The Role of Green Chemistry in Enhancing Occupational and Environmental Health for: A Sustainable Future

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Abstract

Environmental and occupational exposure to toxic chemicals remain a major contributor to global burden of diseases. Many health programs are based on risk management after exposure has occurred, however there is an increasing agreement that preventive strategies should focus on hazard at source. The branch of sustainable chemistry emphasizes safer chemical design and sustainable processes representing an important yet underutilized opportunity to strengthen preventive public health approach. This paper examines how green chemistry can improve occupational and environmental health within sustainable health programs and policymaking. The integration of principles from green chemistry like substitution of hazardous substances, minimization of toxic waste and designing safer chemical processes has the potential to shift paradigms in occupational and environmental health programs from reactive risk management toward strategic approach. This study adopts a qualitative literature review design to examine how green chemistry can improve occupational and environmental health within sustainable health programs and policymaking. Evidence from frameworks in occupational and environmental health will be used in this paper to show how chemical innovation can be applied in program planning, regulatory standard setting and policy decision-making processes. The findings show how embedding green chemistry principles into health programs provides an avenue for reducing workplace exposures that endanger surrounding communities while simultaneously decreasing long-term health care and environmental costs. Green chemistry links chemical sciences with public health and policy by making it possible for preventive evidence-based approaches to improve occupational as well as environmental health outcomes sustainably. This study contributes to both academia and practice by providing an integrated framework for applying green chemistry to improve occupational and environmental health outcomes.

Keywords: green chemistry, occupational, environmental health, primary prevention, sustainable processes

Introduction

The rapid progress of industrialization and chemical-based technologies has greatly improved the standards of living in modern times. This has, in turn, led to progress in the field of healthcare, agriculture, manufacturing and energy (Landrigan et al., 2018). However, this progress has led to higher levels of environmental pollution and exposure to hazardous chemicals, which are negatively affecting humans and the environment (Steffen et al., 2015). This emphasizes the necessity of using chemicals in a more sustainable manner.

Green chemistry is known as a trans-formative approach to designing safer chemical and processes that reduce or eliminate harmful chemicals or material. By focusing on the principles of reducing waste, safe solvent use, energy efficiency, and the best utilization of renewable resources, this approach offers a significant potential to lessen the harmful impacts associated with traditional chemical practices (Anastas & Warner,1998). Thus, it is now seen as a key instrument in safeguarding both environmental and occupational health and enhancing sustainability.

Despite these advancements in green chemistry, current research in green chemistry often views occupational health and environmental health as two separate disciplines. Schulte, P. A., et al. (2013). Occupational health-related research in green chemistry is mainly concerned with protecting human health in the context of chemical exposure in laboratories as well as industries. Environmental health-related research in green chemistry is concerned with the effect of chemical pollutants in the context of air, water, soil, and population health. However, such an approach does not consider the fact that chemical exposure is an integrated entity in which occupational health-related hazards can lead to environmental health-related hazards.

The concept of the exposome, which considers the totality of environmental and chemical exposures across the lifespan (Vermeulen,2020), highlights the necessity of adopting a more integrated and holistic approach. This perspective reinforces the importance of bridging the gap between occupational and environmental health in the context of green chemistry.

Therefore, this paper aims to explore the significance of green chemistry in the context of occupational and environmental health, with particular emphasis on the integration of the two. By exploring existing gaps and proposing a more holistic framework, this study seeks to contribute to development of long-term sustainable strategies that protect human health and the environment simultaneously.

Literature Review

Theoretical Literature Review

This study is grounded in theoretical perspectives that tie green chemistry into occupational and environmental health. Current frameworks include:

Author/Developer	Framework	Purpose	Critical Analysis
Christopher Wild, (2005)	Exposome Concept	Provides a holistic approach to understanding the impact of different routes of exposure such as occupational, environmental and lifestyle exposure influence human health outcomes	Despite its comprehensive nature, it does not offer solutions to reduce these risks. Its emphasis on data collection and analysis prevents it from being used as a tool to design safe processes.

