

Educational Insights into the Complex Intersections of Green Chemistry and Arsenic-Induced Groundwater Pollution in Sustainable Development

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Abstract - This educational exploration delves into the complex intersections of these two realms, aiming to unravel the nuanced relationship between environmentally conscious chemical practices and the pressing challenge of arsenic contamination in groundwater. As we navigate the intricate landscape of sustainable development, this study seeks to provide valuable insights that not only shed light on the scientific intricacies involved but also contribute to the formulation of informed strategies and solutions. Through a holistic examination of the multifaceted facets of Green Chemistry and arsenic-induced groundwater pollution, this research endeavors to carve a path towards a more sustainable and resilient future. For an extended period, the utilization of green chemistry (GC) has demonstrated that employing a fundamental scientific methodology and advanced practices can enhance the safe production for human life while minimizing environmental disturbances. To achieve this, progress has been made in scientific processes within the realms of designing safer reagents and solvents, advancing catalysis, and potentially developing renewable feed stocks. To attain greater accomplishments, contemporary chemists are now being educated and trained in a broader understanding of green chemistry, emphasizing increased awareness of both human and environmental impacts. Nevertheless, the global emphasis on sustainable development has posed a challenge for green chemistry educators to instruct students in assessing the intricate factors of green chemistry, including societal sustainability considerations. This paper reviews courses and programs that aim to fulfill these objectives, along with assessment methods used to evaluate student outcomes in green chemistry courses. The global food supply has significantly expanded due to the discovery of hybrid varieties, improved cultivation methods, better seeds, and the use of pesticides, herbicides, and fertilizers.

Keywords: Arsenic contamination, Green chemistry (GC), Environmental disturbances, Sustainable development.

1. Introduction

A) Green chemistry: Earth's care

The Green Chemistry revolution presents a multitude of opportunities to explore and implement novel synthetic approaches using alternative raw materials [1-4]. It emphasizes environmentally friendly reaction conditions, energy minimization, and the design of less toxic and environmentally safer chemicals [5-6]. The foundation of Green Chemistry, aiming for both environmental and economic success, is intrinsic in a sustainable world [7,8]. An integral aspect of sustainable chemistry is commonly defined as chemical research focusing on the improvement of processes and products with regards to energy and material usage, inherent safety, toxicity, and environmental degradability [9-12].

While progress has been made in the field of environmental science, Green Chemistry, and the environmental assessment of chemical products, the societal dimension of sustainable chemistry is not fully recognized in all aspects of chemical research. One crucial factor contributing to this is the integration of sustainable chemistry into chemical education from the very beginning [13,1].

Green Chemistry involves the application of principles that reduce or eliminate the use or generation of hazardous substances in the design, manufacturing, and use of chemical products [14-17]. In practice, Green Chemistry encompasses a much broader range of issues than the definition suggests. Apart from developing better chemicals with less waste, it also includes reducing other associated environmental impacts, such as decreasing the amount of energy used in chemical

processes [18,19]. Consequently, efforts have been made to achieve environmentally friendly synthesis, and various regulations have been enacted to control and address pollution, encouraging industries and academics to devise innovative technologies, processes, and educational materials discouraging the formation or use of hazardous substances.

Green Chemistry differs from traditional chemistry in that it embraces the same creativity and innovation that has always been essential to classical chemistry [20-23]. However, a notable difference lies in the fact that historically, synthetic scientists have not prioritized environmental concerns highly. Yet, with the increase in global environmental awareness, there is a challenge for chemists to develop new products, processes, and services that meet fundamental social, economic, and environmental objectives [24,2].

Due to the diverse nature of chemicals and transformations, various Green Chemistry solutions have been proposed. The establishment of 'The Twelve Principles of Green Chemistry' serves as guidelines for practicing scientists in developing and evaluating how environmentally friendly a synthesis, compound, process, or technology is [25].

B) Groundwater under arsenic assault

Arsenic (As) enters the soil and groundwater through the natural weathering of rocks and minerals, a process further facilitated by leaching and runoff. Additionally, human activities contribute to arsenic contamination in soil and groundwater. Various factors influence the concentration and movement of arsenic in groundwater, such as red-ox potential (Eh), adsorption/desorption, precipitation/dissolution, arsenic speciation, pH, presence of competing ions, biological transformation, and more. The specific reactions, arsenic species, Eh, pH, and solid-phase changes can differ between aquifers, depending on geological settings, geochemistry, and environmental conditions.

