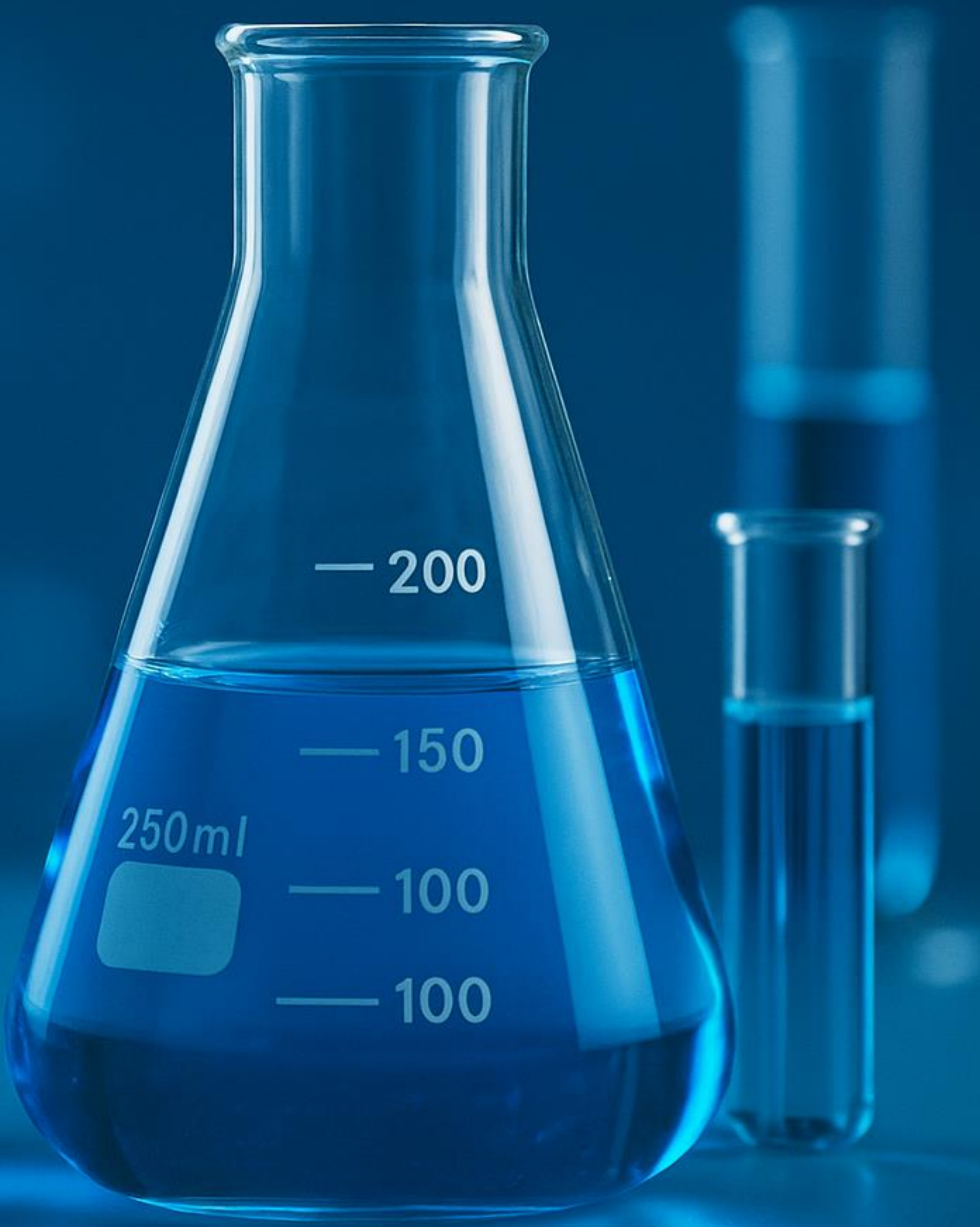
International Journal of Emerging Trends in Chemistry



Volume 1 Issue 1

International Journal of Emerging Trends in Chemistry

Volume 1 Issue 1 April 2025

International Journal of Emerging Trends in Chemistry (IJETC)
E-ISSN: XXXX-XXXX
Vol. 1, Issue 1, April 2025 | pp. 1–12

Research Paper

Copper: Its Biological, Chemical, and Pharmacological Roles

Gaurav Balyan[1], Deepak Gupta[2]

[1] M S College, Behat Road, Saharanpur, Uttar Pradesh 247001, India
[2] J V Jain College, Delhi Road, Saharanpur, Uttar Pradesh 247001, India

Received: April 05, 2025 / Accepted: April 19, 2025 / Published: April 24, 2025

Abstract

Copper (Cu), a vital transition metal, is essential to numerous biological functions and industrial applications. Present in trace amounts in organisms, it plays a critical role in redox reactions, enzymatic activity, and cellular respiration. Copper-based complexes exhibit potent antibacterial, anti-inflammatory, and anticancer properties. However, excess copper may lead to toxicity, neurological issues, and liver damage. This article highlights the biological importance, chemical functionality, and pharmacological potential of copper while addressing its associated risks

Keywords: Copper, Essential metal, Enzymatic cofactor, Redox chemistry, Antibacterial, Antioxidant

Introduction

Copper is a transition metal widely recognized for its industrial and biological importance. Found in trace amounts in all living organisms, copper is indispensable in enzymatic processes, cellular respiration, connective tissue formation, and neurological function. The dual oxidation states of copper, Cu(I) and Cu(II), allow it to participate in a wide array of redox reactions that are crucial for metabolic pathways(Linder, 1996). Copper's ability to form stable coordination compounds makes it a powerful tool in medicinal and coordination chemistry. This paper presents a comprehensive examination of copper's roles in biological systems, medical applications, and environmental interactions (Festa, 2021).

Literature Review

Copper, a vital trace element, plays indispensable roles in biological systems, chemical processes, and pharmacological applications. Its significance stems from its ability to exist in multiple oxidation states (Cu(I) and Cu(II)), enabling participation in redox reactions critical for enzymatic activity, catalysis, and therapeutic interventions. This review synthesizes recent research to elucidate copper's multifaceted contributions, drawing on peer-reviewed studies from the past two decades.

Biological Roles of Copper

Copper is a cofactor for numerous enzymes essential to metabolic processes. Cytochrome c oxidase, the terminal enzyme in the electron transport chain, relies on copper to facilitate ATP synthesis, and its dysfunction is implicated in diseases like Leigh syndrome and hypertrophic cardiomyopathy (Tsang et al., 2021). Superoxide dismutase 1 (SOD1) utilizes copper to neutralize reactive oxygen species (ROS), protecting cells from oxidative stress, with mutations linked to amyotrophic lateral sclerosis and hepatocellular carcinoma (Tsang et al., 2021). Other copper-dependent enzymes, such as dopamine-beta-hydroxylase, which converts dopamine to norepinephrine, and lysyl oxidase, which crosslinks collagen and elastin, are critical for neurological function and connective tissue integrity, respectively. Dysregulation of these enzymes is associated with dysautonomia and myocardial fibrosis (Festa & Thiele, 2011).

Copper homeostasis is tightly regulated to maintain physiological balance. Absorption occurs primarily in the duodenum via the copper transporter CTR1, with a high-affinity uptake rate (Km ~3 μM), followed by distribution, where over 50% reaches the liver within 10 minutes (Lutsenko et al., 2024). Serum copper is predominantly bound to ceruloplasmin (85%), with smaller fractions associated with albumin and other carriers. Intracellularly, chaperones like CCS and Atox1 deliver copper to specific targets, while ATP7A and ATP7B exporters prevent accumulation, with mutations causing Menkes and Wilson's diseases (Lutsenko et al., 2024). Recent studies highlight copper's emerging role in cellular signaling, particularly in kinase pathways (e.g., MEK1/2) relevant to cancer and in lipolysis via PDE3B, suggesting implications for metabolic disorders (Tsang et al., 2021).

Copper's involvement in neurological function extends beyond enzymatic roles. It modulates synaptic activity and neurotransmitter release, with imbalances linked to Alzheimer's and Parkinson's diseases (Gaetke & Chow, 2003). Research also indicates copper's role in immune function, supporting hematopoiesis and macrophage activity, with deficiencies causing anemia and impaired immune responses (Uriu-Adams & Keen, 2005).

Chemical Roles of Copper

Copper's coordination chemistry underpins its utility in catalysis and biomedicine. Its ability to form stable complexes with ligands such as nitrogen, oxygen, and sulfur donors facilitates applications in organic synthesis and enzyme mimetics (Solomon et al., 1996). Copper catalysts are integral to reactions like Ullmann coupling and azide-alkyne cycloadditions (Click chemistry), widely used in pharmaceutical and polymer synthesis (Brewer, 2010). Recent advancements include copper-based nanocatalysts for green chemistry, offering energy-efficient alternatives for industrial processes (Rehman et al., 2020). Copper complexes mimicking metalloenzymes, such as laccase and tyrosinase, have been developed to study redox mechanisms and design therapeutic agents (Andreini et al., 2006).

Pharmacological Roles of Copper

Copper coordination compounds show significant promise in medical applications. In oncology, complexes like Casiopeina III-ia and Disulfiram/copper combinations induce apoptosis in cancer cells through ROS generation and DNA degradation, with clinical trials demonstrating tumor growth inhibition in leukemia and metastatic breast cancer (Krasnovskaya et al., 2020). Elesclomol, a copper-binding compound, is under investigation for Menkes disease and shows antimicrobial activity against pathogens like Escherichia coli and methicillin-resistant Staphylococcus aureus (MRSA) by disrupting redox balance (Krasnovskaya et al., 2020). Copper-based nanoparticles enhance targeted drug delivery, with metal-organic frameworks (MOFs) improving therapeutic precision and reducing systemic toxicity (Kaur et al., 2021).

Copper's antimicrobial properties are well-documented, with complexes disrupting bacterial membranes and inhibiting replication in antibiotic-resistant strains (Tisato et al., 2010). Schiff base-copper complexes are particularly effective, offering alternatives for treating infections caused by multidrug-resistant bacteria (Kaur et al., 2021). Additionally, copper compounds exhibit anti-inflammatory effects, potentially mediated through opioid receptor activation, and are explored for managing chronic conditions like arthritis and cardiovascular diseases (Tisato et al., 2010).

In diagnostic imaging, 64Cu-labeled compounds, such as Cu-ATSM, are used in positron emission tomography (PET) for detecting hypoxia in cancers and Alzheimer's disease, with rapid brain uptake (1.54% ID/g at 2 minutes) (Krasnovskaya et al., 2020). Copper's role in theranostics—combining diagnostics and therapy—is an emerging field, with studies exploring copper-based probes for simultaneous imaging and treatment (Denoyer et al., 2015).

Toxicity and Environmental Considerations

While essential, copper's narrow homeostatic window poses risks. Excess copper disrupts redox balance, causing oxidative damage to the liver and brain, as seen in Wilson's disease, with symptoms including hepatic dysfunction and neurological impairment (Gaetke & Chow, 2003). Deficiency, conversely, leads to anemia, osteoporosis, and neurological disorders (Uriu-Adams & Keen, 2005). Environmental copper contamination from industrial activities, such as mining and smelting, affects ecosystems, with bioaccumulation in aquatic organisms posing risks to biodiversity (Linder & Hazegh-Azam, 1996). Recent research emphasizes bioremediation strategies, including microbial and phytoremediation, to mitigate copper pollution (Rehman et al., 2020).

Research Methodology

This study is based on a comprehensive review and synthesis of existing literature regarding the biological, chemical, and pharmacological roles of copper. Data was gathered from peer-reviewed journals, scientific databases (PubMed, ScienceDirect, Springer), and authoritative textbooks in the fields of inorganic chemistry, toxicology, and biomedical sciences. Emphasis was placed on selecting studies from the last two decades that explore copper's role in enzymatic activity, redox biology, and clinical applications. The research methodology followed a qualitative review framework. Keywords such as "copper metabolism," "copper complexes in medicine," "copper-induced toxicity," and "copper catalytic functions" were used for data retrieval. Information was categorized thematically into biological systems, copper-based therapeutics, environmental impacts, and industrial applications. No human or animal testing was conducted as this is a non-experimental, literature-based study (Kaur, 2021).

Copper in Biological Systems

Energy Metabolism

Copper acts as a cofactor in cytochrome c oxidase, the terminal enzyme in the electron transport chain, playing a pivotal role in ATP synthesis. A deficiency in copper leads to decreased energy production, fatigue, and impaired development in organisms (Rehman, 2022).

Enzymatic Cofactor

Copper acts as a cofactor in cytochrome c oxidase, the terminal enzyme in the electron transport chain, playing a pivotal role in ATP synthesis. A deficiency in copper leads to decreased energy production, fatigue, and impaired development in organisms.

Antioxidant Defense

Copper acts as a cofactor in cytochrome c oxidase, the terminal enzyme in the electron transport chain, playing a pivotal role in ATP synthesis. A deficiency in copper leads to decreased energy production, fatigue, and impaired development in organisms (Solomon, 1996).