Associated with Ludwig Von Bertalanffy (mid-20th century)	Systems Thinking	It is one theory that pushes for seeing how everything connects in complicated setups, instead of just viewing them in isolation	Despite its importance in gaining insights into complex interactions, systems thinking is ineffective as it lacks the means for putting theory into practice in this context. Without integration with practical approaches, it remains largely conceptual.
ISO developed **standardized LCA frameworks (ISO 14040 series)**	Life cycle Thinking	It focuses on evaluating product and process throughout their lifetime-from material extraction through disposal.	Regardless of its strengths, it is primarily assessment-based rather than intervention-focused. It identifies impacts but does not necessarily promote the redesign of chemical processes to reduce hazards.

In overall, the comparative analysis on the above table highlights that while the three approach contribute to an understanding of chemicals and their effects in terms of exposure, interaction and impact respectively, they are limited when considered in isolation. Exposome deals with exposure, whereas systems thinking concentrates on system-level interactions. Life cycle thinking considers impacts at various stages.
However, lack of unifying these theories makes it hard to come up with solutions for risks associated with chemicals. This highlights the need for a more comprehensive and integrated approach.

Empirical Literature Review

Green chemistry has gained significant attention as a sustainable approach to reducing the environmental and health impacts associated with conventional chemical process. The foundational principles proposed by Anastas & Warner (1998) emphasize the design of safer chemicals, reduction of hazardous substances, and minimization of waste, positioning green chemistry as a key strategy in advancing both environmental sustainability and human health. However, the existing literature indicates that the application of green chemistry is dispersed over various domains, particularly in the field of occupational and environmental health.

In the context of the existing research on occupational health, more emphasis is on chemical exposure in the laboratory and industrial environment. Research on safety in the laboratory environment emphasizes the importance of incorporating green chemistry in the culture of the laboratory environment to provide safer working conditions and minimize the risk of hazardous reagent (O'Neal et al., 2020). The application of system thinking approaches further improves proactive risk assessment, and it supports the creation of a safety culture in chemical environments.

On the contrary, research in environmental health has demonstrated through various studies the adverse effects of chemical pollutants in ecosystems and on humans. For example, research on plastic waste has demonstrated how pollutants such as Bisphenol A and phthalates are released into the environment and contributing to pollution and long-term health effects, Alabi et al (2019). Similarly, the use of chemical pesticides, while essential for agricultural productivity, has been associated with significant environmental contamination and health hazards, Nicolopoul-Stamati et al (2016).

A notable contradiction exists within the literature relates to the function of chemicals, such as agrochemicals, in society. O'Riordan (2018) highlights the need for the use of chemical pesticides in the maintenance of food security and agricultural productivity, emphasizing that it is essential in meeting the needs of a growing world population. However, the risks to the environment and health resulting from the use of pesticides have also been identified in the literature as a major concern, including the toxic risks faced by the public (Nicolopoul-Stamati et al (2016). This reflects a striking contradiction in the literature that highlights the need for a balanced and sustainable approach in the green chemistry framework. The divergence in perspectives shows a critical tension between the need to support agricultural productivity and the need to support environmental and public health. Such conflicting evidence points to a need for more balanced approaches in green chemistry.

From the industrial and pharmaceutical perspective, there is empirical evidence that green chemistry-based innovations, such as solvent-free synthesis biocatalysis, and renewable resources, can have a significant impact on reducing environmental effects without compromising the efficacy of the final product (Sheldon, 2016).However, there are challenges in terms of scale, cost, and compatibility of these new approaches with existing industrial processes.

In overall, the literature emphasizes the potential for the improvement of environmental health and occupational health through the application of green chemistry. However, the application of this approach is challenged by the fragmented approach and the lack of integration of health perspectives. Moreover, the lack of comprehensive systems-based frameworks is also a barrier to the effective application of this approach.

Gaps and Contradictions in Literature

The review of the existing literature shows that there are many gaps and inconsistencies in the application of green chemistry for health-related outcomes. One of the limitations of the existing research is that it has adopted a fragmented approach for occupational and environmental health, dealing with both aspects in isolation rather than considering them as a whole system.