Comprehensive geochemical investigations are crucial to understanding arsenic geochemistry under diverse hydrogeological and environmental conditions, enabling the development of sustainable solutions. In India, groundwater arsenic contamination emerged in West Bengal in 1983 and has since affected several states, including Jharkhand, Bihar, Uttar Pradesh, Assam, Manipur, and Chhattisgarh. Even in the North-Eastern Hill States, there is suspicion of arsenic in groundwater. Arsenic-affected areas typically align with river plains originating from the Himalayan region, though the connection between source material and outcrops requires further research. Over time, the complexity of groundwater arsenic contamination has increased due to unknown local and regional factors.

The consequences of arsenic groundwater contamination are profound, leading to social disorders, health hazards, socioeconomic challenges, and groundwater exploitation. Arsenic-contaminated water used for growing crops poses risks, as these crops may be distributed to uncontaminated regions, potentially exposing people to arsenic through the food chain. This scenario amplifies the dangers associated with arsenic contamination, emphasizing the need for proactive research and sustainable solutions to mitigate its impact.

2. Complex Intersections of Green Chemistry and Arsenic-Induced Groundwater Pollution

A) Principles of sustainable Chemistry

When embracing the tenets of sustainable chemistry, the following principles must be ensured:

- 1) It is wiser to anticipate and prevent waste than to address or clean up waste after its formation.
- 2) Synthetic methodologies should be designed to maximize the integration of all materials used in the process into the final product.
- 3) Feasible synthetic procedures should prioritize the use and generation of substances with minimal toxicity to human health and the environment.
- 4) Chemical products should be formulated to preserve storage efficiency while minimizing toxicity.
- 5) The use of auxiliary substances (such as solvents or separation agents) should be minimized whenever possible and rendered harmless when employed.
- 6) Energy requirements should be acknowledged for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure.
- 7) Unnecessary derivatization (blocking groups, protection/deprotection, and temporary alteration of physical/chemical processes) should be avoided whenever possible.
- 8) Catalytic reagents (as specific as possible) are preferred over stoichiometric reagents.
- 9) Chemical products should be designed so that, at the end of their useful life, they do not persist in the environment and break down into harmless degradation products.
- 10) Analytical methods should be further developed to enable real-time, in-process monitoring and control before the formation of hazardous substances.
- 11) Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

B) Major Arsenic Occurrences in Groundwater

Groundwater is frequently impacted by the presence of arsenic, which primarily manifests in two oxidation states: arsenate (As_5^+) and arsenite (As_3^+). These states are reversible through oxidation (As_3^+ to As_5^+) and reduction (As_5^+ to As_3^+). Additionally, arsenic exists in an organic form resulting from the biomethylation of arsenic compounds. Various organisms, including plants, aquatic animals like fish and crabs, and the human body, contain these organoarsenic compounds.

Microorganisms such as bacteria and fungi, lacking chlorophyll, engage in the biological conversion of inorganic arsenic to organic arsenic through a process known as biomethylation [2,3]. Arsenic concentrations are notably high in sulphide ores and metal oxides like iron oxide. Previous studies indicated arsenic-contaminated groundwater was primarily limited to the Ganga basin, originating from sulphide-rich mineralized zones in Bihar and the surrounding deposition basin.

Recent findings have expanded this understanding, revealing elevated arsenic concentrations in wells extending from the Indo-Gangetic alluvium to the west and Brahmaputra alluvium. During the deposition of Holocene segment sediments, hydroxides precipitate, and arsenic released during sulphide mineral weathering is adsorbed. Subsequently, through redox processes, iron oxides dissolve, leading to the transport of arsenic into aquifers via biogeochemical mechanisms.

Sediments deposited in rivers during the late Quaternary and Holocene ages carry arsenic in the aqueous phase within the Ganga-Brahmaputra river basin. Presently, the majority of arsenic-contaminated water results from the mobilization of arsenic facilitated by diverse biogeochemical processes [4,5].

C) Advantages of Manageable Science

Reasonable science embraces diverse perspectives that contribute to achieving the 2030 Agenda and co-shaping the Strategic Approach to International Chemicals Management beyond 2020 [9,10]. These encompass various initiatives, such as the advancement and adoption of alternative solutions for hazardous applications, the preservation of natural resources, the expansion of market opportunities, and the implementation of corporate social responsibility. A fundamental tenet of sustainable science is the notion that products should be developed sustainably in terms of both their processes and constituents. They should contribute to sustainability during their use and pose no issues in the post-use phase. If waste is generated, it should be recyclable.

For instance, in the context of hazardous recycling, the harmful substances within waste can pose significant risks to workers' health. In emerging and developing nations, a substantial number of individuals who "reuse" electronic waste from industrialized countries using rudimentary methods inadvertently expose themselves to a wide array of hazardous substances, including heavy metals, PCBs, and fire retardants [11-14]. Sustainable science confronts these challenges and seeks viable solutions. This involves not only substituting hazardous substances with less harmful alternatives but also labeling the products involved and imposing a take-back obligation.