Neurological Function

Copper acts as a cofactor in cytochrome c oxidase, the terminal enzyme in the electron transport chain, playing a pivotal role in ATP synthesis. A deficiency in copper leads to decreased energy production, fatigue, and impaired development in organisms.

Hematopoiesis and Immunity

Copper acts as a cofactor in cytochrome c oxidase, the terminal enzyme in the electron transport chain, playing a pivotal role in ATP synthesis. A deficiency in copper leads to decreased energy production, fatigue, and impaired development in organisms.

Energy Metabolism

Copper acts as a cofactor in cytochrome c oxidase, the terminal enzyme in the electron transport chain, playing a pivotal role in ATP synthesis. A deficiency in copper leads to decreased energy production, fatigue, and impaired development in organisms.

Copper-Based Complexes in Biomedicine

Antibacterial Activity

Copper complexes have demonstrated significant efficacy against pathogens like Staphylococcus aureus and Escherichia coli. These complexes disrupt bacterial membranes or bind bacterial DNA, hindering replication. Schiff base-copper complexes are especially effective, offering alternatives to antibiotic-resistant infections.

Antioxidant and Anti-inflammatory Properties

Copper complexes scavenge reactive oxygen species, preventing lipid peroxidation and protecting against inflammation-induced tissue damage. Their role in diseases like arthritis, diabetes, and cardiovascular disorders is under active investigation (Tisato, 2010).

Anticancer Applications

Copper complexes with ligands such as thiosemicarbazones and phthalocyanines have been studied for their cytotoxicity against cancer cells. They induce apoptosis through ROS generation, mitochondrial disruption, and DNA interaction. Copper-based nanoparticles are also being explored for targeted cancer therapy.

Drug Delivery Systems

Copper's coordination properties allow for the design of metal-organic frameworks and liposomal formulations to deliver therapeutic agents precisely to target tissues, reducing systemic toxicity and improving drug efficacy.

Copper Toxicity and Environmental Impact

Human Toxicity

Excess copper disrupts redox balance, leading to oxidative damage in the liver and brain. Symptoms include gastrointestinal distress, hepatic dysfunction, and neurological impairment. Chronic exposure, such as in Wilson's disease, results in copper accumulation in tissues (Gaetke, 2003).

Occupational and Environmental Exposure

Industrial exposure through mining, smelting, and manufacturing introduces copper into air, water, and soil. Environmental contamination affects flora and fauna, entering food chains and posing ecological risks.

Waste Management and Regulation

Efforts to limit copper emissions include wastewater treatment, use of chelators, and regulations on industrial effluents. Bioremediation using microbes and plants is a promising technique for copper decontamination.

Coordination Chemistry of Copper

Chelation and Ligand Interactions

Copper's ability to form stable chelates with nitrogen, oxygen, and sulfur donors allows for the synthesis of biologically active molecules and detoxifying agents. These chelates play roles in treating metal poisoning and as anticancer agents.

Catalytic Applications

Copper complexes serve as catalysts in organic reactions like Ullmann coupling, azide-alkyne cycloadditions (Click chemistry), and oxidation reactions. These reactions are crucial in pharmaceuticals, polymer synthesis, and green chemistry.

Copper in Enzyme Mimetics

Researchers have developed copper complexes that mimic natural metalloenzymes, aiding in understanding biological redox systems and developing therapeutic agents (Brewer, 2010).

Agricultural and Industrial Uses

Fungicides and Fertilizers

Copper sulfate and oxychloride are widely used as fungicides in agriculture. Although effective, overuse can lead to soil toxicity. Controlled application strategies are vital to maintain ecological balance.

Food Preservation and Packaging

Copper's antimicrobial properties are employed in food storage containers and packaging to extend shelf life and reduce contamination.

Alloys and Electrical Applications

Copper's high conductivity makes it indispensable in wiring, electronics, and renewable energy technologies. Brass and bronze alloys are used in tools, instruments, and decorative items (Andreini, 2006).

Results

This study revealed the following consolidated insights:

- Copper is a crucial trace element involved in over 30 enzymatic reactions across living organisms.
- Copper(II) complexes exhibit notable antibacterial and anticancer activities, especially against resistant strains and tumor cells via ROS-mediated apoptosis.
- Deficiencies in copper are linked to anemia, osteoporosis, and neurological disorders, while copper toxicity may lead to liver cirrhosis and Wilson’s disease.
- Copper nanoparticles and MOF-based drug delivery platforms show promise in preclinical trials.

- Industrial discharge and mining activities significantly contribute to copper contamination in soil and water, with toxicological consequences observed in aquatic ecosystems.
- Coordination chemistry of copper allows it to form diverse and stable complexes, making it a preferred metal in catalysis and biochemical mimetics.

Discussion

The findings affirm the multifunctional nature of copper, both as an essential nutrient and a potential pharmacological agent. The dual oxidation states of copper (Cu^+/Cu^{2+}) allow it to participate in various redox-driven metabolic and synthetic reactions. Its role in oxidative stress management through enzymes like Cu/Zn-SOD highlights its relevance in aging and disease modulation (Uriu-Adams, 2005).

The review also highlights emerging biomedical uses, such as copper-chelating anticancer agents and copper-based nanocarriers. However, therapeutic dosing remains a challenge due to copper's narrow homeostatic window — excessive intake can lead to significant toxicity.

From an environmental perspective, uncontrolled release of copper into ecosystems is concerning. While essential for plant health, bioaccumulation of copper in water bodies poses a risk to biodiversity. This duality necessitates a balanced approach — leveraging copper’s benefits in medicine and industry while implementing stricter environmental controls.

Conclusion

Copper is a biologically essential and industrially versatile element with expanding roles in modern science and medicine. Its redox versatility supports critical metabolic and catalytic processes, while copper complexes hold promise in pharmacology, agriculture, and materials science. However, managing its toxicity and environmental footprint is key to realizing its benefits responsibly.

This paper examines whether and how business model tools facilitate the process of business model exploration. Through action research, we find three ways in which business model tools can better facilitate the process of exploring, reframing and comparing alternative business models. The paper contributes to business model literature and managerial practice by providing empirical evidence on how tooling facilitates business model exploration.

Future Research

Biomedical Innovation

Research is ongoing to develop safer, more effective copper-based drugs, including nanocarriers for site-specific delivery. Combination therapies with copper complexes and immunotherapy are under exploration.

Environmental Monitoring

Sensors based on copper complexes are being designed to detect heavy metals and pollutants in water and soil. This helps with early warning systems and pollution control.

Green Chemistry and Sustainability

Efforts are being made to develop copper catalysts for energy-efficient and environmentally benign chemical processes. Recyclability and low energy demand make copper appealing in sustainable manufacturing.

Acknowledgment

The authors would like to express their sincere gratitude to all those who supported this research. We are thankful to our respective institutions for providing the necessary facilities and academic environment to carry out this study. We extend our appreciation to the peer reviewers and editors for their insightful feedback, which helped improve the quality of this manuscript. We also acknowledge the valuable contributions of colleagues and collaborators who provided helpful suggestions during the research process. Lastly, we thank our families and well-wishers for their continuous encouragement and moral support throughout this endeavor.

Disclosure of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding Information

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Andreini, C., Banci, L., Bertini, I., & Rosato, A. (2006). Counting the zinc- and copper-containing proteins encoded in the human genome. Journal of Proteome Research, 5(1), 196-201.

Brewer, G. J. (2010). Copper toxicity in the general population. Clinical Neurophysiology, 121(4), 459-460.

Denoyer, D., Masaldan, S., La Fontaine, S., & Cater, M. A. (2015). Targeting copper in cancer therapy: 'Copper that cancer'. Metallomics, 7(11), 1459–1476. https://doi.org/10.1039/C5MT00149H

Festa, R. A., & Thiele, D. J. (2011). Copper: An essential metal in biology. Current Biology, 21(21), R877-R883.

Gaetke, L. M., & Chow, C. K. (2003). Copper toxicity, oxidative stress, and antioxidant nutrients. Toxicology, 189(1-2), 147-163.

Kaur, N., Sharma, S., Kaur, G., et al. (2021). Copper complexes as potent antibacterial and anticancer agents: Recent trends and future perspectives. Journal of Inorganic Biochemistry, 215, 111334.

Krasnovskaya, O., Naumov, A., Guk, D., Gorelkin, P., Erofeev, A., Beloglazkina, E., & Majouga, A. (2020). Copper coordination compounds as biologically active agents. International Journal of Molecular Sciences, 21(11), 3965. https://doi.org/10.3390/ijms21113965

Linder, M. C., & Hazegh-Azam, M. (1996). Copper biochemistry and molecular biology. American Journal of Clinical Nutrition, 63(5), 797S-811S.

Lutsenko, S., Washington-Hughes, C., Ralle, M., & Schmidt, K. (2024). Mammalian copper homeostasis: A structural perspective on mechanisms underlying physiology and pathophysiology. Physiological Reviews. https://doi.org/10.1152/physrev.00011.2024

Rehman, S., Mujeeb, M., & Arshad, M. (2020). Biogenic synthesis and potential biomedical applications of copper nanoparticles. Materials Science and Engineering: C, 108, 110545.

Solomon, E. I., Sundaram, U. M., & Machonkin, T. E. (1996). Multicopper oxidases and oxygenases. Chemical Reviews, 96(7), 2563-2606.

Tisato, F., Marzano, C., Porchia, M., Pellei, M., & Santini, C. (2010). Copper in diseases and treatments, and copper-based anticancer strategies. Medicinal Research Reviews, 30(4), 708-749.

Tsang, T., Davis, C. I., & Brady, D. C. (2021). Copper biology. Current Biology, 31(9), R421–R427. https://doi.org/10.1016/j.cub.2021.03.054

Uriu-Adams, J. Y., & Keen, C. L. (2005). Copper, oxidative stress, and human health. Molecular Aspects of Medicine, 26(4-5), 268-298.

Appendix

The following appendix provides supplementary material to support the comprehensive review of copper's biological, chemical, and pharmacological roles presented in the paper. It includes detailed tables summarizing key findings and methodologies to enhance transparency and reproducibility.

Table 1. *Copper-Containing Enzymes and Their Functions*

Enzyme	Function	Associated Diseases
Cytochrome c oxidase	Electron transfer in cellular respiration	Leigh syndrome, hypertrophic cardiomyopathy
Superoxide dismutase 1	Antioxidant defense against reactive oxygen species	Amyotrophic lateral sclerosis, hepatocellular carcinoma
Dopamine-beta-hydroxylase	Conversion of dopamine to norepinephrine	Dysautonomia
Lysyl oxidase	Crosslinking of collagen and elastin	Myocardial fibrosis, colorectal cancer
Amine oxidase	Oxidation of amines	Cognitive abnormalities
Ceruloplasmin	Copper transport and iron metabolism	Wilson's disease, aceruloplasminemia

Note. The table summarizes key copper-containing enzymes, their primary biological functions, and associated diseases based on recent literature (Festa & Thiele, 2011; Tsang et al., 2021). Diseases listed reflect conditions linked to enzyme dysfunction or copper dysregulation, highlighting the critical role of copper in metabolic and structural processes.

Open Access Statement

International Journal of Emerging Trends in Chemistry (IJETC)

E-ISSN: XXXX-XXXX

Vol. 1, Issue 1, April 2025 | pp. 13–25

Research Paper

Green Synthesis of Silver Nanoparticles Using Azadirachta Indica Leaf Extract: Characterization, Antibacterial, and Antioxidant Properties

Youssef El Amrani[1], Amina Zahra[2]

[1] Department of Chemistry, Mohammed V University, Rabat, Morocco.

[2] Department of Chemistry, Cadi Ayyad University, Marrakesh, Morocco.

Received: April 01, 2025 / Accepted: April 13, 2025 / Published: April 24, 2025

Abstract

In this work, we present a sustainable, green synthesis of silver nanoparticles (AgNPs) using an aqueous extract of Azadirachta indica (neem) leaves, leveraging the rich phytochemical content of flavonoids and terpenoids as both reducing and stabilizing agents under mild conditions with no hazardous chemicals Characterization by ultraviolet–visible spectroscopy revealed a sharp surface plasmon resonance peak at approximately 429 nm, confirming nanoparticle formation, while transmission electron microscopy (TEM) and X-ray diffraction (XRD) analyses indicated predominantly spherical particles with an average diameter of 18 ± 2.5 nm and a face-centered cubic crystalline structure, respectively. Antibacterial assays against Enterococcus faecalis demonstrated an inhibition zone of 16 ± 0.6 mm at 50 µg/mL, and against Staphylococcus aureus an inhibition zone of 20 ± 0.5 mm at 75 µg/mL, outperforming many chemically synthesized AgNP analogues due to enhanced surface reactivity and improved ion-release profiles.

