the European Medicines Agency (EMA) and Food and Drug Administration (FDA) are increasingly prioritizing sustainability. Where, EMA has also developed scientific guidelines on Environmental risk assessment of medicinal products for human use [20].
- Eco-friendly Products as per Consumers Demand: As environmental awareness grows among consumers, the demand for sustainable, eco-friendly pharmaceutical products is enhancing. Here, patients, healthcare providers and stakeholders are becoming more conscientious of how their treatment options impact the environment and this is influencing purchasing and prescribing behavior [21].
- Sustainability and Environmental Impact: As compared to conventional products, sustainable materials generally have a lower environmental footprint and supports green practices. Creating "green" materials which can be more environmentally friendly due to their biodegradable and derived natural products (lower toxicity with safer profile) are essential.

  The biocompatible and biodegradable excipients prevent accumulation of the formulation in the body, which further mitigates adverse effects. This is particularly critical in longer-term therapies that requires for sustained engagement [22].

4. Sustainable Pharmaceutical Formulations

Pharmaceutical formulation isn't just about making drugs effective as it's about making them responsibly. The old "formulate now, worry later" model is being replaced by an approach that considers environmental impact from the very beginning. With green chemistry setting the tone, modern formulation science is shifting toward renewable materials, solvent-free processing, and eco-friendly particle engineering techniques [23]. This shift not only minimizes waste but also improves product safety, scalability, and regulatory compliance.

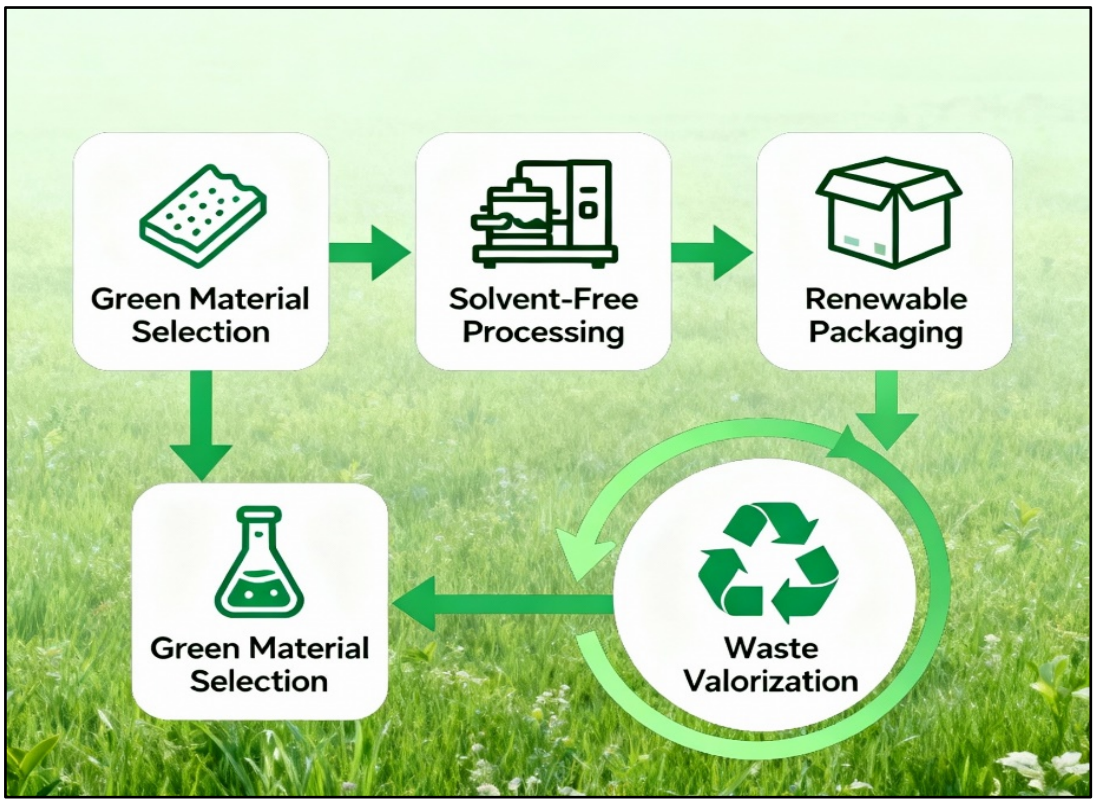
One of the most impactful changes happening in the pharmaceutical world is the move away from synthetic, petroleum-based excipients toward **biodegradable and renewable materials**. For example, **cellulose derivatives**, **chitosan**, and **starch-based polymers** are now widely used to create safer and more sustainable dosage forms [24]. Biodegradable polymers like **PLA (polylactic acid)**, **PCL (polycaprolactone)**, and **PHBV (poly(3-hydroxybutyrate-co-3-hydroxyvalerate))** are finding their place in **nanoparticle and controlled-release formulations**, where they naturally degrade in the body without leaving harmful residues. Additionally, **natural surfactants** such as **lecithin** are replacing synthetic surfactants in emulsions, liposomes, and nano-emulsions, offering a cleaner toxicity profile and improved biocompatibility [24-26]. This pivot toward greener excipients not only reduces environmental load but also enhances patient safety as win-win benefit. Solvents have always been the messy middle child of drug formulation as needed necessary but also problematic. To address this,

modern manufacturing is turning to **solvent-free and dry processing methods** like **dry granulation**, **hot-melt extrusion (HME)**, and **3D printing** [27-28]. HME stands out as a **game-changer** because it allows for continuous processing, superior product uniformity, and minimal waste generation. By eliminating the need for volatile organic solvents, these techniques reduce both environmental emissions and production costs [28].

Plus, 3D printing enables precise dose customization with minimal material loss, aligning perfectly with the principles of green manufacturing and personalized medicine. Particle engineering is another frontier where sustainability is making its mark. Techniques involving **supercritical CO_2**, such as **supercritical CO_2-assisted spray drying** and **rapid expansion of supercritical solutions (RESS)**, provide solvent-free and efficient alternatives for micronization and nanoparticle production [29].

These methods improve drug solubility and bioavailability while cutting down on toxic solvent use. Because CO_2 can be recycled and doesn't produce harmful residues, it's a clear favorite for future-forward pharmaceutical processes. In essence, sustainable formulation isn't just a trend—it's a strategic evolution. By embracing biodegradable materials, solvent-free manufacturing, and green engineering, the pharmaceutical industry is taking meaningful steps toward **cleaner, safer, and more efficient drug production** [30-31] as shown in Figure 1.

