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STRATEGIES FOR REDUCING ENVIRONMENTAL IMPACT IN THE PHARMACEUTICAL INDUSTRY: TRENDS, CHALLENGES AND PERSPECTIVES

BY

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Abstract. The pharmaceutical industry faces increasing pressure to minimize its environmental footprint while ensuring product safety and quality. This article provides a comprehensive analysis of current trends, challenges, and best practices related to environmental sustainability in pharmaceutical production. Using a systematic literature review approach, the study examines key areas such as greenhouse gas emissions, water contamination with active pharmaceutical ingredients (APIs), and hazardous waste management. The findings reveal that large companies in developed countries are leading the adoption of green chemistry principles and life cycle assessment (LCA), driven by regulatory frameworks and financial resources, while producers in emerging economies struggle with inadequate waste management infrastructure and regulatory enforcement. The paper also explores regulatory influences, technological innovations, and digitalization as enablers of sustainable practices. Solutions such as process optimization, renewable energy adoption, solvent recovery, and integration of artificial intelligence in production processes are highlighted as essential for reducing the sector’s ecological impact. This review identifies research gaps and provides recommendations for aligning pharmaceutical manufacturing with global sustainability goals.

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1. Introduction

The pharmaceutical industry is a vital sector for global health, but it has a disproportionate environmental impact relative to its economic size. Recent studies show that the greenhouse gas (GHG) emissions of the pharmaceutical industry exceed those of the automotive sector per unit of revenue (Hagenaars *et al*., 2025). These emissions are generated throughout the entire value chain: production, packaging, transport, storage, use, and disposal of medicines. Additionally, the release of active pharmaceutical ingredients into wastewater contributes to environmental pollution and the phenomenon of antimicrobial resistance (Rayan, 2023). The environmental impact of the pharmaceutical industry manifests in several ways:

- Water pollution: active substances from medications enter waterways through the disposal of industrial waste and unused drugs.
- Generation of hazardous waste: organic solvents, metal catalysts, and highly toxic intermediates.
- CO_2 emissions and energy consumption: the synthesis, separation, and drying processes are energy-intensive.

In this context, reducing environmental impact is no longer just a moral responsibility but also a strategic requirement. The pressure of international regulations (e.g., the European Green Deal launched in 2019 and Sustainable Development Goals in 2015), investor demands for ESG reporting, and consumer preferences towards sustainable products are forcing the pharmaceutical industry to rethink its production and distribution models (Becker *et al*., 2022). The literature also highlights that the pharmaceutical industry has to deal with a difficult balance between rapid drug production and the implementation of green solutions. Companies face dilemmas regarding the high initial costs of green technologies, the need to modernize infrastructure, and the adaptation of the workforce to new digital and green requirements.

The purpose of this article is to analyze current trends, major challenges, and innovative solutions in reducing the environmental impact of the pharmaceutical industry, based on a review of recent literature (2015–2025).

2. Literature review

Sustainability in the pharmaceutical industry has become a global priority in the context of pressures to reduce the environmental impact of pharmaceutical production and increasing awareness of environmental and public health risks (Belkhir and Elmeligi, 2019). Over the past decade, the literature has highlighted