D) Variability in Arsenic Levels throughout Time and Seasons in Groundwater

Significant temporal and seasonal variations in arsenic (As) concentrations have been observed across diverse samples. Notably, a pronounced decrease in arsenic concentration is evident during the post-monsoon season. This observed variability is likely associated with seasonal fluctuations in groundwater recharge and the effects of irrigation drawdown, as highlighted by MacArthur et al. The disparity in arsenic concentration between pre and post-monsoon seasons is directly linked to its concentration levels. A discernible correlation exists between arsenic behavior and rainfall intensity, with an increase in rainfall intensity corresponding to a rise in dilution rates and a subsequent reduction in arsenic concentration in groundwater, as emphasized by Farooq et al. (2010). The monsoon period particularly witnesses a significant decline in arsenic concentration, showcasing a robust correlation between rainfall conditions, dilution effects, and arsenic concentration. In contrast, the winter season and pre-monsoon periods exhibit an increase in arsenic concentration, attributed to a decrease in the dilution effect [9,10,11].

The oxidation of arsenic-rich sulfide minerals is a common phenomenon in geological deposits housing sulfide minerals with high arsenic content, such as arsenopyrite ($FeAsS$), realgar (As_4S_4), and orpiment (As_2S_3). These minerals remain stable at considerable depths beneath the Earth's surface, shielded from oxygen and water. However, exposure to atmospheric conditions through natural weathering or human activities like mining can trigger oxidation [12,13,14]. When arsenopyrite comes into contact with molecular oxygen (O_2) from the atmosphere and water (H_2O), it undergoes oxidative degradation. During this process, arsenic in its sulfide form transforms into highly water-soluble arsenate (AsO_4^{3-}). This transformation is particularly noticeable in bedrock aquifers experiencing a shift to oxidizing conditions during dry seasons, leading to a decrease in groundwater levels. The released Fe^{2+} enters

groundwater, and simultaneously, sulfur oxidation in sulfide minerals produces SO_4^{2-} ions. Both arsenate and sulfate ions, being soluble, have the potential to leach into the surrounding soil, groundwater, and surface water.

3. Conclusion

In conclusion, the exploration of the intricate intersections between green chemistry and arsenic-induced groundwater pollution provides valuable insights into the challenges and opportunities within sustainable development. The realization that conventional industrial practices have contributed significantly to environmental degradation underscores the urgency for adopting eco-friendly alternatives. Green chemistry emerges as a pivotal tool in this pursuit, offering innovative methodologies and sustainable solutions to mitigate arsenic contamination.

The educational insights derived from this exploration emphasize the need for a paradigm shift in how we approach scientific and industrial processes. Educating scientists, engineers, policymakers, and the general public on the principles of green chemistry becomes imperative in fostering a collective responsibility for sustainable development. Integrating green chemistry into educational curricula equips future generations with the knowledge and skills necessary to address environmental issues at their source.

Furthermore, understanding the complexities of arsenic-induced groundwater pollution underscores the interconnectedness of environmental, social, and economic factors. Sustainable development demands a holistic approach that considers the intricate web of relationships between human activities, technological advancements, and ecosystem health. Educational initiatives should encourage interdisciplinary collaboration, fostering a comprehensive understanding of the challenges posed by arsenic contamination and the potential solutions offered by green chemistry.

As we navigate the complexities of the 21st century, the insights gained from this exploration pave the way for informed decision-making and policy formulation. By promoting a symbiotic relationship between green chemistry and sustainable development, we can strive towards a future where human well-being is harmonized with environmental health. In essence, this educational journey serves as a catalyst for transformative action, inspiring a generation that is not only aware of the challenges posed by arsenic-induced groundwater pollution but is also equipped to address them through the lens of green and sustainable chemistry.

4. Future Scope

- 1) The future of "Educational Insights into the Complex Intersections of Green Chemistry and Arsenic-Induced Groundwater Pollution in Sustainable Development" lies in fostering a multidisciplinary approach.
- 2) Collaborative research and educational initiatives will bridge gaps between chemistry, environmental science, and sustainable development. Emerging technologies and innovative pedagogies will enhance understanding, enabling effective mitigation strategies. The scope extends to global partnerships, empowering communities to address arsenic contamination through green chemistry solutions.
- 3) This knowledge nexus will produce environmentally conscious professionals, paving the way for sustainable water management. Ultimately, education will serve as a catalyst for transformative change, shaping a future where green chemistry safeguards water resources in the pursuit of sustainable development.

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