Figure 1: Workflow of Green Formulation Process.



4. Continuous Manufacturing and Process Intensification

Traditional batch manufacturing in the pharmaceutical industry is slow, energy-hungry, and not exactly eco-friendly. Imagine making soup one bowl at a time heating, cooling, cleaning, and starting over for each serving. That's basically how batch processing works. In contrast,

continuous manufacturing functions more like a modern assembly line, where reactions flow in a seamless, uninterrupted manner [32]. This not only saves energy and time but also improves product consistency and minimizes waste generation, making it a powerful tool for sustainable pharma.

Continuous flow systems allow chemical reactions to occur in compact reactors where raw materials are fed and products are collected without interruptions. This eliminates the downtime associated with batch processes and ensures steady-state operation, leading to better control over reaction parameters [33].

By maintaining a constant flow, companies can achieve higher yields, improved reproducibility, and fewer impurities, making the entire process more efficient and environmentally responsible. The benefits of continuous manufacturing are both environmental and economic. It reduces energy use by eliminating repeated heating and cooling cycles, which are common in batch processes [34-35]. With Process Analytical Technology (PAT) integrated into the system, companies can monitor and adjust reaction conditions in real time, ensuring product quality and minimizing errors. Perhaps the most attractive benefit is easy scalability instead of redesigning the entire process for larger production, manufacturers can simply extend the run time, avoiding costly revalidation steps. Major pharmaceutical companies have already embraced this approach. For instance, Janssen's Prezista® (Darunavir) became the first FDA-approved drug produced through continuous manufacturing, paving the way for others to follow system. Similarly, the Novartis–MIT collaboration developed an end-to-end continuous manufacturing plant that reduced production time from weeks to just a few hours [36-37]. These real-world based examples proves that continuous flow technology is not just an experimental idea but a practical, scalable, and sustainable manufacturing solution.

5. Green Manufacturing Practices

Green manufacturing practices are necessary to minimize the overall environmental impact of pharmaceutical products. Such practices include energy consumption, waste management, and minimizing hazardous emissions during production in steps as follows [38-39]:

- **Energy-Efficient Production:** Energy-saving technologies are also being applied in drug manufacturing operations to save fossil fuel usage and its correlated carbon emissions. For instance, microwave-driven reactions, ultrasonic synthesis, and Pulsed Electric Field (PEF) technology are more widely adopted in the manufacture of APIs, markedly reducing the amount of energy used. Drug firms also move toward alternative renewable sources, e.g., solar, wind, or bioenergy, for power at production plants to wean off the usage of non-renewable resources.

- **Waste Minimization and Recycling-Zero-waste production:** It is the aim of most pharmaceutical firms. Hereby, optimal production processes can be achieved through improved material efficiency, and manufacturers can reduce the generation of waste. Closed-loop systems, for instance, recycle solvents and other raw materials, and thereby drastically minimize the environmental impact. By-product reuse is another sustainable practice. Waste pharmaceuticals, like residual chemicals and solvents, can be reused for

other industrial processes or in the manufacturing of other chemicals, minimizing landfills waste.

- **Water Usage and Management:** Water use in pharmaceutical production is a major environmental concern. Environmentally friendly formulations concentrate on reducing water consumption in the production process. Firms are spending money on recycling water systems as well as employing waterless technologies (i.e., solvent-free products) to keep water usage in manufacturing low.

6. Green Packaging and Disposal Solutions

Green packaging and environmentally responsible means of disposal are crucial elements of an environmentally friendly drug product. They are divided into two kinds [40-41]:

- **Eco-Friendly Packaging:** Biodegradable packaging materials, such as plant-based plastics (such as polylactic acid or PLA) and paper products, are substituting for conventional petroleum-derived plastic packaging. These products decompose faster and do not contribute to perennial waste stockpiling in nature. Less-is-more packaging is another strategy, which entails minimizing the volume of material employed in drug packaging and encouraging the utilization of recyclable materials.
- **Disposal and Take-Back Programs:** Proper drug disposal is essential. Take-back initiatives, where unused or expired medications are brought back to pharmacies for proper disposal, keep drugs out of the environment from improper disposal. Moreover, educating consumers on drug disposal educates them on the environmental harm that results from improper drug disposal and prompts them to use proper disposal methods. In order to efficiently design and market environmentally friendly drug products, there is a need for cooperation among pharmaceutical firms, regulatory bodies, and research institutions to address environmental standards, guidelines, and incentives for green practices.
- **Regulatory Standards:** Governments and regulatory agencies are increasingly implementing policies to encourage the environmental safety of drugs. For example, the European Medicines Agency (EMA) and the U.S. Food and Drug Administration (USFDA) are integrating environmental factors into their approval processes for new medicines.
- **Incentives for Green Practices:** Most regulatory systems now provide financial rewards (e.g., tax credits or grants) to firms that use green manufacturing technologies or engage in sustainable production practices. Such programs promote the creation of green drugs and their formulations.

7. Life Cycle Assessment (LCA) and Circular Economy

When it comes to making pharmaceutical production greener, focusing only on the manufacturing step isn't enough. The real game changer is looking at the entire life cycle of a drug from raw material extraction to production, packaging, distribution, and even disposal. This is where Life Cycle Assessment (LCA) comes into play [42]. ISO describes the LCA to quantitatively determine the impact on environmental at all stages of product life cycle [43]. LCA gives a full picture of the environmental footprint of every stage of a product's life, helping companies make data-driven decisions for sustainability. LCA acts as an environmental evaluation tool that measures critical factors like carbon footprint, water consumption, global warming potential, and ecotoxicity. By identifying the most resource-intensive or polluting steps, companies can redesign their processes to reduce impact. Instead of reacting to problems

after they arise, LCA promotes proactive planning, ensuring that sustainability is built into the foundation of pharmaceutical production [44-45]. A truly sustainable pharmaceutical model isn't linear, it's circular.

The circular economy approach focuses on reusing, recycling, and regenerating resources instead of discarding them. In pharma, this can be achieved by recycling solvent waste through distillation and reusing it in future batches, revalorizing pharmaceutical by-products into useful industrial chemicals, and using biodegradable packaging to minimize landfill burden [46-47]. This approach transforms waste from a liability into a valuable resource, creating a closed-loop system that supports both environmental health and economic efficiency. By integrating continuous manufacturing with LCA and circular economy principles, the pharmaceutical industry can move toward a future that is smarter, cleaner, and more sustainable, ensuring that innovation and environmental responsibility go hand in hand [48].

Table 2. Environmental Metrics in LCA for Pharmaceuticals.