major trends in reducing greenhouse gas emissions, managing hazardous waste, and reducing water pollution from active pharmaceutical ingredients (APIs) (Galant *et al*., 2022). However, the implementation of these practices remains uneven, influenced by economic, political, and technological factors. The pharmaceutical industry contributes significantly to global carbon emissions and water pollution from APIs. Belkhir and Elmeligi (2019) estimate that the carbon footprint of the pharmaceutical industry is comparable to that of the automotive sector, relative to turnover. In addition, water contamination with pharmaceutical residues favors the emergence of antibiotic-resistant bacteria, which constitutes a major public health problem. Green chemistry principles and life cycle assessment (LCA) are recognized as key tools for reducing environmental impacts. Large companies in the US and Europe have adopted these practices more quickly, due to financial resources and regulatory pressures. In contrast, manufacturers in Asia, especially India and China, face major challenges in waste treatment infrastructure and the implementation of green technologies (Xu and Tan, 2022). The adoption of sustainable measures is supported by international and regional regulations (Beek *et al*., 2016). The European Green Deal sets clear targets for reducing emissions and using resources efficiently (European Commission, 2020). The Global Reporting Initiative (GRI) is an independent international organization that provides the most widely used standards for sustainability reporting, enabling organizations to understand and communicate their impact on the economy, the environment, and society in a comparable and credible way. These standards are applicable to all organizations, regardless of size or sector, and are modularly structured to provide a complete picture of material topics, their impacts, and how they are managed. The implementation of these standards leads companies to integrate life cycle assessment and adopt cleaner technologies. The application of sustainability in the pharmaceutical industry faces economic, technological, and organizational barriers (Belkhir and Elmeligi, 2019). However, the literature identifies concrete solutions: Optimizing synthetic processes to reduce the number of steps and the use of toxic solvents. Adopting renewable energy sources in factories and logistics centers (Shashi, 2023). Solvent recycling and efficient waste management, Digitalization and the use of artificial intelligence to optimize processes and reduce losses (Shashi, 2023).

3. Methodology

This article uses a narrative literature review, focusing on articles published between 2020 and 2025, from the Web of Science, Scopus database. The inclusion criteria are:

- original articles or reviews published between 2015–2025.

- articles on the environmental impact of the pharmaceutical industry- research on carbon footprint reduction, water management, waste reduction, and the application of green chemistry.
- studies presenting technological solutions, regulations, and implementation strategies.

Exclusion criteria are:

- studies that are not directly related to the pharmaceutical industry environment.
- articles with insufficient or unclear data on the methods used.
- non-scientific publications or popular articles (blogs, news, commercial reports without scientific validation).

The Article Selection Procedure is:

- Step 1: Initial search of the mentioned databases, using keywords such as “pharmaceutical industry,” “environmental impact,” “sustainability,” “green chemistry,” and “life cycle assessment.”
- Step 2: Preliminary filtering based on title and abstract, eliminating irrelevant studies.
- Step 3: Full text review for methodological relevance and data quality.
- Step 4: Final selection of 44 key articles, which were analyzed in detail for trends, challenges, and solutions.

In this context, this study aims to answer the following questions:

- What are the main trends in reducing the environmental impact of the pharmaceutical industry?
- What major challenges do companies face in implementing sustainable strategies?
- What are the solutions and best practices that can be adopted to reduce the environmental impact of the industry?

The following figure highlights the steps taken in the article selection process.

To analyze the structure and evolution of sustainability research in the pharmaceutical industry, the VOSviewer software was used, a bibliometric tool recognized for its ability to build and visualize networks of terms, authors, and publications. The choice of this program is justified by its methodological advantages: it allows the graphical representation of complex relationships between concepts, highlights thematic connections through clusters, and facilitates the understanding of the dynamics of the field through temporal visualizations. The first map generated reflects the network of keywords associated with the analyzed publications. The size of the nodes indicates the frequency of appearance of the terms in the specialized literature, and the colors

show the thematic groupings or their evolution over time. The second map illustrates the network of co-authors, providing an image of the scientific collaborations between researchers. The larger nodes represent authors with a significant presence in the specialized literature, and the links between them reflect the intensity of the collaborations.

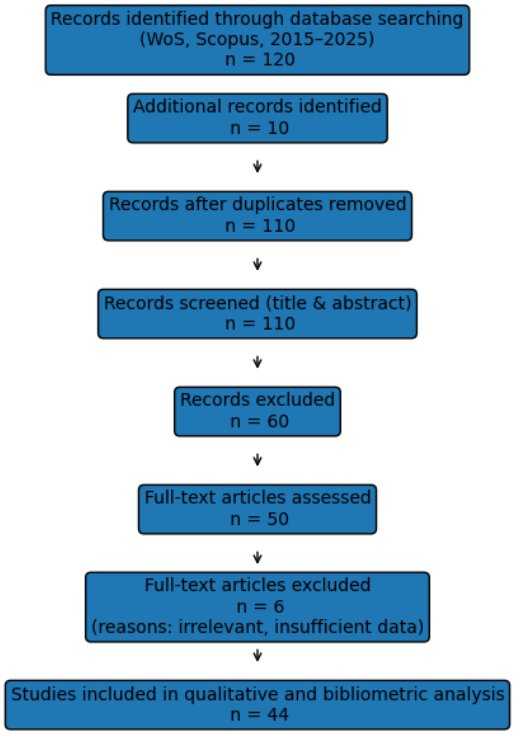

Fig. 1 – PRISMA flow diagram illustrating the systematic selection of studies included in the analysis (2015–2025).