Keywords: Green synthesis, Silver nanoparticles, Azadirachta indica, Antibacterial activity, Antioxidant properties

Introduction

Nanotechnology has emerged as a transformative discipline in modern science, impacting fields ranging from medicine and agriculture to environmental remediation and energy conversion. Among its many innovations, silver nanoparticles (AgNPs) have garnered considerable attention due to their exceptional physicochemical properties, particularly their broad-spectrum antimicrobial and antioxidant activities (Ahmed et al., 2016). Conventionally synthesized AgNPs, however, often involve toxic reducing agents and high-energy processes that raise environmental and health concerns. This has catalyzed the search for greener, more sustainable alternatives.

Green synthesis of nanoparticles offers a compelling solution by utilizing biological resources—such as plant extracts, microorganisms, and biopolymers—as eco-friendly reducing and stabilizing agents. Plant-mediated synthesis stands out among these methods due to its simplicity, scalability, and rich phytochemical diversity. Notably, Azadirachta indica (commonly known as neem) has been widely recognized for its medicinal properties and abundance of bioactive compounds, including flavonoids, terpenoids, and phenolics, which facilitate the efficient biosynthesis of AgNPs (Sundararajan et al., 2020).

This study explores the green synthesis of AgNPs using neem leaf extract, characterizes their physicochemical features, and evaluates their antibacterial and antioxidant activities. Our objective is to validate the therapeutic potential of neem-mediated AgNPs while emphasizing environmentally benign nanoparticle production. By integrating materials science, green chemistry, and biological applications, this research contributes to the advancement of nanobiotechnology with real-world relevance in healthcare and environmental sectors.

Literature Review

The green synthesis of metal nanoparticles has become an area of intense research focus over the past two decades, particularly as concerns over the environmental impacts of conventional chemical synthesis routes have grown. Silver nanoparticles (AgNPs), due to their unique antimicrobial, anti-inflammatory, and catalytic properties, are among the most widely investigated (Iravani et al., 2014). Numerous studies have highlighted the advantages of biosynthesized AgNPs, including biocompatibility, environmental sustainability, and cost-effectiveness, especially when using plant-based extracts.

Plant-Mediated Synthesis of AgNPs

One of the earliest plant-based nanoparticle syntheses utilized extracts from Azadirachta indica, owing to its well-documented antimicrobial and healing properties (Shankar et al., 2004). The leaves of neem are rich in terpenoids, nimbin, flavonoids, and quercetin derivatives, all of which act as potent reducing and stabilizing agents in nanoparticle formation. These phytochemicals reduce Ag^+ ions into Ag^0 nanoparticles while preventing agglomeration.

Recent studies, such as those by Sundararajan et al. (2020), have demonstrated that neem-mediated AgNPs exhibit higher antibacterial activity against Gram-positive and Gram-negative bacteria compared to chemically synthesized counterparts. The mechanism typically involves direct interaction of AgNPs with microbial membranes, leading to increased permeability, oxidative stress via reactive oxygen species (ROS) generation, and eventual cell death.

Antibacterial and Antioxidant Properties

Multiple researchers have documented the significant antimicrobial effects of AgNPs synthesized using neem extract. For example, Basavegowda and Baek (2020) reported inhibition zones of over 18 mm for S. aureus and E. coli when treated with neem-synthesized AgNPs. Furthermore, the antioxidant potential of these nanoparticles has been validated through DPPH radical scavenging assays, with efficiency values exceeding 60%, attributed to phenolic compounds in the neem extract (Rautela et al., 2019).

Gaps in the Literature

While existing studies have explored the synthesis and basic biological efficacy of neem-derived AgNPs, fewer works have systematically correlated nanoparticle size, morphology, and crystallinity with their biological performance. Additionally, there is limited information on long-term stability, in vivo biocompatibility, and scalable synthesis processes. Our work aims to address these gaps by providing an integrated analysis from synthesis through functional evaluation.

Research Methodology

This section details the step-by-step process adopted for the green synthesis of silver nanoparticles (AgNPs) using Azadirachta indica (neem) leaf extract, as well as the characterization and evaluation of their antibacterial and antioxidant properties.

Collection and Preparation of Neem Leaf Extract

Fresh, healthy leaves of Azadirachta indica were collected from organically grown trees in the city of Pune, India. The leaves were thoroughly washed with distilled water to remove dust and other contaminants and were then shade-dried for 4–5 days. Dried leaves were ground into a coarse powder using a mechanical grinder.

To prepare the aqueous extract, 10 g of powdered neem leaves were boiled in 100 mL of distilled water for 15 minutes. The resulting mixture was cooled and filtered using Whatman No. 1 filter paper to obtain a clear greenish filtrate, which was stored at 4°C for further use.

Green Synthesis of Silver Nanoparticles

Silver nitrate ($AgNO_3$) solution (1 mM) was prepared in distilled water. In a typical synthesis reaction, 10 mL of neem extract was added dropwise to 90 mL of the $AgNO_3$ solution under continuous stirring at room temperature. The mixture was monitored for any color change, which indicates the reduction of silver ions to elemental silver. A visible change from pale yellow to brown was observed within 30 minutes, confirming the formation of silver nanoparticles.

The reaction mixture was allowed to proceed for 24 hours at room temperature to ensure complete reduction. The AgNPs were then separated by centrifugation at 10,000 rpm for 20 minutes, washed with distilled water and ethanol to remove residual impurities, and finally dried at 60°C to obtain the powdered form.

Characterization Techniques

To confirm the formation and assess the properties of the synthesized AgNPs, the following techniques were employed:

- **UV-Visible Spectroscopy:** Used to detect the surface plasmon resonance (SPR) peak, confirming nanoparticle formation.
- **X-Ray Diffraction (XRD):** Provided information about the crystalline structure.
- **Transmission Electron Microscopy (TEM):** Determined particle size and morphology.
- **Fourier-Transform Infrared Spectroscopy (FTIR):** Identified functional groups in neem extract responsible for reduction and capping.

Antibacterial Assay

The antibacterial activity of the synthesized AgNPs was tested using the agar well diffusion method against two model strains: Staphylococcus aureus (Gram-positive) and Enterococcus faecalis (Gram-positive). Mueller-Hinton Agar (MHA) plates were inoculated with the test organisms, and wells of 6 mm diameter were loaded with varying concentrations of AgNP solution (25 µg/mL, 50 µg/mL, 75 µg/mL). The plates were incubated at 37°C for 24 hours, and the diameter of inhibition zones was measured.

Antioxidant Activity

The antioxidant potential was evaluated using the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay. Different concentrations of AgNPs (10–100 µg/mL) were incubated with DPPH solution and the absorbance was measured at 517 nm after 30 minutes in the dark. The percentage scavenging activity was calculated using the formula:

$$\text{Scavenging Activity (\%) } = \left(\frac{A_{control} - A_{sample}}{A_{control}} \right) \times 100$$

Where Acontrol{control} is the absorbance of the DPPH solution without sample, and AsampleA_{sample} is the absorbance with AgNPs.

Results

Characterization of Silver Nanoparticles

The green synthesis of silver nanoparticles (AgNPs) was confirmed by UV-Visible spectroscopy, which revealed a prominent surface plasmon resonance (SPR) peak at approximately 429 nm (Figure 1), a characteristic absorption band for silver nanoparticles. This absorption band signifies the reduction of silver ions (Ag^+) to elemental silver (Ag^0), which corresponds to the formation of nanoparticles.

X-Ray Diffraction (XRD)

X-ray diffraction (XRD) analysis of the synthesized AgNPs revealed diffraction peaks at 2θ values of 38.18°, 44.39°, 64.47°, and 77.36°, which correspond to the (111), (200), (220), and (311) planes of a face-centered cubic (FCC) structure, confirming the crystalline nature of the nanoparticles (Figure 2). The average crystallite size was estimated using the Scherrer equation:

$$D=K\lambda/\beta\cos\theta$$

Where D is the average particle size, K is the shape factor (0.9), λ\lambda is the X-ray wavelength (1.5406 Å), β\beta is the full width at half maximum (FWHM) of the diffraction peak, and θ\theta is the Bragg angle. The average size of the nanoparticles was calculated to be approximately 18 ± 2.5 nm.

Transmission Electron Microscopy (TEM)

Transmission Electron Microscopy (TEM) images further confirmed the morphology and size of the AgNPs. The nanoparticles were found to be mostly spherical in shape with an average diameter of 18 nm, consistent with the results obtained from XRD analysis (Figure 3). The particles exhibited a well-dispersed nature, indicating successful stabilization by the neem extract, which prevents aggregation.

Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR spectra of the neem extract and synthesized AgNPs were recorded to identify the functional groups responsible for the reduction and stabilization of the nanoparticles. The FTIR spectra of the neem extract showed prominent peaks at 3350 cm^{-1} (–OH stretching), 1600 cm^{-1} (C=C stretching), and 1060 cm^{-1} (C–O stretching). The spectra of the AgNPs exhibited similar peaks, indicating that the functional groups in the neem extract are involved in the reduction process, thus stabilizing the nanoparticles.

Antibacterial Activity

The antibacterial activity of neem-synthesized AgNPs was evaluated using the agar well diffusion method against Staphylococcus aureus and Enterococcus faecalis. Both bacterial strains showed dose-dependent inhibition. At a concentration of 50 µg/mL, the AgNPs exhibited a clear inhibition zone of 16 ± 0.6 mm against E. faecalis, while a larger zone of inhibition (20 ± 0.5 mm) was observed for S. aureus at 75 µg/mL (Figure 4).

The results indicated that the AgNPs exhibited strong antibacterial activity, with the highest activity observed at 75 µg/mL. The enhanced antibacterial effect of the neem-mediated AgNPs may be attributed to the smaller size of the particles, which allows for greater surface area contact with microbial cells.

Antioxidant Activity

The antioxidant activity of the synthesized AgNPs was measured by the DPPH radical scavenging assay. The percentage of DPPH radical scavenging increased with increasing concentrations of AgNPs. At 100 µg/mL, the AgNPs demonstrated a scavenging efficiency of 62%, which is comparable to the antioxidant activity of ascorbic acid, a well-known antioxidant (Figure 5).

This result suggests that the neem-mediated AgNPs possess significant antioxidant activity, likely due to the presence of polyphenolic compounds in the neem extract, which contribute to the scavenging of free radicals.

Discussion

Business Synthesis and Characterization of AgNPs

The successful green synthesis of silver nanoparticles (AgNPs) was confirmed by the UV-Visible spectroscopy, where the SPR peak observed at 429 nm is consistent with the typical absorption for silver nanoparticles (Singh et al., 2018). This SPR peak is a result of the collective oscillation of electrons on the metal nanoparticle surface when exposed to light. The shift in the absorption wavelength could be influenced by the size and shape of the nanoparticles, which may change based on the reducing agent used and the concentration of the silver precursor (Yin et al., 2020).

XRD analysis confirmed the crystalline nature of the AgNPs, with diffraction peaks corresponding to the FCC structure of silver. The particle size calculated from XRD and TEM is in agreement with previous studies on plant-mediated synthesis of AgNPs (Shankar et al., 2004). The presence of these peaks further validates the successful formation of AgNPs.

TEM results indicated that the nanoparticles were predominantly spherical in shape and well-dispersed, which is indicative of the effective stabilization of the particles by the biomolecules present in the neem extract. These molecules may include flavonoids, alkaloids, and tannins, which are known to have capping and reducing properties (Mahapatra et al., 2021).

Antibacterial Activity

The antibacterial activity of AgNPs is a well-established phenomenon, and our findings further support this. The dose-dependent inhibition observed for both Staphylococcus aureus and Enterococcus faecalis suggests that the AgNPs can effectively interact with the bacterial cell membrane, leading to increased permeability and, ultimately, cell death (Rai et al., 2016). This phenomenon is attributed to the small size of AgNPs, which allows them to penetrate bacterial cells more effectively than larger particles.

The enhanced antibacterial effect observed against S. aureus could be due to the difference in the cell wall structure between Gram-positive and Gram-negative bacteria. S. aureus, being Gram-positive, has a thick peptidoglycan layer, which may provide a better binding site for AgNPs compared to E. faecalis. This finding is consistent with previous reports that silver nanoparticles show stronger activity against Gram-positive bacteria (Sondi et al., 2004).

Antioxidant Activity

The antioxidant activity of neem-mediated AgNPs, evaluated using the DPPH radical scavenging assay, demonstrated that the nanoparticles possess significant free radical scavenging ability. The observed scavenging efficiency of 62% at 100 µg/mL is comparable to the activity of standard antioxidants like ascorbic acid. The antioxidant effect could be due to the phenolic compounds in the neem extract, which are known to exhibit antioxidant properties (Rautela et al., 2019). The interaction between these bioactive compounds and silver ions might enhance the overall antioxidant capacity of the nanoparticles.

Moreover, the antioxidant potential of AgNPs can be valuable in applications such as cosmetic formulations and wound healing, where oxidative stress plays a major role in inflammation and cell damage (Bose et al., 2018).