Indicators	Unit	Goal of Reduction	References
Carbon Footprint	Kg CO_2 eq.	<50% baseline	50
E-factor	Kg waste/ Kg API	<20	51
Water Consumption	L/Kg API	<500	52
Energy Demand	MJ/ Kg Product	-40% minimum	53
Hazard Score	Dimensionless	≤3 (green score-card target)	54

6. Renewable Energy and Resource Optimization

Sustainability in the pharmaceutical sector isn't just about cleaner chemical processes about **rethinking the entire infrastructure.** Energy and resource consumption make up a huge chunk of pharma's environmental footprint, and optimizing these areas can lead to massive gains in both efficiency and eco-friendliness [55]. That's why modern pharmaceutical plants are turning to **renewable energy,** smart resource management, and innovative feedstock solutions to make production cleaner, leaner, and greener. Traditional pharmaceutical plants rely heavily on fossil fuels and outdated equipment, which are both energy-intensive and environmentally damaging. But things are changing fast, [56-57]. **Solar-assisted distillation units** are being introduced to cut down on conventional fuel use, while **heat recovery loops** capture and reuse waste heat, significantly lowering overall energy demand. Even **LED-based photochemical reactors** are replacing older mercury-lamp systems, slashing power consumption and improving reaction efficiency [58-59]. These design innovations don't just reduce costs as they shrink the plant's carbon footprint in a big way. Water plays a critical role in pharmaceutical production, from synthesis to cleaning to formulation. Unfortunately, it's also one of the most wasted resources in conventional setups. To tackle this, modern facilities are adopting **Zero-**

Liquid Discharge (ZLD) systems, which ensure that no wastewater leaves the plant. Instead, every drop is treated and reused [60-61]. **Membrane bioreactors** add another layer of purification efficiency, while **rainwater harvesting systems** supplement the supply and reduce dependency on external sources. Together, these measures create a closed-loop water system that conserves resources and minimizes environmental harm. A truly sustainable pharmaceutical industry also needs to rethink where its raw materials come from [62]. Instead of relying solely on petrochemicals, companies are increasingly turning to **biomass-derived intermediates** like levulinic acid and glycerol, which are renewable and biodegradable. **Carbon capture technologies** are being integrated into production lines to generate CO_2-based chemical precursors, reducing greenhouse gas emissions at the source. Additionally, **fermentation-based routes** for producing vitamins, antibiotics, and amino acids offer a cleaner, bio-based alternative to traditional synthetic pathways [63-64]. By combining **renewable energy systems, efficient water management,** and **green feedstocks,** pharmaceutical companies can drastically cut their environmental impact while maintaining productivity and quality. This shift is not just good for the planet but also becoming a **strategic advantage** in a world that increasingly rewards sustainable innovation [65].

7. Regulatory and Industrial Framework

Sustainability in pharma isn't just a feel-good slogan anymore as becoming **a regulated expectation and a competitive edge**. Governments, global organizations, and the pharmaceutical industry itself are setting strict frameworks to ensure that green manufacturing isn't optional, but standard [66]. These frameworks help companies align their operations with environmental goals, reduce compliance risks, and build a future-ready, responsible brand image. Environmental regulations are tightening worldwide, pushing the pharma sector toward cleaner, safer practices. In the U.S., the **EPA's Green Chemistry Program** encourages companies to adopt safer chemicals and more efficient processes through awards, grants, and public recognition [67-68]. Meanwhile, the **EU REACH Regulation** (Registration, Evaluation, Authorization, and Restriction of Chemicals) enforces strict guidelines on chemical safety, requiring industries to minimize environmental impact and ensure traceability of hazardous substances. On a global scale, the **United Nations Sustainable Development Goals (SDG 12)** emphasize responsible consumption and production, encouraging pharmaceutical companies to cut waste, lower emissions, and make sustainability a core business strategy [69-70]. Beyond regulatory pressure, many pharmaceutical giants are taking proactive steps to lead the green transition. **Pfizer's Green Chemistry Metrics Toolkit** provides standardized methods to assess and improve process sustainability. **GSK's Solvent Selection Guide** helps scientists choose safer, more eco-friendly solvents during formulation and synthesis. Similarly, **AstraZeneca's Sustainable Product Design Framework** ensures that sustainability principles are embedded right from the R&D stage to full-scale production. These initiatives show that going green is not just about compliance about **innovating smarter and staying ahead of the curve** [71-72].

To build trust and transparency, companies are increasingly seeking third-party certifications that validate their environmental practices. **ISO 14001** certification sets global standards for environmental management systems, helping organizations minimize their ecological footprint. **LEED certification** focuses on sustainable building and plant design, promoting

energy efficiency and resource conservation. Meanwhile, **B Corp certification** reflects a company's commitment to broader environmental and social impact goals [73-74]. Together, these certifications serve as **badges of credibility,** signaling to regulators, investors, and consumers that a company is serious about sustainability. By aligning **regulatory compliance, industry innovation,** and **certification standards,** the pharmaceutical sector is creating a solid foundation for **green transformation.** This isn't just about avoiding fines or winning award that it's about building a **resilient, future-proof industry** that can thrive in a world where environmental responsibility is no longer optional [75-76].

8. Case Studies in Green Pharmaceutical Manufacturing Industry

The best way to understand the impact of green pharmaceutical manufacturing is to look at companies that are already **walking the talk.** Across the globe, major players like Pfizer, GSK, Novartis, Roche, and AstraZeneca are proving that sustainability isn't just a buzzword i.e. a **practical approach with profitable strategy [77].** These case studies highlight how targeted green initiatives can dramatically cut waste, lower emissions, and improve operational efficiency, all while maintaining product quality and regulatory compliance. Pfizer revolutionized its production of sertraline (the active ingredient in Zoloft®) by switching to an **enzyme-catalyzed synthesis route [78-79].** This green process significantly reduced the use of hazardous reagents and simplified downstream purification. As the result, an **80% reduction in waste generation** and a cleaner, more cost-effective production cycle. This also reduced solvent use Sildenafil/Viagra by 75% cutting 1,000 Tons hazardous waste annually. This case is often cited as one of the earliest large-scale examples of green chemistry in action within the pharmaceutical industry [80-81].