This methodological approach allows not only identifying dominant trends in the literature but also critically evaluating current research directions. By correlating bibliometric results with narrative analysis, the study provides a solid basis for integrating engineering perspectives into the analysis of the sustainability of the pharmaceutical industry.

4. Discussion

The adoption of sustainability in the pharmaceutical industry has evolved significantly over the past decade; however, its application remains uneven and is strongly influenced by economic and political factors. The reviewed studies

indicate that the implementation of green chemistry and life cycle analysis (LCA) is more advanced in large companies in the US and Europe, primarily due to the availability of financial resources and regulatory pressure (Tarpani and Azapagic, 2018). In contrast, manufacturers in Asia, particularly India and China, which are responsible for a significant share of active pharmaceutical ingredients (APIs), face substantial challenges regarding waste treatment infrastructure and pollution control (Veleva *et al*., 2018; Kumar *et al*., 2018).

Among the current trends in terms of increasing environmental sustainability in the pharmaceutical industry, we find:

Digitalization and Industry 4.0- the implementation of digital technologies like the Internet of Things (IoT), artificial intelligence (AI), and machine learning- allow real-time monitoring of production processes, identification of losses, and optimization of resource consumption (Weaver *et al*., 2022). The use of smart sensors for solvent monitoring or prediction algorithms for energy consumption can have the impact of reducing process variability by up to 15% and decreasing energy consumption by 8–10% (Duarte *et al*., 2022).

Green Chemistry- the adoption of green chemistry principles is one of the most important directions that involves replacing hazardous solvents with environmentally friendly solvents, biocompatible catalysts, and enzymatically catalyzed processes, and reducing synthesis steps through integrated reactions (Ganesh *et al*., 2021; Hayler *et al*., 2018).

Circular economy and solvent recovery- the pharmaceutical industry uses large quantities of solvents, and the lack of recovery leads to high emissions and costs. The current trend is the recovery and reuse of solvents through advanced technologies (vacuum distillation, selective membranes) (Savelski *et al*., 2017).

Renewable energy and decarbonization- companies such as Novartis, Roche, and *Sustainable drug design*- the concept of "benign by design" involves designing molecules so that they degrade quickly in the environment without generating toxic compounds (Puhlmann *et al*., 2024, Souza *et al*., 2021).

Although the aforementioned trends indicate a positive change, their implementation faces multiple obstacles:

- High costs: investments in green infrastructure and equipment are prohibitive for SMEs.
- Pressure on time to market: Emphasis on the speed of drug delivery reduces the space for technological experiments.
- Complexity of regulations: lack of global standardization creates legal uncertainty.
- Pharmaceutical waste management: In emerging countries, expired drugs often end up in landfills or wastewater, promoting antimicrobial resistance (Rayan, 2023).

  A critical aspect is the economic impact of the transition to sustainable processes. In the short term, the adoption of clean technologies, such as

flow chemistry and biocatalysis, involves high upfront costs, with estimates indicating an increase in operating expenses of 10–20% in the first years (Van Vliet *et al*., 2025). However, in the long term, the benefits become clear: reduced losses, optimized energy consumption, and lower environmental taxes lead to significant savings and an improved reputation, which attracts ESG-oriented investors (Wang *and Du*, 2025).