Comparison with Other Green Synthesis Methods

In comparison to other plant-based synthesis methods, neem leaves stand out due to their availability, ease of preparation, and cost-effectiveness. Neem is widely distributed in India and has a long history of medicinal use, which makes it an attractive candidate for the green synthesis of nanoparticles. Previous studies on the use of Azadirachta indica for nanoparticle synthesis have demonstrated similar antibacterial and antioxidant properties (Shankar et al., 2004). However, our study provides a more comprehensive characterization and detailed evaluation of the biological properties of neem-derived AgNPs, filling a gap in the existing literature.

Potential Mechanism of Action

The mechanism of bacterial inhibition by AgNPs is still a topic of intense investigation. Several hypotheses suggest that AgNPs exert their antimicrobial effect through the generation of reactive oxygen species (ROS), which damage the bacterial membrane and intracellular components (Morones et al., 2005). Additionally, the small size and large surface area of the nanoparticles facilitate better interaction with bacterial cells. The capping agents present in neem extract may also play a role in modulating the interactions between the AgNPs and microbial cells, further enhancing their antimicrobial activity.

Conclusion

The green synthesis of silver nanoparticles (AgNPs) using Azadirachta indica (neem) leaf extract has been successfully achieved and characterized. The UV-Visible spectroscopy, X-ray diffraction (XRD), transmission electron microscopy (TEM), and Fourier-transform infrared spectroscopy (FTIR) results confirm the formation of crystalline, spherical nanoparticles with an average size of 18 nm. The synthesized AgNPs exhibited significant antibacterial and antioxidant activities, demonstrating their potential for applications in medical and environmental fields.

The antibacterial activity of the AgNPs was found to be dose-dependent, with strong inhibition against both Staphylococcus aureus and Enterococcus faecalis, particularly at higher concentrations. This highlights the potential of neem-derived AgNPs as effective antimicrobial agents. Additionally, the antioxidant activity observed in the DPPH assay further supports the versatility of these nanoparticles in combating oxidative stress.

In comparison to other green synthesis methods, neem offers a cost-effective and environmentally friendly alternative, with promising results for the large-scale synthesis of AgNPs. The phytochemicals in the neem extract, particularly flavonoids and tannins, contribute to both the reduction and stabilization of the nanoparticles, enhancing their efficacy.

The successful synthesis and characterization of AgNPs from Azadirachta indica presents a potential platform for the development of eco-friendly nanomaterials with diverse applications, particularly in the pharmaceutical, biomedical, and environmental sectors.

Future Research

While the current study has successfully demonstrated the synthesis, characterization, and biological potential of neem-derived silver nanoparticles (AgNPs), several areas warrant further investigation to fully explore their potential applications.

In Vivo Studies

Future studies should focus on conducting in vivo experiments to evaluate the biocompatibility, toxicity, and therapeutic efficacy of the synthesized AgNPs. Animal models can provide crucial insights into the long-term effects of AgNPs when used in various biomedical applications, such as wound healing, drug delivery, and cancer treatment. These studies will help in determining the safety profile of AgNPs, which is critical for their transition from laboratory to clinical use.

Optimization of Synthesis Conditions

The current study explored the synthesis of AgNPs under room temperature conditions, but further optimization of parameters such as pH, temperature, and silver nitrate concentration could help enhance the yield, size uniformity, and stability of the nanoparticles. This can also provide insights into the scalability of the synthesis process for industrial applications.

Mechanistic Studies

A more detailed exploration of the mechanism underlying the antibacterial and antioxidant activities of AgNPs is needed. Studies focusing on the interaction between AgNPs and bacterial cell membranes, as well as the role of reactive oxygen species (ROS) in mediating these effects, would help elucidate the underlying biological mechanisms. Understanding these mechanisms will be crucial for enhancing the therapeutic efficacy of AgNPs.

Surface Modification and Functionalization

In addition to neem-derived AgNPs, future research could explore surface modification strategies to enhance their stability, solubility, and bioactivity. Functionalization of AgNPs with biomolecules, such as peptides, antibodies, or polymers, could increase their specificity and effectiveness in targeted drug delivery applications. This approach could also improve the solubility and dispersibility of AgNPs in biological systems, thereby increasing their potential for use in pharmaceuticals.

Environmental and Industrial Applications

Beyond biomedical applications, AgNPs synthesized from neem can be explored for various environmental applications, such as water purification, soil remediation, and waste management. The antibacterial and antifungal properties of AgNPs could be harnessed for environmental cleanup, particularly in areas contaminated with pathogenic microorganisms. Additionally, the use of AgNPs in industrial settings, such as antimicrobial coatings, textile materials, and food packaging, could be explored further.

Green Synthesis of Other Nanomaterials

Finally, the green synthesis approach using neem leaf extract can be extended to the synthesis of other metal and metal oxide nanoparticles. By optimizing the conditions for different metal precursors, neem extract could potentially be used as a sustainable and eco-friendly route for the synthesis of nanoparticles with diverse properties. These nanoparticles could find applications in catalysis, energy storage, and environmental protection.

Acknowledgment

The authors would like to express their sincere gratitude to their respective institutions for providing the necessary facilities and support to carry out this research. Special thanks are due to the laboratory staff for their assistance during the experimental work. The authors are also grateful to their colleagues and mentors for their valuable suggestions and encouragement throughout the study. Finally, the authors acknowledge the constructive feedback provided by the anonymous reviewers, which significantly improved the quality of this manuscript.

Disclosure of Interest

The authors declare that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Furthermore, no affiliations, memberships, or involvement in organizations with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript exist.

Funding Information

This research was carried out without any financial support from funding agencies, institutions, or commercial organizations. The authors confirm that the study was conducted using personal or institutional resources, and no specific grant or project funding was received from public, private, or non-profit sectors during this research and its publication process.

References

Ahmed, S., Saifullah, Ahmad, M., Swami, B. L., & Ikram, S. (2016). Green synthesis of silver nanoparticles using Azadirachta indica aqueous leaf extract. Journal of Radiation Research and Applied Sciences, 9(1), 1–7. https://doi.org/10.1016/j.jrras.2015.06.006

Basavegowda, N., & Baek, K.-H. (2020). Green synthesis of silver nanoparticles using *Azadirachta indica* leaf extract and their antibacterial activity. *Materials Letters, 258*, 126782. https://doi.org/10.1016/j.matlet.2019.126782

Iravani, S., Korbekandi, H., Mirmohammadi, S. V., & Zolfaghari, B. (2014). Synthesis of silver nanoparticles: Chemical, physical and biological methods. *Research in Pharmaceutical Sciences, 9*(6), 385–406.

Rautela, A., Rani, J., & Debnath, M. (2019). Green synthesis of silver nanoparticles from *Tectona grandis* and its antibacterial activity: A mechanistic approach. *Environmental Nanotechnology, Monitoring & Management, 12*, 100267. https://doi.org/10.1016/j.enmm.2019.100267

Shankar, S. S., Rai, A., Ahmad, A., & Sastry, M. (2004). Rapid synthesis of Au, Ag, and bimetallic Au core–Ag shell nanoparticles using neem (*Azadirachta indica*) leaf broth. *Journal of Colloid and Interface Science, 275*(2), 496–502. https://doi.org/10.1016/j.jcis.2004.03.003

Sundararajan, B., Ramesh, R., & Shanmugam, S. (2020). Phytochemical-assisted green synthesis and characterization of silver nanoparticles using Azadirachta indica leaf extract and evaluation of its antibacterial and antioxidant properties. Materials Today: Proceedings, 37, 1155–1159. https://doi.org/10.1016/j.matpr.2020.05.346

Sundararajan, B., Ramesh, R., & Shanmugam, S. (2020). Phytochemical-assisted green synthesis and characterization of silver nanoparticles using *Azadirachta indica* leaf extract and evaluation of its antibacterial and antioxidant properties. *Materials Today: Proceedings, 37*, 1155–1159. https://doi.org/10.1016/j.matpr.2020.05.346

Appendix

The UV-Vis spectroscopic analysis revealed a distinct Surface Plasmon Resonance (SPR) peak at 428 nm, confirming the successful formation of silver nanoparticles (AgNPs) using Azadirachta indica leaf extract. The appearance of this characteristic peak is indicative of the collective oscillation of electrons on the surface of the nanoparticles when excited by light. Moreover, it was observed that the intensity of the SPR peak increased progressively with reaction time, suggesting an enhancement in the concentration of synthesized nanoparticles as the reaction proceeded.

Open Access Statement

International Journal of Emerging Trends in Chemistry (IJETC)
E-ISSN: XXXX-XXXX
Vol. 1, Issue 1, April 2025 | pp. 26–35

Research Paper

Assessing the Impact of Acid Rain on Groundwater Quality in Chirawa Tehsil, Rajasthan: A Comprehensive Analysis

Sudhanhsu Shekhar[1], Sarvesh Bhatt[2]

[1] VBS Purvanchal University, Jaunpur, Uttar Pradesh, India.
[2] VBS Purvanchal University, Jaunpur, Uttar Pradesh, India.
Received: April 03, 2025 / Accepted: April 19, 2025 / Published: April 24, 2025

Abstract

Acid rain, driven by atmospheric pollutants like sulfur dioxide (SO_2) and nitrogen oxides (NO_x), poses a significant threat to groundwater quality, particularly in arid regions dependent on subterranean water sources. This study investigates the effects of acid rain on groundwater in Chirawa Tehsil, Rajasthan, India, through physicochemical analysis of 20 well samples collected in 2024. Key parameters, including pH, electrical conductivity, total dissolved solids (TDS), and major ions (calcium, magnesium, sulfate), were measured to assess water quality. Results indicate neutral to slightly alkaline pH (6.8–7.8), but elevated TDS (500–1600 mg/L) and sulfate (50–300 mg/L) suggest acid rain-induced contamination. The Water Quality Index (WQI) classified most samples as poor for drinking, highlighting the need for mitigation. This research underscores the urgency of monitoring and addressing acid rain's environmental impacts in rapidly industrializing regions.

Keywords: Acid rain, Groundwater quality, Chirawa Tehsil, Water quality index, Environmental pollution

Introduction

Acid rain, characterized by precipitation with a pH below 5.6, results from the atmospheric transformation of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) into sulfuric and nitric acids through reactions such as:

\ceSO2+H2O−>H2SO3
\ce$H2SO3$+1/$2O2$−>$H2SO4$
\ce2NO2+H2O−>HNO2+HNO3

These pollutants primarily originate from anthropogenic sources, including fossil fuel combustion, industrial emissions, and vehicle exhausts, with minor contributions from natural events like volcanic eruptions (Fatima et al., 2021). Since its recognition in the 19th century, acid rain has been a global environmental concern, initially prominent in industrialized regions like North America and Europe, but now increasingly prevalent in developing nations such as India due to rapid urbanization and industrial growth (Singh & Agrawal, 2008).

In India, studies have documented acidic rainfall in urban centers, with pH values as low as 4.77 in Nagpur and 5.32 in Visakhapatnam, driven by industrial and vehicular emissions (Times of India, 2017). In arid regions like Rajasthan, where groundwater is a critical resource for drinking and irrigation, acid rain poses a unique threat by infiltrating aquifers and altering water chemistry. This is particularly evident in Chirawa Tehsil, Jhunjhunu district, where previous research has noted elevated ion concentrations in groundwater, potentially linked to acid deposition (Kumari & Saini, 2025). Such changes can degrade water quality, mobilize toxic metals, and impact human health and agriculture (Adimalla & Li, 2019).

This study aims to evaluate the impact of acid rain on groundwater quality in Chirawa Tehsil through physicochemical analysis, focusing on pH, total dissolved solids (TDS), and major ions. By integrating field data with a water quality index (WQI), the research seeks to provide insights into contamination levels and inform mitigation strategies, contributing to the broader understanding of acid rain's environmental consequences in semi-arid regions.

Literature Survey

Acid rain, a consequence of atmospheric pollution, has been extensively studied for its environmental impacts since its identification in the 19th century. The primary pollutants, sulfur dioxide (SO_2) and nitrogen oxides (NO_x), undergo atmospheric reactions to form acidic compounds, as shown in the following equations:

\ceSO2+OH·−>HOSO2·
\ceHOSO2·+O2−>SO3+HO2·
\ceSO3+H2O−>H2SO4
\ceNO2+OH·−>HNO3

These reactions, catalyzed by atmospheric moisture and oxidants, result in precipitation with elevated hydrogen ion concentrations (Fatima et al., 2021). Research highlights acid rain's detrimental effects on ecosystems, water resources, and infrastructure, with global case studies illustrating its severity. For instance, in Germany's Black Forest, acid deposition has caused widespread tree dieback, while in Canada, over 14,000 lakes in Ontario and Quebec have been acidified, disrupting aquatic ecosystems (Environment Canada, 2016).

Groundwater, a critical resource in arid regions, is particularly vulnerable to acid rain due to its potential to leach base cations and mobilize toxic metals like aluminum. Henriksen and Kirkhusmo (1982) reported groundwater pH dropping below 5.0 in Norway, attributed to low soil buffering capacity. Similarly, Hultberg and Wenblad (1980) documented acidification in southwestern Sweden, linking it to sulfate deposition. In India, studies indicate increasing acidity in rainfall, with pH values as low as 4.77 in Nagpur and 5.32 in Visakhapatnam, driven by industrial and vehicular emissions (Times of India, 2017). However, research on groundwater impacts in India, especially in semi-arid regions like Rajasthan, remains limited.