GSK (GlaxoSmithKline) tackled the environmental impact of its ibuprofen manufacturing process by replacing conventional toxic solvents with **greener alternatives provides sustainability metrics in Research & Development (R&D)**. Through careful solvent selection and recovery strategies, the company achieved a **50% solvent recovery rate**, dramatically cutting down on emissions and disposal costs [82]. This shift not only reduced the carbon footprint of production but also improved worker safety and compliance with environmental regulations. Novartis embraced **continuous flow reactors hydrogenation** to replace batch reactors in one of its key synthesis steps of anti-hypertensive dugs. This innovation allowed for more controlled reactions, better heat management, and reduced energy demand. Most impressively, it resulted in a **70% reduction in CO_2 emissions,** showcasing how process intensification and green chemistry can go hand in hand [83]. Roche turned its attention to the often-overlooked environmental burden of pharmaceutical packaging. By adopting **biodegradable packaging materials**, the company achieved a **40% reduction in plastic waste.** This move not only lessened environmental pollution but also improved the company's sustainability credentials with regulators and consumers alike. AstraZeneca installed an advanced **energy recovery system** in its pilot plants to capture and reuse waste heat from various processes [84]. This investment led to **25% total energy savings,** significantly cutting operational costs and carbon emissions. Merck & Codexis hereby won the Presidential Green Chemistry Challenge Award for the manufacturing of Sitagliptin drugs as bio-catalytically route by the U.S. Environmental Protection Agency, 2010. Hereby, Indian brands

such as Cipla as for reduces emissions in solvent recovery systems and Dr. Reddy's effluent treatment plants possess Zero-liquid discharge. As these industries adopts batch flow hybrids approaches for safe and robust manufacturer ability for the green chemistry cover in processing mass intensity, atom efficiency, effluent water and hazardous waste management [85].

It's a clear example of how energy efficiency measures can deliver both environmental and financial benefits. These case studies prove that **green pharmaceutical manufacturing is more than just theory but it's a working reality** [86]. By integrating enzyme catalysis, solvent recovery, continuous processing, biodegradable packaging, and energy optimization, these companies are not only shrinking their environmental footprint but also **gaining a competitive advantage** in an industry increasingly shaped by sustainability standards [87].

8. Applications of Green Chemistry to Adapt Sustainable Pharmaceutical Formulation

Sustainable pharmaceutical formulation involves creating drug products that are not only safe and effective for patients but also environmentally friendly. This approach considers the entire lifecycle of a drug, from the sourcing of raw materials to manufacturing, supplying, usage and disposal. Sustainable practices aim to minimize waste, reduce energy consumption and limit the use of hazardous substances while ensuring the quality and efficiency of pharmaceutical products. There are various applications for adopting sustainable formulations as follows [88-89]:

- Use of Eco-friendly Excipients: Excipients play an important role in **pharmaceutical formulations affecting drug stability, release and bioavailability. The excipients choice can significantly impact the environmental footprint of the formulation. The development of** eco-friendly excipients derived from renewable resources is gaining traction. For example, natural polymers such as chitosan, alginate and cellulose derivatives can replace synthetic polymers in formulations offering biodegradable options that align with **sustainable goals.**
- **Green Solvents in Formulation Processes: Traditional organic solvents often pose environmental and health risks. The shift towards using green solvents is an essential strategy for** sustainable pharmaceutical formulation development. Solvents such as ethanol, isopropyl alcohol and even supercritical CO_2 are being explored as alternatives to toxic solvents (like chloroform or benzene). These green solvents not only reduce environmental harm but also improve safety for pharmaceutical workers.
- **Continuous Manufacturing Techniques: The traditional batch manufacturing processes in** pharmaceutical formulation can generate significant waste and require bulk quantities of raw materials. These techniques will integrate the production processes into a seamless flow that can enhance efficiency and reduce waste. By optimizing reaction conditions in real-time, continuous processes can yield higher-quality products with less resource consumption, supporting the principles of green chemistry.
- **Optimization of Formulation Processes:** Implementing Process Analytical Technology (PAT) can significantly improve the efficiency and **sustainability of pharmaceutical formulation** development. PAT involves the use of real-time monitoring and control of manufacturing processes, allowing for the identification of inefficiencies and waste. This

optimization can lead to reduced material use and lower energy consumption while ensuring product quality.

- **Recycling and Reuse of Materials:** The incorporation recycling and reuse strategies into **pharmaceutical** formulation development can further enhance sustainability. For instance, solvents and other materials used in manufacturing can be recovered and purified for reuse, minimizing waste and reducing the demand for new raw materials. Additionally, promoting the take-back of unused medications can help to minimize the environment impact of pharmaceuticals after their use.

9. Upcoming Challenges and Future Perspectives

While the promise of green pharmaceutical manufacturing is exciting, the road to full-scale adoption isn't exactly a smooth ride. Behind every eco-friendly success story lies a **series of practical, regulatory, and technological hurdles** that the industry must address head-on. The shift toward sustainability demands not just new tools and processes but also a complete **rethink of how pharma operates** from R&D to packaging to post-consumer waste management [90-91]. One of the biggest roadblocks to implementing green technologies is **the high upfront investment**. Transitioning from conventional batch processing to continuous, green-compatible systems often requires new reactors, advanced monitoring equipment, upgraded waste treatment units, and comprehensive validation studies. For smaller companies, these costs can seem intimidating. However, the flip side is that these **investments pay off in the long run**, through reduced energy consumption, lower waste management costs, improved regulatory compliance, and a stronger market reputation [92-93]. In fact, many early adopters have already seen net savings over time, proving that going green isn't just good for the planet as a good for business. Another major challenge is the **regulatory lag**. Green technologies are advancing at breakneck speed think bio-based solvents, continuous flow systems, and novel excipients while **regulatory frameworks are still catching up** [94]. Agencies like the FDA and EMA are beginning to adapt, but there's still a gap between innovation and policy. Companies often face uncertainty over how new processes will be evaluated, which can slow down adoption. Faster regulatory adaptation, clearer guidelines, and global harmonization of green manufacturing standards will be crucial to overcoming this barrier. The future of sustainable pharma lies in **deep tech integration** and **systemic redesign**. Emerging trends point toward the **integration of AI and Interest of Things (IoT) technologies** to monitor energy use, emissions, and waste in real time, making sustainability data-driven and transparent [95-96].