The existing literature reflects conflicting views on agrochemical use, as noted in previous studies (O'Riordan, 2018; Nicolopoul-Stamati et al., 2016). This disproportion shows that there is a need for urgent and integrative solutions that have the potential to balance this competing demand. In this context, green chemistry has the potential to serve as a bridge that offers strategies to optimize chemical process and products in a way that maintains efficiency in agriculture while avoiding adverse effects on human health and the environment. Achieving such a balance requires moving beyond fragmented approaches and moving to more holistic approaches that integrate both occupational and environmental health aspects.

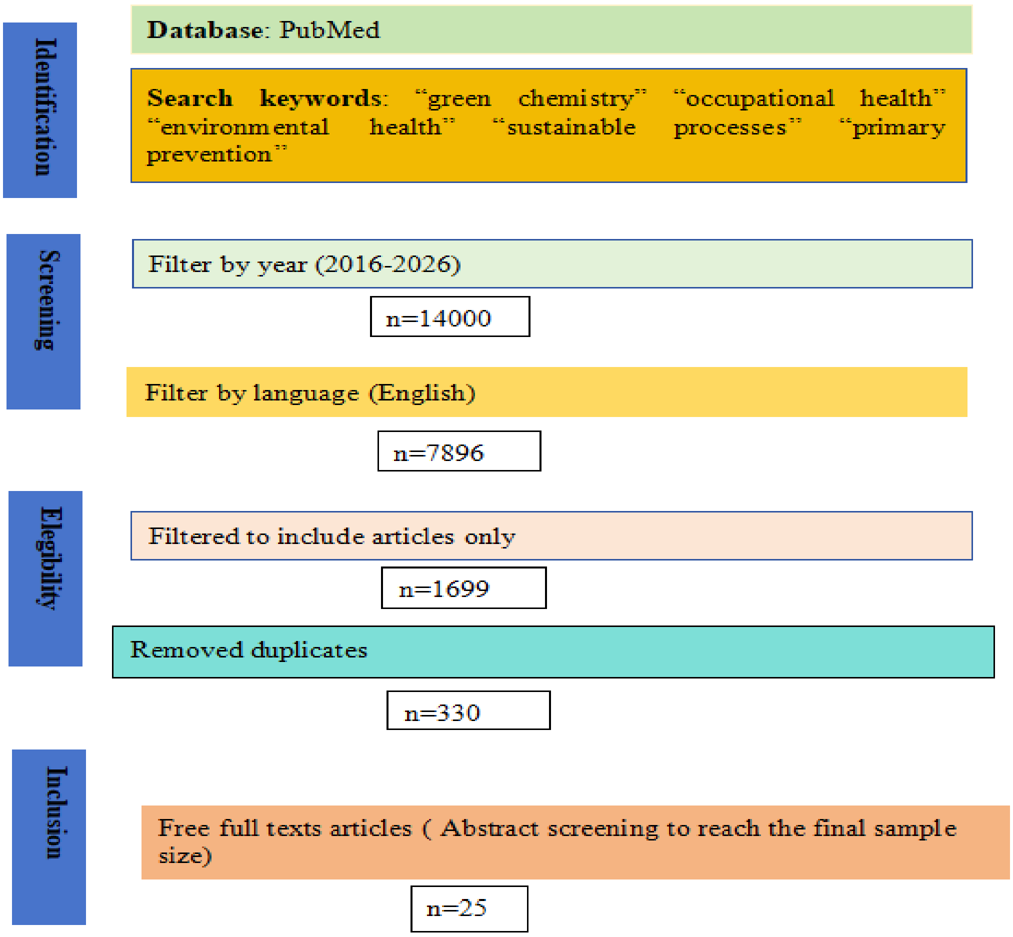
There is a gap between advancements made in green chemistry through research and their practical implementation. Most studies show innovations of green chemistry, including energy-saving technologies,

green solvents, and the use of no solvents. However, because of their cost, scalability and compatibility with current industrial systems, these technologies have not been widely adopted in the real world. This gap restricts the total impact of green chemistry since theoretical and experimental advances may not always translate into real-world benefits for human health or the environment, implying that even if traditional methods are harmful to the environment and public health.
Another critical gap is the lack of integrating the concept of life cycle thinking in the assessment of chemical processes. In most of the literature, there is a focus on individual stages of the chemical process, such as production or usage, without considering the entire life cycle of the chemical from raw material acquisition to final product distribution. The failure to perform a comprehensive life-cycle assessment of chemical processes might lead to unforeseen consequences, whereby the improvement of one aspect of the chemical process might lead to negative consequences in another. For example, a chemical process deemed "green" during production may generate hazardous waste during disposal. This fragmented evaluation undermines the overall sustainability of green chemistry initiatives and highlights the need for more holistic, systems-based approaches.