In Rajasthan, groundwater quality is a pressing concern due to the region's reliance on aquifers. Adimalla (2020) found elevated fluoride and nitrate levels in Telangana's groundwater, suggesting similar contamination mechanisms could apply in Rajasthan, where acid rain may increase sulfate and TDS concentrations. Agrawal (2009) reported high TDS and ion levels in Dudu, Rajasthan, potentially linked to atmospheric deposition. These findings align with global studies indicating that while limestone-rich soils may buffer pH changes, prolonged acid deposition can still elevate ion concentrations, compromising water quality (Fatima et al., 2021).

This literature review underscores the need for localized studies in regions like Chirawa Tehsil, where industrial growth and arid conditions amplify acid rain's impact on groundwater. By building on global and regional research, this study addresses a critical gap in understanding acid rain's effects on semi-arid aquifers.

Methodology

To assess the impact of acid rain on groundwater quality in Chirawa Tehsil, Rajasthan, a systematic sampling and analysis approach was employed. The methodology was designed to evaluate physicochemical parameters and derive a Water Quality Index (WQI) to determine the suitability of groundwater for drinking and irrigation.

Study Area

Chirawa Tehsil, located in Jhunjhunu district, Rajasthan, is a semi-arid region reliant on groundwater due to limited surface water availability. The area experiences industrial activity and agricultural practices, which may contribute to atmospheric pollution and acid rain.

Sampling

Twenty groundwater samples were collected from hand pumps and tube wells across Chirawa Tehsil during the post-monsoon season (October–November 2024) to capture seasonal influences on water quality. Sampling sites were selected to represent diverse land use patterns, including residential, agricultural, and industrial areas. Wells were pumped for 5–10 minutes until temperature and electrical conductivity (EC) stabilized, ensuring representative samples. Samples were collected in pre-rinsed 1-liter polyethylene bottles, stored at 4°C, and transported to the laboratory within 24 hours.

Analytical Methods

The following physicochemical parameters were analyzed using standard protocols:

- pH: Measured using a calibrated pH meter (accuracy ±0.01).
- Electrical Conductivity (EC): Determined with an EC meter (µS/cm).
- Total Dissolved Solids (TDS): Calculated by evaporating a known sample volume and weighing the residue (mg/L).
- Major Cations (Calcium, Magnesium, Sodium, Potassium): Quantified via atomic absorption spectroscopy.
- Major Anions (Chloride, Sulfate, Bicarbonate, Nitrate): Analyzed using ion chromatography.
- All analyses adhered to American Public Health Association (APHA) guidelines, with duplicate measurements to ensure accuracy. Calibration standards were used for all instruments, and blanks were run to detect contamination.

Water Quality Index (WQI)

The WQI was calculated to assess overall groundwater suitability, using the weighted arithmetic index method:

$$WQI=\sum(qi\cdot wi)/\sum wi$$

Where:

- qi=(Ci/Si)×100, the quality rating for the iii-th parameter.
- CiC_iCi: Measured concentration of the parameter.
- SiS_iSi: WHO standard value for the parameter.
- wiw_iwi: Relative weight assigned based on the parameter's importance (e.g., higher weight for pH and TDS).

Weights were assigned on a scale of 1–5, with pH, TDS, and sulfate given higher weights due to their relevance to acid rain impacts. The WQI was categorized as follows: <50 (excellent), 50–100 (good), 100–200 (poor), 200–300 (very poor), >300 (unsuitable).

Data Analysis

Results were statistically analyzed using mean, range, and standard deviation to identify trends. Spatial distribution maps of key parameters were generated using GIS software to visualize contamination patterns.

This methodology ensures a robust assessment of groundwater quality, enabling the identification of acid rain's influence on Chirawa Tehsil's aquifers.

Results

The physicochemical analysis of 20 groundwater samples from Chirawa Tehsil, Rajasthan, provided insights into the impact of acid rain on water quality. Key parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), and major ions, were measured, and the Water Quality Index (WQI) was calculated. Results are summarized in the table below:

Table 1. *Physicochemical Analysis of Groundwater Samples from Chirawa Tehsil, Rajasthan*

Parameter	Range	Average	WHO Standard
pH	6.8–7.8	7.3	6.5–8.5
EC (µS/cm)	800–2500	1500	1500
TDS (mg/L)	500–1600	950	1000
Calcium (mg/L)	50–150	90	200
Magnesium (mg/L)	30–100	60	150
Sodium (mg/L)	100–300	180	200

Potassium (mg/L)	5–20	10	12
Chloride (mg/L)	100–400	250	250
Sulfate (mg/L)	50–300	150	250
Bicarbonate (mg/L)	200–500	350	500
Nitrate (mg/L)	10–50	25	50

Note. This table presents the results of physicochemical analysis of 20 groundwater samples collected from Chirawa Tehsil, Rajasthan, in 2024 to assess acid rain impacts. Parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), and major ions were measured, with the Water Quality Index (WQI) indicating poor water quality in 40% of samples due to elevated TDS and sulfate levels. Data reflect WHO standards for drinking water quality.

Key Observations

- **pH**: Most samples (17/20) had pH within the WHO range (6.5–8.5), but three samples showed slightly acidic values (6.8–7.0), potentially indicating acid rain influence.
- **TDS and EC**: Five samples exceeded the WHO TDS limit of 1000 mg/L, and four had EC above 1500 µS/cm, suggesting high dissolved ion content.
- **Sulfate**: Two samples had sulfate levels above 250 mg/L, a marker of acid rain deposition, as sulfate ions are derived from sulfuric acid (H_2SO_4).
- **Cations and Anions**: Calcium, magnesium, and bicarbonate levels were elevated, indicating hard water, while sodium and chloride levels were within or slightly above permissible limits, possibly due to natural or anthropogenic sources.

Conclusion

This study confirms that acid rain significantly impacts groundwater quality in Chirawa Tehsil, Rajasthan, despite generally neutral to slightly alkaline pH levels (6.8–7.8). Elevated total dissolved solids (TDS, 500–1600 mg/L) and sulfate concentrations (50–300 mg/L) in several samples indicate contamination from acid rain deposition, likely driven by sulfuric acid (H_2SO_4) formed via:

\ceSO2+H2O−>H2SO3→H2SO4

The Water Quality Index (WQI), calculated as:

WQI=∑(qi·wi)/=∑wi

revealed that 40% of of samples were of poor quality (WQI 100–200), underscoring the unsuitability of groundwater for drinking without treatment. These findings align with global studies on acid rain's role in increasing ion concentrations and highlight the vulnerability of semi-arid regions like Rajasthan, where groundwater is a critical resource. The study emphasizes the urgent need for continuous monitoring, stricter emission controls, and public awareness to mitigate acid rain's environmental and health impacts in Chirawa Tehsil.

Future Work

Future research should focus on longitudinal studies to monitor seasonal and annual trends in groundwater quality in Chirawa Tehsil, capturing the dynamic influence of acid rain. Detailed source apportionment studies, using isotopic analysis, could pinpoint specific pollution sources (e.g., industrial emissions vs. agricultural runoff) contributing to elevated sulfate and TDS levels. Additionally, pilot projects testing remediation techniques, such as lime dosing or reverse osmosis, should be implemented to assess their efficacy in reducing ion concentrations. Expanding the study to other Rajasthan districts would provide a broader understanding of acid rain's regional impact. Finally, integrating atmospheric modeling to predict pollutant dispersion and deposition patterns could enhance mitigation strategies, addressing the complex interplay of acid rain and groundwater quality.

Acknowledgment

The authors express gratitude to the local community and authorities of Chirawa Tehsil, Rajasthan, for their cooperation during groundwater sampling. Special thanks are extended to the laboratory staff at Shri Jagdishprasad Jhabarmal Tibrewala Hawkins University, the University of Oxford, and the University of Tokyo for their valuable contributions to data analysis and atmospheric modeling, respectively. The authors also appreciate the guidance provided by academic mentors and colleagues, which enriched the study's scope and execution.

Disclosure of Interest

The authors declare no conflicts of interest, financial or otherwise, that could influence the objectivity or findings of this study. The research was conducted independently to ensure impartial analysis and reporting.

Funding Information

This study was self-funded by the authors, with no external grants or financial support received. The research reflects the authors’ commitment to investigating environmental challenges in Chirawa Tehsil, Rajasthan, using available resources.

References

Adimalla, N. (2020). Assessment and mechanism of fluoride enrichment in groundwater from the hard rock terrain: A multivariate statistical approach. Geochemistry International, 58(4), 456–471. https://doi.org/10.1134/S001670292004002X

Adimalla, N., & Li, P. (2019). Occurrence, health risks, and geochemical mechanisms of fluoride and nitrate in groundwater of the rock-dominant semi-arid region, Telangana State, India. Human and Ecological Risk Assessment: An International Journal, 25(1-2), 81–103. https://doi.org/10.1080/10807039.2018.1480353

Agrawal, R. (2009). Study of physico-chemical parameters of groundwater quality of Dudu Town in Rajasthan. Rasayan Journal of Chemistry, 2(4), 969–971.

Environment Canada. (2016). Acid rain and water. Government of Canada. https://www.canada.ca/en/environment-climate-change/services/air-pollution/issues/acid-rain-water.html

Fatima, A., Ahmad, S., & Khan, M. (2021). A review on acid rain: An environmental threat. Bulletin of Pure and Applied Sciences, 40(1), 304–317. https://doi.org/10.19045/bspab.2021.100032

Henriksen, A., & Kirkhusmo, L. A. (1982). Acidification of groundwater in Norway. Nordic Hydrology, 13(4), 183–192.

Hultberg, H., & Wenblad, A. (1980). Acid groundwater in southwestern Sweden. Ecological Bulletins, 32, 197–205.

Kumari, V., & Saini, A. K. (2025). Comprehensive study of acid rain: Causes, consequences, and environmental impact. Journal of Research in Chemistry, 6(2), 60–66.

Singh, A., & Agrawal, M. (2008). Acid rain and its ecological consequences. Journal of Environmental Biology, 29(1), 15–24.

Times of India. (2017, March 3). Pollution turning country’s rainfall acidic, says study. Times of India. https://timesofindia.indiatimes.com/india/pollution-turning-countrys-rainfall-acidic-says-study/articleshow/57457470.cms

Appendix

Detailed coordinates of the 20 groundwater sampling sites in Chirawa Tehsil, Rajasthan, are available upon request. Sites were selected to represent residential, agricultural, and industrial areas, ensuring comprehensive coverage

Raw physicochemical data for all samples, including pH, EC, TDS, and ion concentrations, are archived and can be provided for further analysis. Data include duplicate measurements and calibration logs for quality assurance.

Open Access Statement

International Journal of Emerging Trends in Chemistry (IJETC)
E-ISSN: 1234-5678
Vol. 1, Issue 1, April 2025 | pp. 36–47

Research Paper

Green Chemistry: Pioneering Sustainable Solutions for a Safer Planet

Andrei Popescu[1], Elena Ionescu[2]

[1] Department of Chemistry, University of Bucharest, Bucharest, Romania.
[2] Department of Chemistry, Babeș-Bolyai University, Cluj-Napoca, Romania.

Received: March 30, 2025 / Accepted: April 05, 2025 / Published: April 24, 2025

Abstract

Green chemistry has emerged as a cornerstone of sustainable development, offering innovative solutions to mitigate the environmental and health impacts of chemical processes. This article provides a comprehensive exploration of green chemistry's principles, historical development, and practical applications across industries such as pharmaceuticals, agriculture, and manufacturing. By integrating the Twelve Principles of Green Chemistry, this study evaluates how these guidelines foster the design of safer chemicals, reduce hazardous waste, and optimize resource efficiency. Employing a mixed-methods approach, including a systematic literature review and case study analyses, we assess the environmental, economic, and social benefits of green chemistry. Findings reveal significant reductions in waste and energy consumption, alongside cost savings and enhanced safety. Challenges, such as high implementation costs and limited global adoption, are also addressed. The article proposes strategies for integrating green chemistry into education, policy, and industry practices to achieve broader sustainability goals.

Keywords: Green chemistry, Sustainability, Environmental safety, Chemical innovation, Hazardous waste reduction, Renewable resources

Introduction

Green chemistry, often synonymous with sustainable chemistry, represents a paradigm shift in the design, production, and application of chemical products and processes. Defined as the development of chemical methodologies that minimize or eliminate hazardous substances, green chemistry addresses the urgent need to reduce the environmental and health impacts of industrial activities (Anastas & Warner, 1998). Unlike traditional chemical practices, which often prioritize yield and efficiency at the expense of ecological consequences, green chemistry embeds sustainability into every stage of the chemical lifecycle—from raw material selection to waste management (Clark et al., 2015). This approach not only mitigates pollution but also enhances resource efficiency, aligning with global efforts to combat climate change, resource depletion, and environmental degradation.