Another promising direction is **green-by-design APIs**, where sustainability metrics are built into the molecular design phase itself minimizing environmental impact before a single reactor is even fired up. And ultimately, the vision is to build **circular pharmaceutical ecosystems**, where what was once considered "waste" is **repurposed as feedstock** for new processes, closing the loop entirely. In short, the challenges are real, but so are the opportunities [97-98]. By embracing innovation, adapting regulatory frameworks, and thinking sustainably from the ground up, the pharmaceutical industry can **transform itself from a major environmental contributor to a model of green innovation** [99]. Additionally, the upfront costs associated with transitioning to sustainable practices can deter companies from making the necessary investments. Thus, looking forward, collaboration between **pharmaceutical formulative**

companies, academics and regulatory agencies will be crucial to overcoming these challenges. Continued research into new **sustainable materials and processes, coupled with the development of supportive regulatory policies, will be essential for driven adoption of sustainable practices in the pharmaceutical industry** [100]**.** The next decade will be less about asking "if" and more about **"how fast"** we can make that transition.

10. Conclusions

Green pharmaceutical manufacturing has moved from being a niche initiative to a **strategic imperative** for the modern pharmaceutical industry. It is no longer sufficient to focus solely on efficacy, safety, and profitability; environmental responsibility has become equally critical. Companies that integrate **green chemistry principles,** adopt **continuous and energy-efficient processing,** utilize **renewable feedstocks,** and implement **circular economy practices** are not just complying with regulations that they are **setting the benchmark for global sustainability standards**. The path forward envisions a pharmaceutical sector that can **deliver life-saving medicines while minimizing environmental impact.** From enzyme-catalyzed synthesis and solvent-free formulations to real-time monitoring using AI and IoT, the tools and technologies for sustainable manufacturing are already available. While challenges such as high transition costs, regulatory uncertainty, and technological adaptation remain, the combination of **scientific innovation, ethical responsibility, and forward-thinking policy** makes a sustainable pharmaceutical future achievable. Ultimately, the goal is clear with a world where the industry's mission to heal humanity does not come at the expense of the planet. By embedding sustainability at every stage from drug design to production, packaging, and waste management in the pharmaceutical sector can **thrive responsibly**, transforming itself into a model of innovation that balances human health with environmental stewardship. The journey may be complex, but the direction is unmistakable towards a **truly green, resilient, and sustainable pharmaceutical ecosystem.**

11. References

1. Aghahosseini, H., Saadati, M.R., Rezaei, S.J.T., Ramazani, A., Asadi, N., Yahiro, H., *et al.* (2021). A robust polyfunctional Pd(II)-based magnetic amphiphilic nanocatalyst for the Suzuki–Miyaura coupling reaction. *Scientific Reports, 11*, 89424. DOI: https://doi.org/10.1038/s41598-021-89424-7
2. Babazadeh, M., Sheidaei, M., Abbaspour, S., & Edjlali, L. (2013). Synthesis, characterization, and in vitro evaluation of new ibuprofen polymeric prodrugs based on 2-hydroxypropyl methacrylate. *Scientia Pharmaceutica, 81*, 281–296. DOI: https://doi.org/10.3797/scipharm.1211-10
3. Bailey, J. D., Helbling, E., Mankar, A., Stirling, M., Hicks, F., & Leahy, D. K. (2021). Beyond organic solvents: Synthesis of a 5-HT4 receptor agonist in water. *Green Chemistry, 23*, 788–795. DOI: https://doi.org/10.1039/d0gc03802d

4. Banik, B. K., Sahoo, B. M., Kumar, B. V. V. R., Panda, K. C., Jena, J., Mahapatra, M. K., & Borah, P. (2021). Green synthetic approach: An efficient, eco-friendly tool for the synthesis of biologically active oxadiazole derivatives. *Molecules, 26*, 1163. DOI: https://doi.org/10.3390/molecules26041163
5. Bekker, C., van den Bemt, B. J. F., Egberts, A. C. G., Bouvy, M. L., & Gardarsdottir, H. (2018). Patient and medication factors associated with preventable medication waste and possibilities for redispensing. *International Journal of Clinical Pharmacy, 40*, 704–711. DOI: https://doi.org/10.1007/s11096-018-0671-0
6. Brown, D., & Boström, J. (2015). Analysis of past and present synthetic methodologies on medicinal chemistry: Where have all the new reactions gone? *Journal of Medicinal Chemistry, 59*, 4443–4458. DOI: https://doi.org/10.1021/acs.jmedchem.5b00170
7. Bullock, R. M., & Helm, M. L. (2015). Molecular electrocatalysts for oxidation of hydrogen using earth-abundant metals: Shoving protons around with proton relays. *Accounts of Chemical Research, 48*, 2015–2023. DOI: https://doi.org/10.1021/ar500494v
8. Cai, Z., Wang, X., Zhang, Z., Zhang, W., & Wang, J. (2019). Large-scale and fast synthesis of nano-hydroxyapatite powder by a microwave-hydrothermal method. *RSC Advances, 9*, 13623–13630. DOI: https://doi.org/10.1039/C9RA01825K
9. Chapman, J., Ismail, A. E., & Dinu, C. Z. (2018). Industrial applications of enzymes: Recent advances, techniques, and outlooks. *Catalysts, 8*, 238. DOI: https://doi.org/10.3390/catal8070238
10. Ciriminna, R., & Pagliaro, M. (2013). Green chemistry in the fine chemicals and pharmaceutical industries. *Organic Process Research & Development, 17*, 1479–1484. DOI: https://doi.org/10.1021/op400258d
11. Corona, S.P., & Generali, D. (2018). Abemaciclib: A CDK4/6 inhibitor for the treatment of HR+/HER2- advanced breast cancer. *Drug Design, Development and Therapy, 12*, 321–330. DOI: https://doi.org/10.2147/DDDT.S125678
12. Desai, A.A. (2011). Sitagliptin manufacture: A compelling tale of green chemistry, process intensification, and industrial asymmetric catalysis. *Angewandte Chemie International Edition, 50*, 1974–1976. DOI: https://doi.org/10.1002/anie.201007929
13. France, S. P., & Lewis, R. D., & Martinez, C. A. (2023). The evolving nature of biocatalysis in pharmaceutical research and development. *JACS Au, 3*, 715–735. DOI: https://doi.org/10.1021/jacsau.3c00035
14. Gabano, E., & Ravera, M. (2022). Microwave-assisted synthesis: Can transition metal complexes take advantage of this “green” method? *Molecules, 27*, 4249. DOI: https://doi.org/10.3390/molecules27134249
15. Golemac, L., & Kondža, M. (2023). Synthesis of acetylsalicylic acid—An environmentally friendly approach. *Annals of Biomedical and Clinical Research, 2*, 100–108.
DOI: https://doi.org/10.18231/abc.2023.019
16. Ha, M.-W., & Paek, S.-M. (2021). Recent advances in the synthesis of ibuprofen and naproxen. *Molecules, 26*, 4792. DOI: https://doi.org/10.3390/molecules26164792
17. Huang, H., & Kang, J. Y. (2017). Mitsunobu reaction using basic amines as pronucleophiles. *Journal of Organic Chemistry, 82*, 6604–6614. DOI: https://doi.org/10.1021/acs.joc.7b00801

18. U.L. Vidya, K. Ramesh Kumar, Damayanthi R. Devi, G. Arun Kumar, R. Meenakshi, & Mirunalini G. (2025). Sustainable and green injectable formulations: Innovations, challenges and future perspectives in pharmaceutical development. *IJPPR, 31, 1,* 160-167.