Methodology

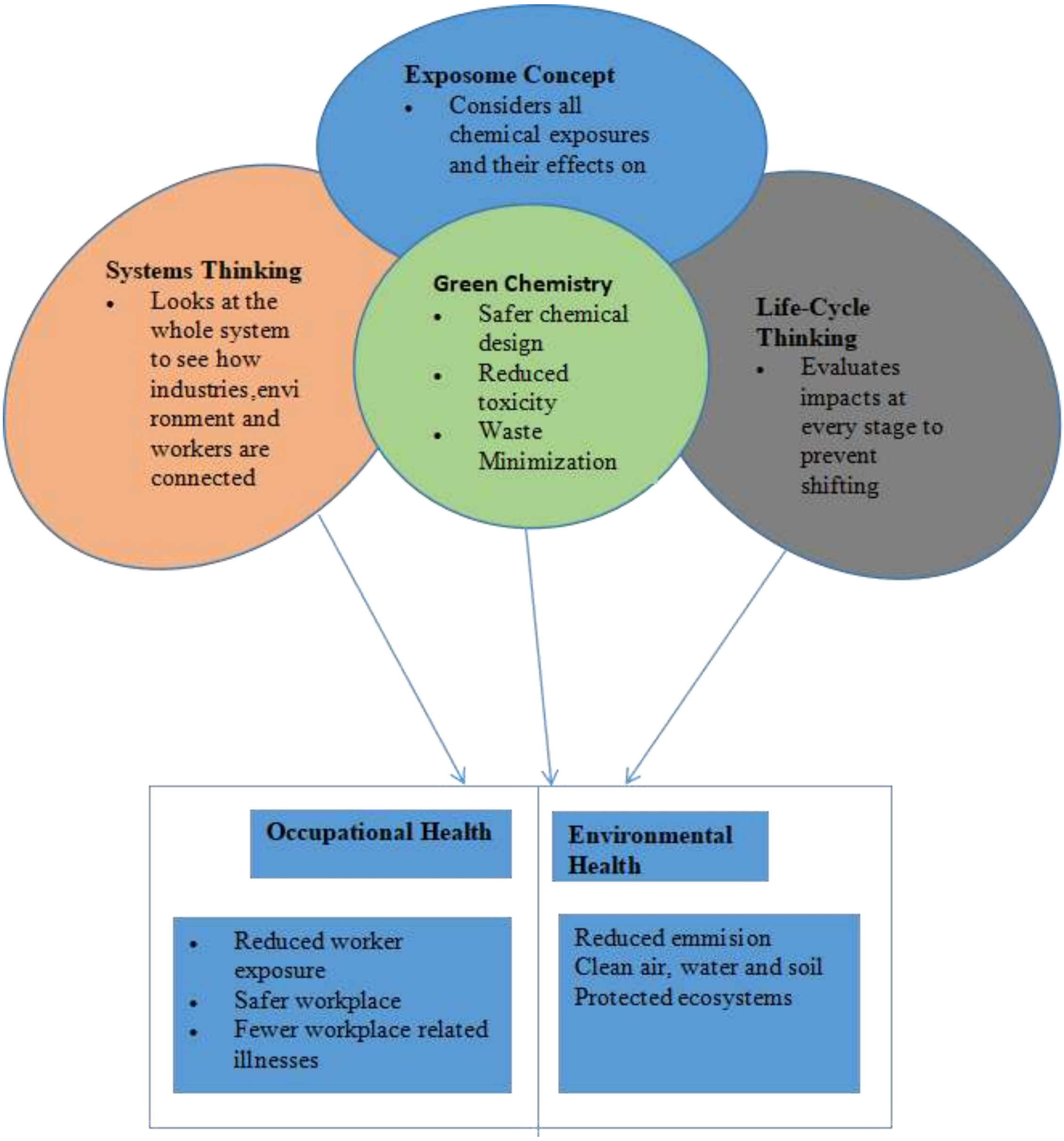
The PRISMA approach was adopted to search and obtain papers for inclusion in the study. The approach offers a systematic and transparent review process which ensures both validity and credibility.