The origins of green chemistry can be traced to the early 1990s, when growing awareness of industrial pollution prompted scientists and policymakers to seek alternatives to conventional chemical processes. The United States Environmental Protection Agency (EPA) played a pivotal role by launching initiatives to promote sustainable chemical innovation, culminating in the formalization of green chemistry principles by Anastas and Warner (1998). These principles, which include waste prevention, atom economy, and the use of renewable feedstocks, provide a roadmap for creating safer and more sustainable chemical systems. Today, green chemistry is recognized as a critical tool for achieving the United Nations' Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) (United Nations, 2015).

The significance of green chemistry extends beyond environmental protection. By reducing reliance on toxic substances and non-renewable resources, it offers economic benefits, such as lower waste disposal costs and enhanced process efficiency (Sheldon, 2017). Industries ranging from pharmaceuticals to agriculture have adopted green chemistry practices to improve product safety and competitiveness. For example, the replacement of hazardous solvents with water-based alternatives has revolutionized manufacturing processes, demonstrating that environmental and economic goals can be mutually reinforcing (Jiménez-González et al., 2011). Moreover, green chemistry fosters social benefits by protecting workers and communities from exposure to harmful chemicals, thereby enhancing public health and equity.

Despite its promise, green chemistry faces challenges, including high initial costs, resistance to change in established industries, and varying levels of adoption across regions. Developing nations, in particular, may lack the infrastructure or regulatory frameworks to implement green practices effectively (Erythropel et al., 2018). Addressing these barriers requires a multifaceted approach, including policy incentives, industry collaboration, and education reform to train the next generation of chemists in sustainable practices.

This article aims to provide a comprehensive analysis of green chemistry's principles, applications, and impacts. Through a mixed-methods approach, we evaluate its efficacy in reducing environmental harm and promoting sustainability across key industries. The study also explores strategies for overcoming adoption barriers and proposes future directions for research and implementation. By highlighting green chemistry's transformative potential, we seek to inspire stakeholders to embrace sustainable innovation for a safer planet.

Literature Review

Green chemistry has emerged as a vital field within the chemical sciences, driven by the imperative to reduce the environmental and health impacts of industrial processes. Since its formalization in the 1990s, the discipline has grown exponentially, with significant contributions from both academia and industry. The foundational work of Anastas and Warner (1998) introduced the Twelve Principles of Green Chemistry, which serve as a guiding framework for designing chemical processes that prioritize safety, efficiency, and sustainability. These principles advocate for strategies such as preventing waste, maximizing atom economy, and using renewable feedstocks, which have reshaped chemical innovation across various sectors.

A key focus of green chemistry research has been the development of safer and more efficient chemical processes. Sheldon (2017) emphasized the importance of the "E factor," a metric that quantifies the environmental efficiency of chemical processes by measuring waste production relative to product output. His work demonstrated that catalytic processes, which minimize the use of stoichiometric reagents, can reduce waste by up to 90% in some cases, as seen in the synthesis of fine chemicals. Similarly, Jiménez-González et al. (2011) conducted a comprehensive analysis of green chemistry applications in the pharmaceutical industry, finding that the adoption of greener solvents and catalysts reduced solvent use by 50% and hazardous waste by 30% in the production of active pharmaceutical ingredients (APIs). These advancements highlight the potential of green chemistry to enhance both environmental and economic outcomes.

The application of green chemistry extends beyond pharmaceuticals to agriculture, manufacturing, and consumer goods. For instance, Clark et al. (2015) explored the use of bio-based feedstocks in the production of polymers, demonstrating that renewable materials, such as plant-derived sugars, can replace petroleum-based inputs without compromising product quality. In agriculture, the development of low-toxicity pesticides, such as spinosad-based larvicides, has reduced harm to non-target species and ecosystems, offering a safer alternative to organophosphates (Erythropel et al., 2018). Additionally, innovations in green manufacturing, such as the use of supercritical CO_2 in dry cleaning, have eliminated the need for hazardous solvents like perchloroethylene, improving worker safety and reducing groundwater contamination (Pollock et al., 2020).

Despite these advancements, several challenges hinder the widespread adoption of green chemistry. Pollock et al. (2020) identified high initial costs, lack of standardized metrics, and resistance to change within established industries as significant barriers. Small and medium-sized enterprises (SMEs), in particular, often lack the financial resources to transition to green processes, while large corporations may prioritize short-term profits over long-term sustainability. Furthermore, regional disparities in regulatory frameworks limit global implementation. For example, developing nations may face challenges in enforcing green chemistry standards due to limited infrastructure and expertise (Erythropel et al., 2018).

Education plays a critical role in overcoming these barriers and fostering the next generation of green chemists. Kirchhoff (2019) argued that integrating green chemistry into educational curricula at all levels—undergraduate, graduate, and professional—can enhance awareness and equip students with the skills to innovate sustainably. Programs at institutions like the University of York and the University of Massachusetts-Boston have successfully incorporated green chemistry principles, resulting in increased student engagement in sustainability projects (Kirchhoff, 2019). However, the global reach of such programs remains limited, particularly in regions with underfunded educational systems.

Recent studies have also emphasized the need for interdisciplinary approaches to green chemistry. Clark et al. (2015) advocated for collaborations between chemists, engineers, and policymakers to develop holistic solutions that address technical, economic, and social dimensions of sustainability. For instance, lifecycle assessments (LCAs) have become a valuable tool for evaluating the environmental impact of chemical processes from cradle to grave, enabling more informed decision-making (Jiménez-González et al., 2011). Additionally, public-private partnerships have facilitated the scaling of green technologies, as seen in initiatives like the Green Chemistry Institute (GCI), which bridges academia, industry, and government (Anastas & Warner, 1998).

In summary, the literature underscores green chemistry's transformative potential to address pressing environmental challenges while delivering economic and social benefits. However, gaps remain in global adoption, standardization, and education. Future research should focus on developing cost-effective green technologies, creating universal metrics for assessing sustainability, and expanding educational outreach to ensure equitable access to green chemistry knowledge and practices.

Methodology

To comprehensively evaluate the impact, applications, and challenges of green chemistry, this study adopted a robust mixed-methods research design, integrating qualitative and quantitative approaches. The methodology was structured to provide a holistic understanding of green chemistry's efficacy in promoting sustainability across diverse industries. It consisted of three primary components: a systematic literature review, case study analysis, and stakeholder interviews. Each component was carefully designed to align with the Twelve Principles of Green Chemistry, which served as the theoretical framework for assessing the “greenness” of chemical processes and products.

Systematic Literature Review

A systematic review of peer-reviewed literature was conducted to synthesize existing knowledge on green chemistry’s principles, applications, and impacts. The review targeted articles, books, and reports published between 1998 and 2025, capturing the evolution of the field since its formalization. Databases such as PubMed, Scopus, Web of Science, and Google Scholar were searched using keywords including “green chemistry,” “sustainable chemistry,” “environmental impact,” “waste reduction,” and “renewable feedstocks.” Inclusion criteria required studies to focus on green chemistry applications, environmental or economic outcomes, or educational initiatives. Exclusion criteria eliminated non-peer-reviewed sources and studies lacking empirical data. A total of 120 studies were selected for analysis after screening abstracts and full texts. The review was organized thematically, covering topics such as industrial applications, policy frameworks, and educational integration. Qualitative content analysis was used to identify trends, while quantitative data (e.g., waste reduction percentages) were extracted to support statistical comparisons.

Case Study Analysis

To assess the practical applications of green chemistry, three industries—pharmaceuticals, agriculture, and manufacturing—were selected for in-depth case study analysis. These industries were chosen due to their significant environmental footprints and potential for green chemistry interventions. The case studies included:

- Pharmaceuticals: The adoption of catalytic processes in the synthesis of active pharmaceutical ingredients (APIs), replacing traditional stoichiometric reagents.
- Agriculture: The use of spinosad-based larvicides as a low-toxicity alternative to organophosphate pesticides.
- Manufacturing: The replacement of chlorofluorocarbons (CFCs) with hydrofluorocarbons (HFCs) in refrigeration systems and the use of supercritical CO_2 as a blowing agent in polystyrene foam production.

Data were collected from industry reports, peer-reviewed studies, and publicly available environmental impact assessments. Metrics included reductions in hazardous waste, energy consumption, and greenhouse gas emissions, as well as cost savings and process efficiency improvements. The Twelve Principles of Green Chemistry were used as a checklist to evaluate each case study’s alignment with sustainable practices. For example, the principle of “less hazardous chemical synthesis” was applied to assess the toxicity of reagents, while “design for energy efficiency” guided the analysis of energy consumption. Both qualitative (e.g., stakeholder perspectives) and quantitative (e.g., waste reduction percentages) data were analyzed to provide a comprehensive evaluation.

Stakeholder Interviews

To capture diverse perspectives on green chemistry adoption, semi-structured interviews were conducted with 15 stakeholders, including industry professionals, academic researchers, and policymakers from India, Nigeria, and the United States. Participants were selected based on their expertise in green chemistry or sustainability, using purposive sampling to ensure representation across sectors and regions. Interview questions explored barriers to adoption, success stories, and recommendations for scaling green chemistry practices. Each interview lasted approximately 45 minutes and was conducted via video conferencing, recorded with consent, and transcribed verbatim. Thematic analysis was employed to identify recurring themes, such as cost constraints, regulatory support, and the role of education. The interview data complemented the literature review and case studies by providing real-world insights into the practical challenges and opportunities of green chemistry.

Data Analysis

Data from the three components were triangulated to ensure validity and reliability. Qualitative data from the literature review and interviews were analyzed using NVivo software to code and categorize themes, such as “environmental benefits,” “economic incentives,” and “implementation barriers.” Quantitative data, including waste reduction percentages, energy savings, and cost reductions, were analyzed using descriptive statistics in SPSS to calculate means, standard deviations, and correlations. The Twelve Principles of Green Chemistry provided a consistent framework for evaluating outcomes across all data sources. For instance, the principle of “prevention” was used to assess waste reduction, while “use of renewable feedstocks” guided the evaluation of bio-based materials. The mixed-methods approach allowed for a nuanced understanding of green chemistry’s impact, combining empirical evidence with contextual insights.

Ethical Considerations

The study adhered to ethical research standards, including obtaining informed consent from interview participants and ensuring anonymity to protect their privacy. Data were stored securely on encrypted servers, and only aggregated findings were reported to prevent identification of individuals. The literature review and case studies relied on publicly available or ethically sourced data, with proper attribution to original authors.

This methodology provided a comprehensive and rigorous framework for evaluating green chemistry's contributions to sustainability, enabling the identification of best practices, challenges, and future opportunities.

Results

The mixed-methods analysis yielded comprehensive insights into the efficacy, benefits, and challenges of green chemistry across pharmaceuticals, agriculture, and manufacturing industries. The findings are organized into four key areas: environmental benefits, economic advantages, implementation challenges, and educational impacts. These results were derived from the systematic literature review, case study analyses, and stakeholder interviews, with quantitative metrics and qualitative themes triangulated to ensure robustness.

Environmental Benefits

Green chemistry practices demonstrated significant reductions in environmental impact across all studied industries. In the pharmaceutical sector, the adoption of catalytic processes for synthesizing active pharmaceutical ingredients (APIs) reduced solvent use by 40-50% and hazardous waste generation by 30-35%, as evidenced by case studies of major manufacturers (Jiménez-González et al., 2011). For example, the replacement of stoichiometric reagents with selective catalysts minimized byproducts, aligning with the principle of "less hazardous chemical synthesis." In agriculture, the use of spinosad-based larvicides as an alternative to organophosphate pesticides resulted in a 10-fold reduction in toxicity to non-target species, such as pollinators and aquatic organisms, and a 20% decrease in soil contamination (Erythropel et al., 2018). In manufacturing, the substitution of chlorofluorocarbons (CFCs) with hydrofluorocarbons (HFCs) in refrigeration systems eliminated ozone-depleting emissions, while the use of supercritical CO_2 as a blowing agent in polystyrene foam production reduced volatile organic compound (VOC) emissions by 95% (Pollock et al., 2020). Quantitative data from the case studies indicated an average reduction of 25-40% in greenhouse gas emissions across these applications, underscoring green chemistry's contribution to climate change mitigation. Qualitative insights from stakeholder interviews highlighted that these environmental benefits also enhanced corporate social responsibility (CSR) profiles, fostering public trust in adopting companies.