19. Riikonen S., Timonen J., & Sikanen T. (2024). Environmental considerations along the life cycle of pharmaceuticals: Interview study on views regarding environmental challenges, concerns, strategies and prospects within the pharmaceutical industry. *Eur J Pharm Sci., 196,* 106743.

20. Kuster A., & Adler N. (2014). Pharmaceuticals in the environment: Scientific evidence of risks and its regulation. *Philos Trans R Soc Lond B Biol Sci., 19;369(1656),* 20130587.

21. Camilleri M.A., Cricelli L., Mauriello R., & Strazzullo S. (2023). Consumer perceptions of sustainable products: A systematic literature review. *Sustainability, 15, 11,* 8923.

22. Ashiwaju B, Uzougobo C, Orikpete O. (2024). Environmental impact of pharmaceuticals: A comprehensive review. *Matrix Sci Pharma. 7,* 85-94.

23. Kendall, D. M., Cuddihy, R. M., & Bergenstal, R. M. (2009). Clinical application of incretin-based therapy: Therapeutic potential, patient selection, and clinical use. *American Journal of Medicine, 122*(Suppl. S6), S37–S50. https://doi.org/10.1016/j.amjmed.2009.02.011

24. Kar, S., Sanderson, H., Roy, K., Benfenati, E., & Leszczynski, J. (2021). Green chemistry in the synthesis of pharmaceuticals. *Chemical Reviews, 122*, 3637–3710. https://doi.org/10.1021/acs.chemrev.0c01116

25. Kjellin, M., Wesslén, T., Löfblad, E., Lennerstrand, J., & Lannergård, A. (2018). The effect of the first-generation HCV-protease inhibitors boceprevir and telaprevir and the relation to baseline NS3 resistance mutations in genotype 1: Experience from a small Swedish cohort. *Upsala Journal of Medical Sciences, 123*, 50–56. https://doi.org/10.1080/03009734.2018.1459691

26. Li, T., Liang, J., Ambrogelly, A., Brennan, T., Gloor, G., Huisman, G., *et al*. (2012). Efficient, chemoenzymatic process for the manufacture of the Boceprevir bicyclic [3.1.0]proline intermediate based on amine oxidase-catalyzed desymmetrization. *Journal of the American Chemical Society, 134*, 6467–6472. https://doi.org/10.1021/ja210478d

27. Lungu, I. I., Cioanca, O., Mircea, C., Tuchilus, C., Stefanache, A., Huzum, R., & Hancianu, M. (2024). Insights into catechin–copper complex structure and biologic activity modulation. *Molecules, 29*, 4969. https://doi.org/10.3390/molecules29124969

28. Meyer, H. P., Eichhorn, E. J., Hanlon, S. P., Lütz, S., Schürmann, M., Wohlgemuth, R., & Coppolecchia, R. (2013). The use of enzymes in organic synthesis and the life sciences: Perspectives from the Swiss Industrial Biocatalysis Consortium (SIBC). *Catalysis Science & Technology, 3*, 29–40.

29. European Commission. (2020a, October 14). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Chemicals strategy for sustainability towards a toxic-free environment* (COM(2020) 667 Final). Publications Office of the European Union.

30. European Commission. (2020b, November 25). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Pharmaceutical strategy for Europe* (COM(2020) 761 Final). Publications Office of the European Union.

31. European Commission. (2021, May 12). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Pathway to a healthy planet for all* (COM(2021) 400 Final). Publications Office of the European Union.

32. European Union. (2006, December 18). *Regulation (EC) No 1907/2006 of the European Parliament and of the Council concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)*. OJ L 396, 1–849. European Union.

33. EEA Glossary. (2025). Green chemistry. European Environment Agency. https://www.eea.europa.eu/help/glossary/eea-glossary/green-chemistry

34. European Medicines Agency. (2025). Post-authorisation referral procedures for human medicines. https://www.ema.europa.eu/en/human-regulatory-overview/post-authorisation/pharmacovigilance-post-authorisation/referral-procedures-human-medicines

35. Shanab, K., Neudorfer, C., & Spreitzer, H. (2016). Green solvents in organic synthesis: An overview II. *Current Organic Chemistry, 20*(18), 1576–1583.

36. Jain, A., Shakya, A. K., Prajapati, S. K., Eldesoqui, M., Mody, N., Jain, S. K., Naik, R. R., & Patil, U. K. (2024). An insight into pharmaceutical challenges with ionic liquids: Where do we stand in transdermal delivery? *Frontiers in Bioengineering and Biotechnology, 12,* 1454247.

37. Kapre, S., Palakurthi, S. S., Jain, A., & Palakurthi, S. (2024). DES-igning the future of drug delivery: A journey from fundamentals to drug delivery applications. *Journal of Molecular Liquids, 400,* 124517.

38. Daughton, C.G., & Ternes, T.A. (1999). Pharmaceuticals and personal care products in the environment: Agents of subtle change? *Environmental Health Perspectives, 107(Suppl 6),* 907-938.

39. Glassmeyer, S.T., *et al.* (2009). Disposal practices for unused medications in the United States: A pilot survey of community pharmacies. *Environmental Science & Technology, 43, 15,* 5512-5518.

40. Anastas, P.T., & Warner, J.C. (1998). *Green chemistry*: Theory and practice. Oxford University Press.

41. Sheldon, R.A. (2014). Green chemistry and the pharmaceutical industry. *Green chemistry, 16, 7,* 2213-2237.

42. Jesus, A. R., Soromenho, M. R. C., Raposo, L. R., Esperança, J. M. S. S., Baptista, P. V., Fernandes, A. R., & Reis, P. M. (2019). Enhancement of water solubility of poorly water-soluble drugs by new biocompatible N-acetyl amino acid N-alkyl cholinium-based ionic liquids. *European Journal of Pharmaceutics and Biopharmaceutics, 137,* 227–232.