Figure 1: PRISMA flow diagram of the study selection process



Source: Adapted from PRISMA guidelines.

Figure 2: Proposed Green Chemistry and Occupational–Environmental Health Nexus Framework



Source: Author's own conceptualization.

Summary of the proposed framework

All three approaches act as fundamental building blocks that help define how chemical risks are perceived, analysed, and managed.

In other words, chemical exposure and release of substances into the environment don't happen in a vacuum. They are instead part of a larger system that connects industries to workers and ecosystems. Systems thinking recognizes this interconnection allowing health and environmental hazards to be seen as parts of a living web, paving the way for more effective and sustainable solutions.

The idea is further explored by the exposome concept which expands on this by encompassing the sum of chemical exposures over time across both occupational and ambient exposure. It follows people, year after year, how they are exposed to different chemicals over time. It underscores the need to develop more integrated approaches that do not treat exposures as isolated incidents and do account for cumulative health risks.

This is further supported by the life cycle approach, which allows to assess the impacts of chemicals throughout their entire life, from extraction and manufacturing, through use, to disposal. This circumvents the burden-shifting dynamic across phases and furthermore facilitates a more sustainable and informed decision-making process.

If applied, these principles enable safer chemical design, reduced reliance on hazardous materials and minimized waste The cross-domain benefits are better occupational health (measured in lower work- based ill-health), safer work places and reduced exposure to hazardous products where health is a concern, as well as environmental health from less pollution / contamination and ecosystems recovery. This integrated approach not only continues to advance the practice of science itself, but it moves us closer to a healthier, more sustainable future in which human well- being and custodianship for our environment are permanently intertwined.

CONCLUSION

Within the much broader understanding of sustainable development, we discuss green chemistry in terms of its implications for environmental and occupational health of societies. However, current practice tends to be rather fragmented and mostly misses the developments of chemical life cycles yet often slow in adjusting to new paradigms (e.g. exposome) The limitations reveal the need of theoretical approaches that can connect green chemistry with more unified practice and integrates between largely disparate (theoretical) notions on what constitutes a green chemical

One of the key conclusions is that little research still fails to recognize their common ground; occupational and environmental health are all in the human experience, since we exist because of chemical exposure almost every moment of our time. These findings provide insights into the underlying tensions between sustainability aspirations and production demands, underscoring a significant reliance on agricultural chemicals.

These differences highlight the necessity to adopt a more holistic and forward-looking perspective of green chemistry, one that compiles health, environment, sustainability and fosters an integrated framework that can adequately cope with chemical use challenges in modern society. To overcome the above negative aspects, the design of chemistry (i.e. via its functionalization) was connected to occupational exposure and environmental impact whilst the latter impacts could be combined in various sectors (with a cumulative effect on human exposure). Integrating life cycle assessment and chemo-prospective processes is a method that could help Gaps closing. This approach will maximize co-benefits for both systems in the realm of economic growth through innovation, i.e. develop strategies or materials that prevent generation of end-of-life product streams and facilitate direct engagement with a respective general public area(s) in identifying innovative solutions for health issues where those approaches do not generate new unwanted by products nor exacerbate adverse health condition.

Therefore, mixing ideas from green chemistry with those from occupational and environmental health is a move toward long term health perks.

Green chemistry really needs to shift from just theory to actual practice. It should help create policy frameworks and indicators that push for safer and more sustainable chemical methods. Project like these will matter a lot for making green chemistry a part of sustainable development and safeguarding public health.

This theoretical model has not been tested in real life settings. It needs validation, which calls for institutional studies across various fields and labs to make sure its solid.
Conceptual formalization requires population-relevant indicators to let implementation and evaluation happen. The potential of green chemistry lies in innovative technologies and research aimed at reducing challenges related to cost, adaptability and public awareness.

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