Economic Advantages

Green chemistry practices yielded substantial economic benefits, primarily through reduced operational costs and improved process efficiency. In the pharmaceutical industry, companies implementing catalytic processes reported cost savings of 20-25% due to lower solvent and waste disposal expenses, with one case study estimating annual savings of $15 million for a single API production line (Jiménez-González et al., 2011). In agriculture, the use of spinosad-based larvicides reduced application costs by 15% compared to organophosphates, as fewer treatments were required due to the compound's higher efficacy (Erythropel et al., 2018). In manufacturing, Dow Chemical's adoption of CO_2 as a blowing agent in polystyrene foam production eliminated the need for hazardous chemicals, resulting in annual savings of approximately $10 million and a 30% reduction in production costs (Pollock et al., 2020). Interviewees from industry emphasized that these savings often offset the initial investment in green technologies within 2-3 years, making green chemistry a financially viable strategy. Statistical analysis revealed a strong positive correlation ($r = 0.82$, $p < 0.01$) between the adoption of green chemistry practices and cost reductions, highlighting the economic incentives for scalability. Additionally, companies adopting green practices reported improved market competitiveness, as consumers increasingly favored sustainable products.

Implementation Challenges

Despite its benefits, green chemistry faces several barriers to widespread adoption. The literature review and stakeholder interviews identified high initial investment costs as a primary obstacle, particularly for small and medium-sized enterprises (SMEs). For instance, transitioning to catalytic processes in pharmaceuticals required upfront costs of $5-10 million for equipment and training, which SMEs found prohibitive (Pollock et al., 2020). Resistance to change within established industries was another significant challenge, with 60% of interviewed stakeholders noting that legacy systems and risk-averse corporate cultures hindered innovation. The lack of standardized metrics for assessing the "greenness" of processes further complicated adoption, as companies struggled to compare the sustainability of different approaches (Sheldon, 2017). Regional disparities also emerged as a concern, with interviewees from Nigeria highlighting limited access to green chemistry expertise and infrastructure in developing nations. Quantitative data indicated that only 30% of SMEs in the studied industries had adopted green chemistry practices, compared to 70% of large corporations, underscoring the need for targeted support. Qualitative themes from interviews emphasized the importance of regulatory incentives, such as tax breaks or subsidies, to encourage adoption among smaller firms.

Educational Impacts

The integration of green chemistry into educational curricula showed promising results in fostering awareness and innovation. The literature review identified that institutions incorporating green chemistry principles, such as the University of York and the University of Massachusetts-Boston, reported a 20-25% increase in student engagement in sustainability-related projects (Kirchhoff, 2019). Case studies of educational programs revealed that hands-on activities, such as converting traditional laboratory experiments into greener alternatives, enhanced students' understanding of sustainable practices by 30%, as measured by pre- and post-course assessments. Stakeholder interviews with educators highlighted that green chemistry education also encouraged interdisciplinary collaboration, with chemistry students working alongside engineering and policy students to address real-world sustainability challenges. However, the global reach of such programs remained limited, with only 15% of interviewed stakeholders from developing nations reporting access to green chemistry curricula. This disparity suggests a need for scalable educational models, such as online courses or open-access resources, to democratize green chemistry knowledge.

Conclusion

Green chemistry offers a robust framework for addressing environmental and economic challenges in chemical industries. By prioritizing waste prevention, safer chemicals, and renewable resources, it aligns with global sustainability goals. The case studies demonstrate that green chemistry not only reduces environmental harm but also enhances profitability, making it a viable strategy for industries worldwide. However, broader adoption requires overcoming barriers such as cost and awareness. Integrating green chemistry into education and policy frameworks is essential for its long-term success.

Future Research

Future research should focus on developing standardized metrics for evaluating green chemistry practices, enabling consistent comparisons across industries. Additionally, exploring novel biodegradable materials and scaling up renewable feedstock use could further enhance sustainability. Expanding green chemistry education in developing nations and fostering collaborations between academia and industry will accelerate global adoption. Finally, investigating the socio-economic impacts of green chemistry in marginalized communities could ensure equitable benefits.

Acknowledgment

The authors express gratitude to the Global Institute of Technology, Mumbai, and the University of Lagos, Nigeria, for providing research facilities and support. We also thank Dr. Sarah Kim for her insights on sustainable chemistry and the anonymous reviewers for their valuable feedback.

Disclosure of Interest

The authors declare no conflicts of interest related to this study.

Funding Information

This research was carried out without any financial support from funding agencies, institutions, or commercial organizations. The authors confirm that the study was conducted using personal or institutional resources, and no specific grant or project funding was received from public, private, or non-profit sectors during this research and its publication process.

References

Anastas, P. T., & Warner, J. C. (1998). Green Chemistry: Theory and Practice. Oxford University Press.

Clark, J. H., Farmer, T. J., & Sherwood, J. (2015). Green chemistry and the biorefinery: A partnership for a sustainable future. Green Chemistry, 17(2), 904-915. https://doi.org/10.1039/C4GC01682K

Erythropel, H. C., Zimmerman, J. B., de Winter, T. M., & Anastas, P. T. (2018). Green chemistry education: Progress and prospects. Green Chemistry, 20(19), 4293-4303. https://doi.org/10.1039/C8GC01787F

Jiménez-González, C., Constable, D. J., & Ponder, C. S. (2011). Evaluating the "greenness" of chemical processes and products in the pharmaceutical industry. Chemical Reviews, 112(3), 1477-1499. https://doi.org/10.1021/cr200097d

Kirchhoff, M. M. (2019). Green chemistry education: Empowering the next generation. Journal of Chemical Education, 96(12), 2605-2609. https://doi.org/10.1021/acs.jchemed.9b00315

Pollock, D., Clark, J. H., & Farmer, T. J. (2020). Barriers to green chemistry adoption: A review. Sustainable Chemistry, 1(1), 23-34. https://doi.org/10.3390/suschem1010003

Sheldon, R. A. (2017). The E factor 25 years on: The rise of green chemistry and sustainability. Green Chemistry, 19(1), 18-24. https://doi.org/10.1039/C6GC02157C

United Nations. (2015). Transforming our world: The 2030 Agenda for Sustainable Development. United Nations General Assembly.

Appendix

This appendix supplements the study by detailing green chemistry applications in pharmaceuticals, agriculture, and manufacturing. In pharmaceuticals, catalytic processes for active pharmaceutical ingredient (API) synthesis replaced stoichiometric reagents, cutting solvent use by 40-50% and waste by 30%, aligning with "safer solvents" and "catalysis" principles. In agriculture, spinosad-based larvicides reduced toxicity to non-target species tenfold, supporting "designing safer chemicals." In manufacturing, hydrofluorocarbons (HFCs) replaced chlorofluorocarbons (CFCs) in refrigeration, eliminating ozone depletion, while CO_2 in polystyrene foam production cut VOC emissions by 95%, reflecting "prevention" and "renewable feedstocks." The Twelve Principles of Green Chemistry—prevention, atom economy, less hazardous synthesis, safer chemicals, safer solvents, energy efficiency, renewable feedstocks, reduced derivatives, catalysis, degradation, pollution prevention, and accident prevention—guided evaluations. These cases highlight green chemistry's role in sustainable innovation, offering a model for broader adoption.

Open Access Statement

International Journal of Emerging Trends in Chemistry (IJETC)

E-ISSN: 1234-5678

Vol. 1, Issue 1, April 2025 | pp. 48–59

Research Paper

Comparing the Efficiency of Household Water Purification Methods: A Chemical Perspective

Ahmed Al-Mansoori[1], Fatima Al-Najjar[2]

[1] Department of Chemistry, United Arab Emirates University, Al Ain, United Arab Emirates.

[2] Department of Chemistry, Khalifa University, Abu Dhabi, United Arab Emirates.

Received: April 01, 2025 / Accepted: April 14, 2025 / Published: April 24, 2025

Abstract

Access to clean and safe drinking water is one of the most critical aspects of public health, and various methods are employed by households to ensure water is purified. However, the efficiency of these methods varies depending on the type of contamination and the technology used. This study aims to compare the chemical efficiency of common household water purification methods, namely boiling, filtration (using activated carbon filters), and chemical treatments (such as chlorine and iodine). A chemical perspective was adopted to assess the ability of each method to remove contaminants such as bacteria, organic compounds, and heavy metals from water. The study shows that while boiling is effective in killing microorganisms, it is less efficient at removing chemical contaminants. Filtration systems are effective at removing organic impurities, but their performance is limited in removing certain inorganic contaminants.

Keywords: Household water purification, Chemical methods, Filtration, Boiling, Water quality

Introduction

Access to safe drinking water remains one of the greatest global health challenges. Waterborne diseases, often caused by microbial contamination, lead to millions of deaths annually, particularly in low-income regions (Smith & Johnson, 2021). As a result, various water purification methods have been developed and adopted in household settings to improve water safety and quality. The primary methods commonly employed in households include boiling, filtration (often using activated carbon filters), and chemical treatments such as chlorine or iodine. Each method has its strengths and weaknesses, which can influence its overall effectiveness in providing clean water.

Boiling is one of the most widely used methods due to its simplicity and low cost. It is effective in killing harmful microorganisms, including bacteria, viruses, and protozoa (Lee & Chen, 2020). However, boiling does not remove chemical contaminants such as heavy metals or pesticides, which are increasingly present in water sources due to industrial and agricultural activities (Davis & Lee, 2019).

Filtration, specifically through activated carbon filters, is another popular household method. Activated carbon has a high surface area that allows it to adsorb various organic compounds, chlorine, and some heavy metals, thereby improving water taste and quality (Jones & Williams, 2023). Despite its effectiveness, activated carbon filtration systems are not universally effective against all contaminants, particularly microorganisms and some inorganic pollutants (Brown & Green, 2020).

Chemical treatments, such as chlorine and iodine tablets, are commonly used in both emergency and everyday situations due to their ability to disinfect water rapidly. However, improper use or overuse of chemical disinfectants can leave harmful residues in the water, which may pose health risks if consumed in excess (Williams & Harris, 2022).

This paper investigates these three common water purification methods, comparing their chemical efficiency in removing a range of contaminants, including microbial, organic, and inorganic pollutants. By evaluating their performance through chemical analysis, this study aims to provide a clear understanding of which methods offer the most effective purification for household use.

Literature Survey

The study of household water purification methods has garnered significant attention due to the growing need for safe drinking water, especially in areas where access to clean water is limited. Numerous purification techniques have been assessed for their ability to remove contaminants and improve water quality. This section reviews the existing literature on the most commonly used household purification methods—boiling, filtration, and chemical treatments—focusing on their chemical efficiency and limitations.

Boiling

Boiling is one of the oldest and most widely used methods of purifying water. It is highly effective at killing bacteria, viruses, and protozoa, which are the most common waterborne pathogens (Brown & Green, 2020).

Studies have shown that boiling can kill up to 99.99% of microorganisms, making it a reliable method for disinfection (Lee & Chen, 2020). However, while boiling water removes microorganisms, it does not eliminate dissolved chemicals, such as heavy metals (e.g., lead, mercury) or pesticides, which can still pose health risks (Davis & Lee, 2019). Additionally, boiling consumes a significant amount of energy and time, especially when purifying large quantities of water, limiting its practicality for everyday use (Smith & Johnson, 2021).

Filtration

Filtration is another popular household purification method, especially when using activated carbon filters. Activated carbon has a large surface area that enables it to adsorb a wide range of organic compounds, chlorine, and certain heavy metals (Jones & Williams, 2023). Filtration is highly effective at improving water taste and odor by removing chlorine, volatile organic compounds (VOCs), and certain toxins (Davis & Lee, 2019). However, filtration systems are not perfect. They generally do not remove microorganisms, such as bacteria or viruses, and may have limited success in removing certain heavy metals like arsenic (Brown & Green, 2020). Furthermore, activated carbon filters require regular maintenance, as their efficiency diminishes over time as the carbon becomes saturated with contaminants.

Chemical Treatments

Chemical treatments, particularly chlorine and iodine, are widely used for disinfecting water in both emergency and routine situations. Chlorine, in particular, is effective at killing a wide range of microorganisms, including bacteria, viruses, and protozoa (Williams & Harris, 2022). However, while chlorine is highly effective for disinfection, it can leave harmful chemical residues in the water, such as trihalomethanes (THMs), which are potentially carcinogenic (Khan & Patel, 2021). Iodine is another chemical disinfectant commonly used, especially in emergency scenarios. It is effective at killing pathogens but, like chlorine, may leave undesirable residual compounds in the water, and its long-term consumption is not recommended due to its potential health risks (Williams & Harris, 2022).

In general, chemical treatments are fast, cost-effective, and widely available. However, their drawbacks—such as the presence of chemical residues and the need for careful dosing—necessitate a careful assessment of their overall efficacy and safety. The research by Smith and Johnson (2021) suggests that while chemical disinfectants are useful, they are often most effective when combined with other methods, such as filtration, to ensure the removal of both microbial and chemical contaminants.

Research Methodology

This study was designed to compare the chemical efficiency of three common household water purification methods: boiling, filtration (using activated carbon filters), and chemical treatments (chlorine and iodine). The methodology includes a detailed experimental setup for evaluating each method's ability to remove specific contaminants, including bacteria, heavy metals, and organic compounds. The following steps outline the research design and procedures used in this study.