43. Becker, J., Manske, J., & Randl, S. (2022). Green chemistry and sustainability metrics in the pharmaceutical manufacturing sector. *Curr Opin Green Sustain Chem. 33,* 100562

44. Sangiorgi, S., Albertini, B., Bertoni, S., & Passerini, N. (2025). An overview of the role of ionic liquids and deep eutectic solvents in oral pharmaceuticals. *Pharmaceutics, 17,* 300.

45. Zhang, X., Zhang, J., Liu, Z., Bi, W., Shen, J., & Li, G. (2024). Efficient solvent-free synthesis of indolizines using CuBr catalyst from pyridine, acetophenone, and electron-deficient alkenes. *Molecules, 29,* 2061.

46. Sharma, N., Sharma, H., Kumar, M., Grishina, M., Pandit, U., Poonam, & Rathi, B. (2022). Solvent-free mechanochemical grinding facilitates clean synthesis of N-substituted amines. *Organic & Biomolecular Chemistry, 20,* 6673–6679.

47. Porta, R., Benaglia, M., & Puglisi, A. (2015). Flow chemistry: Recent developments in the synthesis of pharmaceutical products. *Organic Process Research & Development, 20*, *1,* 2–25.

48. Gutmann, B., Cantillo, D., & Kappe, C. O. (2015). Continuous-flow technology-A tool for the safe manufacturing of active pharmaceutical ingredients. *Angewandte Chemie International Edition, 54*(23), 6688–6728.

49. Baumann, M., & Baxendale, I. R. (2015). The synthesis of active pharmaceutical ingredients (APIs) using continuous flow chemistry. *Beilstein Journal of Organic Chemistry, 11,* 1194–1219.

50. Hopkin, M. D., Baxendale, I. R., & Ley, S. V. (2010). A flow-based synthesis of imatinib: The API of Gleevec. *Chemical Communications, 46*(14), 2450–2452.

51. Lévesque, F., & Seeberger, P. H. (2012). Continuous-flow synthesis of the anti-malaria drug artemisinin. *Angewandte Chemie International Edition, 51*(8), 1706–1709.

52. Correia, C., Gilmore, K., McQuade, D., & Seeberger, P. (2015). A concise flow synthesis of Efavirenz. *Angewandte Chemie International Edition, 54*(17), 4945–4948.

53. Nicholas, R., McGuire, M., Hyun, S.-H., Cullison, M., & Thompson, D. (2022). Development of an efficient, high-purity continuous flow synthesis of diazepam. *Frontiers in Chemical Engineering, 4,* 877498.

54. Constable, D. J. C., Dunn, P. J., Hayler, J. D., Humphrey, G. R., Leazer, J. L., Linderman, R. J., Lorenz, K., Manley, J., Pearlman, B. A., Wells, A., Zaks, A., & Zhang, T. (2007). Key green chemistry research areas: A perspective from pharmaceutical manufacturers. *Green Chemistry, 9,* 411–420.

55. Jiménez-González, C., Poechlauer, P., Broxterman, R., am Ende, D., Yang, B. S., Bertsch, C., Hannah, R. E., Baird, J., Dell'Orco, P., Reintjens, R., Noorman, H., & Massonneau, V. (2009, November). Key green engineering research areas. Paper presented at the AIChE 2009 Annual Meeting, Nashville, TN.

56. Jiménez-González, C., Poechlauer, P., Broxterman, R., am Ende, D., Yang, B. S., Bertsch, C., Hannah, R. E., Baird, J., Dell'Orco, P., Reintjens, R., Noorman, H., & Massonneau, V. (2009, June). Key green engineering research areas. Paper presented at the 14th Annual Green Chemistry and Engineering Conference, Washington, DC. http://acswebcontent.acs.org/gcande/

57. Pradeep, S., & Basu, P. K. (2008). Improving pharmaceutical product development and manufacturing: Impact on cost of drug development and cost of goods sold of pharmaceuticals. *Journal of Pharmaceutical Innovation, 3,* 175–187.

58. The Gold Sheet. (2009). Attention turns to the business case of quality by design. *Pharmaceutical and Biotechnology Quality Control*. Elsevier Business Intelligence.

59. Ritter, S. (2004). Green innovations. *Chemical & Engineering News, 82*(28), 25–30.

60. Kopach, M. E., Braden, T. M., Kobierski, M. E., & Williams, O. L. (2009). Improved synthesis of 1-(azidomethyl)-3,5-bis-(trifluoromethyl)benzene in development of batch and microflow azide processes. *Organic Process Research & Development, 13,* 152–160.

61. Kulkarni, A. A., Kalyani, V. S., Joshi, R. A., & Joshi, R. R. (2009). Continuous flow nitration of benzaldehyde. *Organic Process Research & Development, 13*(5), 999–1002.

62. Pelleter, J., & Renaud, F. (2009). Facile, fast and safe process development of nitration and bromination reactions using continuous flow reactors. *Organic Process Research & Development, 13*(4), 698–705.

63. Rios, M. (2007). Continuous processing finally. *Pharmaceutical Technology.*

64. Mason, B. P., Price, K. E., Steinbacher, J. L., Bogdan, A. R., & McQuade, D. T. (2007). Greener approaches to organic synthesis using microreactor technology. *Chemical Reviews, 107,* 2300–2318.

65. Haswell, S. J., & Watts, P. (2003). Green chemistry: Synthesis in microreactors. *Green Chemistry, 5,* 240–249.

66. Jensen, K. F. (1999). Microchemical systems: Status, challenges, and opportunities. *AIChE Journal, 45*(10), 2051–2054.

67. Krummradt, H., et al. (2000). Experiences with the use of microreactors in organic synthesis. In W. Ehrfeld (Ed.), *Microreaction Technology: Industrial Prospects. IMRET 3: Proceedings of the 3rd International Conference in Microreaction Technology* (pp. 181–186). Springer.

68. Ragauskas, A. J., *et al.* (2006). The path forward for biofuels and biomaterials. *Science, 311,* 484–489.

69. World Economic Forum. (2010). *The future of industrial biorefineries.* Geneva, Switzerland: Author. http://www3.weforum.org/docs/WEF_FutureIndustrialBiorefineries_Report_2010.pdf

70. Gavrilescu, M., & Chisti, Y. (2007). Biotechnology: A sustainable alternative for chemical industry. *Biotechnology Advances, 25,* 471–499.