From a chemical engineering perspective, sustainability in the pharmaceutical industry should not be analyzed exclusively at the strategic level but especially at the process level. Parameters such as reaction yield, selectivity, specific energy consumption, and efficiency of raw material use are essential for assessing environmental impact. The reviewed literature indicates that the transition to sustainable processes is closely linked to the adoption of advanced engineering solutions, such as process intensification and the use of continuous reactors. Compared to conventional batch processes, continuous processes allow for more precise control of operating conditions, reduce variability, and lead to a significant decrease in energy consumption and the amount of waste generated. Also, the integration of efficient separation technologies and solvent recovery contributes to increasing the overall efficiency of the process. In this context, sustainability becomes an engineering optimization problem, in which environmental objectives must be integrated with the economic and technological performance of the processes. Despite significant progress in the literature, there is a lack of studies that integrate quantitative models and process simulations in sustainability assessment. Most research remains descriptive and does not provide a rigorous quantification of technological benefits. In this regard, the development of integrated models that combine life cycle analysis with chemical process simulation represents a promising direction for future research. Although these trends point in a positive direction, the effectiveness of implementation depends largely on the technological maturity of the processes and the ability of companies to integrate digital solutions into the existing infrastructure. Compared to traditional approaches based on incremental optimizations, modern solutions oriented towards process intensification offer a significantly higher potential for reducing environmental impact. This difference highlights the fact that sustainability is not only a technological issue but also a structural one, influenced by access to capital, the level of industrial development, and the regulatory framework.

5. Results

Reducing the environmental impact of the pharmaceutical industry requires a multi-dimensional approach, combining technological innovation, sustainable management, and public policies. The literature shows that leading companies in the industry are already applying a series of effective solutions, which can be grouped into several directions presented in Table 1.

Table 1

Measures applied in the pharmaceutical industry to reduce environmental impact, according to the literature

Measures applied	Examples from the literature
Application of green chemistry principles	- Reducing the use of toxic solvents by replacing them with bio-derived solvents or water (e.g., the Novartis process for the synthesis of DMF-free APIs) (Adeyemo *et al*., 2024). - Reducing the number of steps in chemical synthesis by using heterogeneous catalysts and multi-component reactions (Nolan *et al*., 2024). - Modernization of industrial equipment and use of renewable energy in factories (Domingues *et al*., 2025)
Sustainable manufacturing processes	- Continuous flow chemistry technology replaces traditional batch processes, reducing waste of raw materials and energy. - Reduction of solvent waste and chemical waste and reuse of by-products - circular economy (Domingues *et al*., 2025)
Sustainable supply chain management	- Selecting suppliers according to ESG (Environmental, Social, Governance) criteria to ensure responsible practices throughout the value chain. - Optimizing transportation through low-emission routes, using green logistics, and using recyclable packaging (Situmorang, 2025). - Accelerated growth in the importance of sustainable practices in correlation with organizational performance (Chen and Zhang, 2026)
Digital technologies for monitoring and reducing emissions	- IoT systems for real-time energy and water consumption monitoring. - Artificial Intelligence (AI) for optimizing chemical processes and reducing losses. - Real-time monitoring, predictive decisions, traceability, increases sustainability and waste optimization (Zhang *et al*., 2025).
Collection and recycling programs for unused medicines	- Take-back programs for expired medications have been implemented in pharmacies (EU and US). - Educational campaigns for the population on the correct disposal of medications (González-González *et al*., 2021).
Sustainable certifications and reporting	- ISO 14001 for environmental management - GHG Protocol for calculating and reporting greenhouse gas emissions.
Public policies and intersectoral collaboration	- Financial incentives for companies investing in green technologies (Siddiquee *et al*., 2024). - Strict regulations on the discharge of APIs into wastewater. - Partnerships between industry, authorities, and academia to develop remediation technologies.