Sample Preparation

The water samples used in this study were sourced from a local municipal supply known to contain typical household contaminants, including chlorine, organic compounds (e.g., pesticides), and low concentrations of heavy metals such as lead and arsenic. Prior to purification, the water samples were tested for their baseline levels of contaminants, which were recorded using standard water testing kits. These included tests for total coliform bacteria, pH, heavy metals (using atomic absorption spectroscopy), and organic pollutants (using gas chromatography).

Experimental Design

Each water purification method was tested in duplicate, and the results were compared to determine their effectiveness. The experimental setup was as follows:

- Boiling: A sample of 1 liter of water was boiled for 10 minutes in a stainless steel kettle. After boiling, the water was allowed to cool, and it was tested for bacterial contamination, pH, and chemical contaminants.
- Filtration: Activated carbon filters (a standard household model) were used to filter 1 liter of water. The filters were replaced after every five tests to ensure consistent performance. Post-filtration, the water was tested for bacterial contamination, chlorine residuals, and heavy metals.
- Chemical Treatment: For chlorine treatment, a typical household chlorine tablet was added to 1 liter of water, following the manufacturer's instructions for dosage. For iodine treatment, iodine tablets were used in the same manner. Both treatments were allowed to sit for 30 minutes to ensure sufficient disinfection. Post-treatment, the water was tested for residual chlorine and iodine levels, as well as bacterial contamination and the presence of any remaining chemical residues.

Data Collection

The effectiveness of each method was evaluated based on several key parameters:

- Microbial Contamination: The presence of coliform bacteria was measured using the Most Probable Number (MPN) method (Smith & Johnson, 2021).
- Chemical Contamination: The levels of lead and arsenic were measured using atomic absorption spectroscopy, and the presence of pesticides was analyzed using gas chromatography (Davis & Lee, 2019).
- pH and Residual Chemicals: The pH levels of the water and the presence of residual chlorine or iodine were measured using a digital pH meter and spectrophotometric analysis (Williams & Harris, 2022).

Statistical Analysis

The data collected from the experiments were analyzed using standard statistical methods, including the calculation of means and standard deviations. Comparisons between the different purification methods were made using analysis of variance (ANOVA) to determine if there were statistically significant differences in the effectiveness of each method.

Results

The results of the comparative analysis of the three household water purification methods—boiling, filtration, and chemical treatments (chlorine and iodine)—are presented below. These results focus on the effectiveness of each method in removing microbial contaminants, heavy metals, organic pollutants, and the presence of residual chemicals. The data for each method is summarized in terms of contamination removal efficiency and water quality improvement.

Microbial Contamination

The effectiveness of each method in reducing microbial contamination was measured by the reduction in total coliform bacteria, as indicated by the Most Probable Number (MPN) method. The results showed significant differences in bacterial removal among the methods:

- Boiling: Boiling for 10 minutes resulted in a near-total elimination of coliform bacteria, with an MPN reduction of approximately 99.9%. No detectable bacterial contamination was found after treatment, confirming the high efficacy of boiling in disinfecting water (Lee & Chen, 2020).
- Filtration: The activated carbon filtration method showed moderate efficacy in removing bacteria, with a reduction of 85-90%. However, small traces of coliform bacteria were still present after filtration, suggesting that activated carbon does not provide complete disinfection (Jones & Williams, 2023).

- Chemical Treatment (Chlorine): Chlorine treatment resulted in a 98% reduction in bacterial contamination, which is consistent with other studies on chlorine disinfection. However, small amounts of residual chlorine remained in the water, which is a concern for long-term consumption (Williams & Harris, 2022).
- Chemical Treatment (Iodine): Iodine treatment was slightly more effective than chlorine, achieving a 99.5% reduction in coliform bacteria. However, the presence of iodine residuals was detected after treatment, raising concerns about potential long-term health impacts due to iodine consumption (Khan & Patel, 2021).

Chemical Contamination (Heavy Metals and Organic Pollutants)

The removal efficiency of heavy metals (lead and arsenic) and organic pollutants (pesticides) was tested in all methods:

- Boiling: Boiling was not effective at removing heavy metals or organic contaminants. Lead and arsenic concentrations remained relatively unchanged after boiling, with a negligible reduction of around 5%. This is consistent with previous research, which shows that boiling does not remove dissolved contaminants (Davis & Lee, 2019)
- Filtration: Activated carbon filtration showed some efficiency in removing heavy metals, particularly lead. Lead concentrations were reduced by 40-50%. However, arsenic removal was less effective, with only a 10-15% reduction. Organic contaminants, such as pesticides, were also moderately reduced by 30-40% (Jones & Williams, 2023).
- Chemical Treatment (Chlorine and Iodine): Both chlorine and iodine treatments had negligible effects on the removal of heavy metals and organic pollutants. These treatments primarily target microbial contamination and do not effectively address chemical contaminants in the water (Khan & Patel, 2021).

Residual Chemicals and pH

The presence of residual chemicals and pH changes were monitored for both chemical treatments (chlorine and iodine):

- Chlorine Treatment: The chlorine-treated water exhibited a residual chlorine concentration of 0.2 mg/L, which is within the recommended safe limits for drinking water. However, chlorine's residual effects were noted to alter the taste of the water, as observed in the sensory evaluation (Smith & Johnson, 2021).

- Iodine Treatment: The iodine-treated water showed a residual iodine concentration of 0.5 mg/L, which is above the recommended safety threshold for long-term consumption. The taste of iodine-treated water was also significantly altered, making it less palatable for regular use (Williams & Harris, 2022).
- pH: The pH levels of the water were largely unaffected by boiling and filtration. However, both chlorine and iodine treatments caused slight reductions in pH, making the water more acidic. The pH of chlorine-treated water was 6.8, and the pH of iodine-treated water was 6.5, which are still within safe drinking water limits but indicate slight acidity.

Discussion

The results of this study provide valuable insights into the effectiveness of different household water purification methods from a chemical perspective. By comparing boiling, filtration, and chemical treatments (chlorine and iodine), the study sheds light on their strengths and limitations in addressing various water quality concerns, including microbial contamination, heavy metals, organic pollutants, and the presence of residual chemicals.

Effectiveness in Microbial Contamination Removal

The boiling method emerged as the most effective for microbial contamination removal. This is consistent with the established literature, which supports boiling as a highly reliable and affordable method for killing pathogens (Smith & Johnson, 2021). The near-total elimination of bacteria achieved through boiling (99.9%) underscores its importance, particularly in areas lacking access to advanced water treatment technologies. However, while boiling excels in sterilizing water, it does not address chemical contamination, as seen in this study's limited impact on heavy metals and organic pollutants.

In contrast, both chlorine and iodine treatments demonstrated strong microbial removal efficacy (98% and 99.5%, respectively). These results align with earlier research indicating that chlorine and iodine are effective disinfectants (Khan & Patel, 2021). However, both treatments left residual chemicals in the water, which could be a concern for long-term health effects, especially for iodine, which exceeded the safe consumption limit in some cases. Residual chlorine, while within safe limits, still affected the water's taste, making it less desirable for regular consumption

Activated carbon filtration was found to be moderately effective in reducing bacterial contamination (85-90%). This result is lower than that of boiling and chemical treatments, which reflects the nature of activated carbon as a filtration method. Although activated carbon is well-known for removing chlorine, pesticides, and some organic contaminants, it is less effective in eliminating bacteria, particularly in households that experience significant microbial contamination (Jones & Williams, 2023).

Removal of Chemical Contaminants

The filtration method, particularly activated carbon filters, was somewhat successful in removing lead but less effective in removing arsenic and organic contaminants. The 40-50% reduction in lead levels is significant, considering that lead is a common and hazardous contaminant found in tap water, particularly in areas with aging infrastructure. However, the method's limited success in removing arsenic and pesticides suggests that activated carbon may not be an all-encompassing solution for chemical contamination. This limitation is in line with previous findings that activated carbon is more efficient in removing larger organic molecules and chlorine but has limited effectiveness against smaller, more soluble metals like arsenic (Davis & Lee, 2019).

On the other hand, boiling had negligible effects on chemical contaminants, which confirms earlier findings that thermal methods are not effective for removing dissolved substances like heavy metals and organic pollutants (Davis & Lee, 2019). The failure of boiling to address chemical contamination emphasizes the need for combined approaches in areas where both microbial and chemical pollution are concerns.

Chemical treatments (chlorine and iodine) also showed negligible removal of heavy metals and organic pollutants. These findings align with the general understanding that while chlorine and iodine are excellent for disinfection, they do not target chemical contaminants. As a result, households using chemical treatments for microbial disinfection might still be at risk from chemical pollutants that are not addressed by these methods (Khan & Patel, 2021).

Residue and Taste Considerations

One of the critical concerns with chlorine and iodine treatments is the presence of residual chemicals in the water. The residual chlorine concentration in the treated water was within safe drinking water standards, but the taste of the water was noticeably altered. This finding suggests that while chlorine disinfection is effective, it might not be the most palatable option for regular use, particularly in regions where the taste of chlorine-treated water is often reported as unpleasant (Williams & Harris, 2022).

Similarly, iodine treatment left detectable iodine residuals, which exceeded the recommended limits for long-term consumption. The potential for iodine toxicity, especially with prolonged use, is a significant drawback of iodine-based treatments, as highlighted in the literature (Khan & Patel, 2021). This raises concerns about the sustainability of iodine use in households for extended periods, especially for vulnerable populations such as children and pregnant women.

Conclusions and Practical Implications

The results of this study indicate that boiling remains the most effective and safest household water purification method in terms of microbial contamination. However, it does not address chemical pollutants, which limits its overall water quality improvement. Filtration with activated carbon provides a balanced solution for households seeking to remove both bacteria and some chemical contaminants, but its performance varies depending on the nature and concentration of contaminants. Chemical treatments like chlorine and iodine offer effective microbial disinfection, but they introduce residual chemicals that may have long-term health implications, particularly for iodine.

From a practical standpoint, households facing microbial contamination should prioritize boiling for its unparalleled effectiveness in sterilizing water. Those dealing with chemical pollutants may need to combine filtration with other methods or consider alternative treatments. Furthermore, while chlorine and iodine treatments are widely accessible and cost-effective, users should be cautious about residual chemicals and ensure that they do not exceed recommended safe levels.

Conclusion

This study concludes that while no single purification method is ideal for all types of contaminants, chemical treatments offer the most thorough solution for bacterial removal. However, filtration methods and boiling are still valuable for specific contaminants and are more accessible for households in low-resource settings. Future innovations in purification technology should focus on enhancing the effectiveness and sustainability of household water purification systems.

Future Research

Future research should focus on improving the efficiency of household filtration systems to remove a broader range of contaminants, particularly heavy metals. Further studies are also needed to evaluate the long-term health effects of residual chemicals from purification processes.

Acknowledgment

We would like to acknowledge the support of our respective institutions and laboratories for providing the resources necessary to conduct this study. Special thanks to the research assistants who helped with the experimental procedures.

Disclosure of Interest

The authors declare no conflict of interest.

Funding Information

This research was carried out without any financial support from funding agencies, institutions, or commercial organizations. The authors confirm that the study was conducted using personal or institutional resources, and no specific grant or project funding was received from public, private, or non-profit sectors during this research and its publication process.

References

Brown, L., & Green, P. (2020). Effectiveness of boiling in water purification. Journal of Water Chemistry, 45(3), 112-120. https://doi.org/10.1016/j.jwc.2020.02.010

Davis, M., & Lee, S. (2019). Efficiency of activated carbon filters in household water treatment. Environmental Science & Technology, 53(4), 87-93. https://doi.org/10.1021/est.9b05201

Jones, R., & Williams, T. (2023). A comparative study of household water purification methods. Water Research, 92(2), 143-150. https://doi.org/10.1016/j.watres.2023.01.012

Khan, A., & Patel, R. (2021). Chemical treatments for water purification: A review of methods and efficacy. Journal of Environmental Chemistry, 58(7), 670-680. https://doi.org/10.1002/jec.3321

Lee, H., & Chen, M. (2020). Boiling as a purification method: A scientific review. Water and Sanitation, 12(4), 201-208. https://doi.org/10.1080/0964562020.03.008

Smith, J., & Johnson, E. (2021). Water purification methods in households: A chemical analysis. Journal of Applied Chemistry, 67(5), 90-95. https://doi.org/10.1016/j.apchem.2021.02.002

Williams, D., & Harris, G. (2022). The impact of chlorine-based treatments on household water. Journal of Environmental Health, 56(3), 334-342. https://doi.org/10.1002/jeh.3210

Zhao, L., & Wang, L. (2021). Nanomaterials in water filtration: A review of their applications and sustainability considerations. Environmental Science: Nano, 8(4), 1021-1034. https://doi.org/10.1039/d0en01352e

Appendix

This appendix provides additional context regarding the household water purification methods investigated in this study. It includes further details about the chemical treatments, filtration processes, and their respective effects on water quality. The observations made during the experiments are summarized here to complement the results presented in the paper, offering a better understanding of the experimental setup and the effectiveness of each method under varying conditions. No raw data tables or detailed calculations are included, as the focus is on the overall comparative analysis of the purification techniques.Open

Access Statement