71. Demain, A. L. (2007). The business of biotechnology. *Industrial Biotechnology, 3,* 269–283.

72. Henderson, R. K., Jiménez-González, C., Preston, C., Constable, D. J. C., Woodley, J. M., & EHS, L. C. A. (2008). Assessment for 7-ACA synthesis: A case study for comparing biocatalytic and chemical synthesis. *Industrial Biotechnology, 4*(2), 180–192.

73. Kim, S., Jiménez-González, C., & Dale, B. E. (2009). Enzymes for pharmaceutical applications: A cradle-to-gate life cycle assessment. *International Journal of Life Cycle Assessment, 14*(5), 392–400.

74. Whittall, J., & Sutton, P. (2009). *Practical methods for biocatalysis and biotransformations.* Wiley-Blackwell.

75. Liese, A., Seelbach, K., & Wandrey, C. (Eds.). (2006). *Industrial biotransformations.* Wiley-VCH.

76. Jödicke, G., Zenklusen, O., Weidenhaupt, A., & Hungerbühler, K. (1999). [Title not provided]. *Journal of Cleaner Production, 7,* 159–166.

77. Schott, C. (2008). Proactive debottlenecking: Planning ahead for the downstream bottleneck. *Bioprocess International, 6,* 18–23.

78. Guidager, N. (2009). Next-generation facilities for monoclonal antibody production. *Pharmaceutical Technology, 33,* S68–S73.

79. Rawlings, B., & Pora, H. (2009). Environmental impact of single use and reusable bioprocess systems. *Bioprocess International, 7,* 18–26.

80. Dale, B. E. (2003). 'Greening' the chemical industry: Research and development priorities for biobased industrial products. *Journal of Chemical Technology and Biotechnology, 78,* 1093–1103.

81. De Braal, H. (2009, January). Sustainability in green pharmaceutical production. *Pharmaceutical Technology Europe,* 21, 33–41.

82. Pollard, D. J., & Woodley, J. M. (2007). Biocatalysis for pharmaceutical intermediates: The future is now. *Trends in Biotechnology, 25,* 66–73.

83. Woodley, J. M. (2008). New opportunities for biocatalysis: Making pharmaceutical processes greener. *Trends in Biotechnology, 26,* 321–327.

84. Jiménez-González, C., & Woodley, J. M. (2010). Bioprocesses: Modeling needs for process evaluation and sustainability assessment. *Computers & Chemical Engineering, 34,*
1009–1017.

85. Mishra Mohit, Sharma Mansi, Dubey Ragini, Kumari Pooja, Ranjan Vikas, Jaya Pandey. (2021). Green synthesis interventions of pharmaceutical industries for sustainable development. *Current Research in Green and Sustainable Chemistry. Science Direct, 4, 100174,* 1-7.

86. Harmsen, J. (2007). Reactive distillation: The front-runner of industrial process intensification. A full review of commercial applications, research, scale-up, design, and operation. *Chemical Engineering and Processing, 46,* 774.

87. Tsoka, C., Johns, W. R., Linke, P., & Kokossis, A. (2004). Towards sustainability and green chemical engineering: Tools and technology requirements. *Green Chemistry, 6,* 401–409.

88. Moreno Rowan. (2024). Pharmaceutical formulation development: A focus on sustainability and green chemistry. *RRJPA, 13, 3,* 14-16.

89. Verma V.S., Pandey A., Jha A.K., Badwaik H.K.R., Alexander A. & Ajazuddin. (2024). Polyethylene glycol–based polymer-drug conjugates: Novel design and synthesis strategies for enhanced therapeutic efficacy and targeted drug delivery. *Applied Biochemistry and Biotechnology, 196, 10*, 7325–61. Available Link: https://link.springer.com/article/10.1007/s12010-024-04895-6

90. Charpentier, J. (2005). Four main objectives for the future of chemical and process engineering, mainly concerned by the science and technologies of new material production. *Chemical Engineering Journal, 107,* 3.

91. Behr, A., Brehme, V. A., Ewers, C. L. J., Groen, H., Kimmel, T., Kueppers, S., & Symietz, I. (2004). New developments in chemical engineering for the production of drug substances. *Engineering in Life Sciences, 4*, *1*, 15–24.

92. Birch, M., Fussell, S. J., Higginson, P. D., McDowall, N., & Marziano, I. (2005). Towards a PAT-based strategy for crystallization development. *Organic Process Research & Development, 9*, *3,* 360–364.

93. Hu, Y., Liang, J. K., Myerson, A. S., & Taylor, L. S. (2005). Crystallization monitoring by Raman spectroscopy: Simultaneous measurement of desupersaturation profile and polymorphic form in flufenamic acid systems. *Industrial & Engineering Chemistry Research, 44*, *5,* 1233–1240.

94. Wei, C., & Yang, B.-S. (2006). Crystallization via high-shear transformation. U.S. Patent Application Publication 0160841, pp. 10

95. Yang, B.-S., & Wei, C. (2005, March 13–17). Producing small crystals of a BMS compound via polymorph transformation. Abstracts of Papers, 229th American Chemical Society National Meeting, San Diego, CA, United States.

96. Li, Z., Yang, B.-S., Jiang, M., Eriksson, M., Spinelli, E., Yee, N., & Senanayake, C. (2009). A practical solid form screen approach to identify a pharmaceutical glutaric acid cocrystal for development. *Organic Process Research & Development, 13, 6,* 1307–1314.

97. McKenzie, P., Kiang, S., Tom, J., Rubin, A. E., & Futran, M. (2006). Can pharmaceutical process development become high tech? *AIChE Journal, 52, 12,* 3990–3994.

98. Henderson, R. K., Kindervater, J., & Manley, J. (2006). Lessons learned through measuring green chemistry performance: The pharmaceutical experience. In *American Chemical Society Green Chemistry Institute Pharmaceutical Roundtable Benchmarking* (Washington, DC). Available Link: http://portal.acs.org/portal/PublicWebSite/greenchemistry/industriainnovation/roundtable/CTP_005585

99. Gaykwad Ragha Rajkumar, Mhaske Shivshankar D., Gawande Vikas & Gaikwad Sarla Yadav. (2025). Advancing eco-friendly drug formulations for environmental sustainability: Toward a greener pharmaceutical future. *JETIR. 12, 5,* h259-h276.

100. Verma V.S., Sakure K. & Badwaik H.R. (2017, Apr). Xanthan gum a versatile biopolymer: Current status and future prospectus in hydro gel drug delivery. *Curr Chem Biol [Internet]. 27, 11, 1,* 10–20. Available Link: http://www.eurekaselect.com/openurl/content.php?genre=article&issn=2212-7968&volume=11&issue=1&spage=10