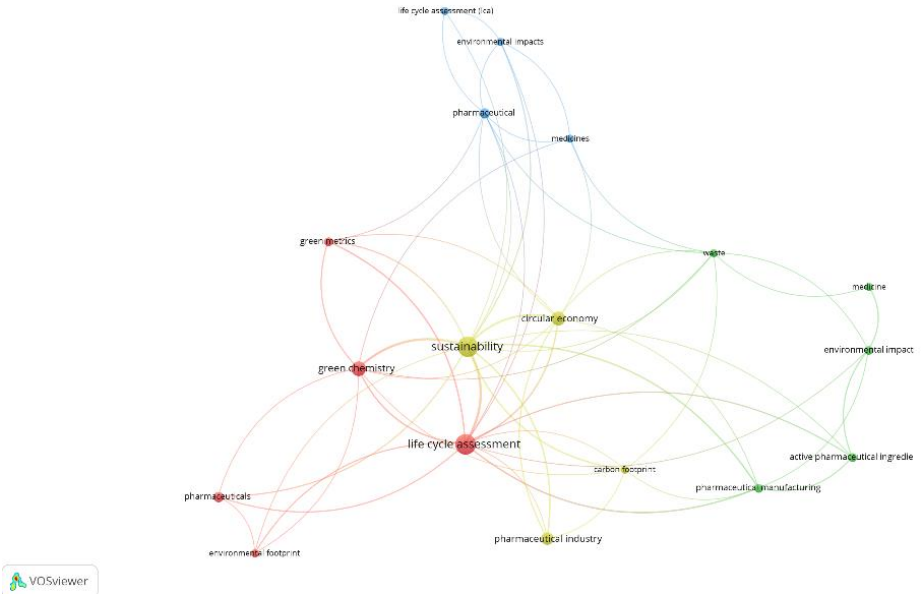

Fig. 2 – Keyword network and thematic evolution of sustainability research in the pharmaceutical industry.

Figure 2 presents the keyword co-occurrence network generated using VOSviewer, highlighting the main research directions in pharmaceutical sustainability. The results indicate a strong dominance of terms such as “life cycle assessment” and “sustainability”, suggesting that the field is primarily focused on environmental impact evaluation and monitoring. The clustering structure reveals several major research themes, including green chemistry and environmental metrics, life cycle assessment, waste management and pharmaceutical manufacturing, as well as environmental impact analysis. Notably, “life cycle assessment” emerges as the most prominent term, confirming its central role as a methodological framework in the literature. At the same time, the limited presence of terms related to process intensification, continuous manufacturing, or process simulation indicates that engineering-oriented approaches remain underexplored. This highlights a significant research gap and supports the need for integrating quantitative, process-based methods into sustainability assessments in the pharmaceutical industry.

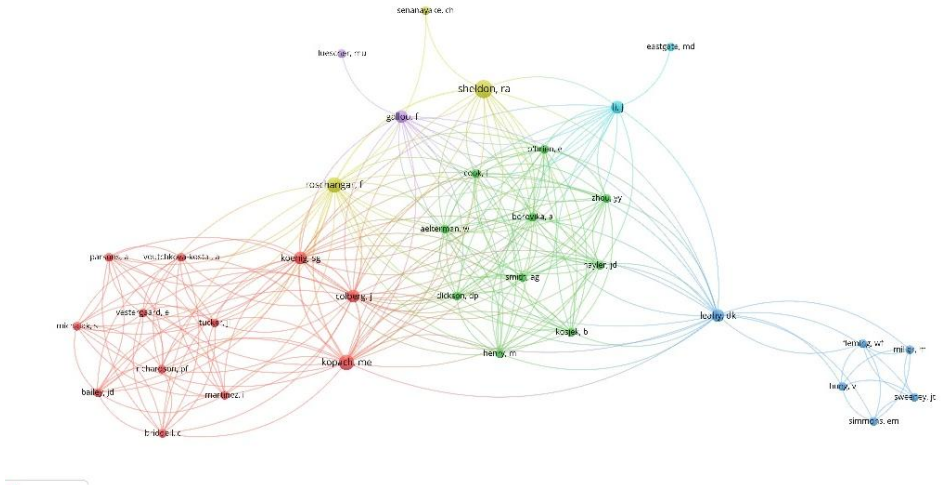

Fig. 3 – The network of co-authors and the structure of scientific collaborations in the field of pharmaceutical sustainability.

Figure 3 illustrates the co-authorship network in the field of pharmaceutical sustainability, highlighting the main collaboration patterns between researchers. The results reveal the presence of several well-defined clusters, indicating the existence of established research groups and strong collaborative structures.

Highly connected authors, such as Sheldon (2017) and Roshanzamir (Rahimi *et al*., 2020), appear as central nodes, suggesting their significant influence in advancing green chemistry and sustainable pharmaceutical processes. The clustering pattern also indicates that research activity is often organized around industrial and applied research environments.

Notably, many of the identified collaboration clusters are associated with major pharmaceutical companies or industry-linked research centers, suggesting that innovation in this field is largely driven by industry–academia partnerships. This highlights the applied nature of sustainability research in the pharmaceutical sector and its strong connection to process development and industrial implementation.

From a chemical engineering perspective, the environmental sustainability of pharmaceutical manufacturing processes can be objectively assessed using quantitative green metrics such as the E-factor (Environmental Factor) and Process Mass Intensity (PMI). These indicators provide a standardized framework for evaluating material efficiency, waste generation, and resource utilization across different production technologies. Recently, the transition from traditional batch processing to advanced manufacturing approaches, such as continuous flow chemistry, green synthesis, and intensified separation technologies, has been driven by the need to reduce environmental

impact while maintaining process performance. At the same time, end-of-pipe solutions, including advanced oxidation processes (AOPs) and solvent recovery systems, play a critical role in mitigating emissions and improving circularity within pharmaceutical production systems. Table 2 presents a comparative overview of the main engineering technologies and sustainability metrics reported in recent literature, highlighting their performance in terms of waste reduction, solvent usage, and process efficiency.

Table 2

Comparison of green engineering metrics and technologies in pharmaceutical manufacturing

Process / Technology	PMI (Process Mass Intensity)	Solvent Reduction	Key Advantages	Limitations	Source
Batch Processing (traditional)	50–200%	-	Established technology, flexibility	High waste generation, low efficiency	Sheldon, 2017; Kümmerer *et al*., 2020
Continuous Flow Chemistry	5–20%	20–40%	Enhanced heat/mass transfer, process intensification	High CAPEX	Plutschack *et al*., 2017; Sanoja-López *et al.*, 2025
Green Chemistry Processes	<10%	max 50%	Safer reagents, atom economy, reduced toxicity	Requires redesign	Becker *et al*., 2022,
Advanced Oxidation Processes (AOPs)	-	>90%	Efficient degradation of pharmaceutical pollutants	Energy intensive	Miklos *et al*., 2018, Van Vliet *et al.*, 2025
Solvent Recovery & Circular Processes	30-70%	30–70%	Waste minimization, circular economy	Extra unit operations	Becker *et al.*, 2022

The data summarized in Table 2 clearly demonstrate that traditional batch processes are associated with significantly higher E-factors and material inefficiencies, reflecting their inherently waste-intensive nature. In contrast, advanced engineering approaches, particularly continuous flow chemistry and

green synthesis strategies, show substantial improvements in both resource utilization and waste reduction. Technologies such as solvent recovery systems and supercritical fluid extraction further contribute to minimizing environmental impact by supporting circularity and reducing reliance on hazardous solvents. These findings emphasize that the adoption of engineering-driven solutions is essential for achieving measurable sustainability improvements in pharmaceutical production systems.

The quantitative results presented in Table 2 are consistent with the bibliometric analysis performed using VOSviewer. The keyword co-occurrence map highlights a strong clustering around terms such as “life cycle assessment”, “green chemistry”, and “sustainability”, indicating that current research is predominantly focused on evaluation and environmental impact assessment. However, the relatively limited presence of terms related to “process intensification”, “continuous flow”, or “process simulation” suggests that engineering-oriented approaches remain underrepresented in the literature. This gap confirms the need to integrate quantitative process-based metrics, such as E-factor and PMI, with bibliometric insights in order to better support the transition toward sustainable pharmaceutical manufacturing.

The main strategies to reduce the environmental impact in the pharmaceutical industry are:

- Green chemistry and eco-design: The use of green chemistry principles (atom economy, catalysis, safer solvents, design for degradation) waste reduction, the decrease in energy consumption, and the use of hazardous substances (Onagun and Gbenga, 2024).
- Process optimization and waste management: Implementation of Life Cycle Assessment (LCA) to identify the stages with the highest impact, optimization of waste gas treatment, emission reduction, and material recycling (Zhang *et al*., 2024; Chaturvedi, 2023).
- Sustainable packaging and transport: Eco-design of packaging (volume reduction, biodegradable materials, low-emission transport) and the use of renewable energy in distribution (Souza *et al*., 2021).
- Green Supply Chain Management (GSCM): Green procurement, collaboration with suppliers for sustainable practices, reduction of resource consumption, and responsible waste management throughout the supply chain (Agrawal *et al*., 2025).
- Innovation and eco-innovation: Investment in new technologies (biocatalysis, continuous processes, alternative materials), digitalization, and circularity to reduce drug waste (Ahmed *et al*., 2021; Wen *et al*., 2021)
- Advanced wastewater treatment: Use of technologies such as membrane bioreactors, phytoremediation, and sorption on biochar or activated carbon for efficient removal of pharmaceutical compounds (Helwig *et al*., 2023; Nguyen *et al*., 2023; Pawar *et al*., 2023).

6. Conclusions

The pharmaceutical industry is undergoing a significant transformation, in which sustainability is increasingly recognized as a prerequisite for long-term competitiveness and regulatory compliance. The present study has shown that the reduction of environmental impact is closely linked to the combined implementation of technological innovation, process optimization, and strategic management practices. The analysis of the selected literature indicates that current research is predominantly oriented toward environmental assessment, with particular emphasis on life cycle assessment (LCA), green chemistry principles, and digitalization. At the same time, the results suggest that the integration of engineering-based approaches remains limited, despite their potential to provide more robust and quantifiable improvements in process sustainability. From a chemical engineering perspective, the most effective strategies are those applied at the process level, including process intensification, continuous manufacturing, and optimization of energy and material flows. These approaches enable measurable reductions in waste generation and resource consumption, while also contributing to improved operational efficiency. Nevertheless, the implementation of such solutions is uneven across regions, being influenced by economic constraints, regulatory heterogeneity, and differences in technological development. In particular, pharmaceutical production in emerging economies continues to face challenges related to infrastructure and access to advanced technologies. The findings of this study underline the need for a more systematic integration of process engineering tools within sustainability assessments. In this context, future research should focus on the development of quantitative frameworks that combine process modeling with environmental evaluation methods in order to support decision-making at the industrial level. Overall, the transition toward sustainable pharmaceutical manufacturing requires a coherent approach that connects engineering innovation with environmental objectives across the entire production and supply chain system.

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STRATEGII PENTRU REDUCEREA IMPACTULUI ASUPRA MEDIULUI ÎN INDUSTRIA FARMACEUTICĂ: TENDINȚE, PROVOCĂRI ȘI PERSPECTIVE

(Rezumat)

Industria farmaceutică se confruntă cu presiuni tot mai mari pentru reducerea amprentei ecologice, menținând în același timp siguranța și calitatea produselor. Acest articol oferă o analiză cuprinzătoare a tendințelor actuale, provocărilor și bunelor practici legate de sustenabilitatea de mediu în producția farmaceutică. Printr-o abordare bazată pe revizuirea sistematică a literaturii, studiul examinează aspecte-cheie precum emisiile de gaze cu efect de seră, contaminarea apei cu ingrediente farmaceutice active (API) și gestionarea deșeurilor periculoase. Rezultatele arată că marile companii din țările dezvoltate conduc în adoptarea principiilor chimiei verzi și a analizei ciclului de viață (LCA), datorită cadrului de reglementare și resurselor financiare, în timp ce producătorii din economiile emergente se confruntă cu infrastructură deficitară pentru tratarea deșeurilor și o aplicare slabă a reglementărilor. Lucrarea explorează, de asemenea, rolul reglementărilor, inovațiilor tehnologice și digitalizării în facilitarea practicilor sustenabile. Sunt evidențiate soluții precum optimizarea proceselor, utilizarea energiei regenerabile, reciclarea solvenților și integrarea inteligenței artificiale în procesele de producție, ca elemente esențiale pentru reducerea impactului ecologic al industriei. Revizuirea identifică lacune în cercetare și oferă recomandări pentru alinierea producției farmaceutice la obiectivele globale de sustenabilitate.