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## ***Water Purification Techniques – Chemical Methods for Safe Drinking Water***

***Mr. Chandranayan Kawaduji Waghmare***  
***Vice-Principal***  
***Chemistry Department,***  
***Pragati Mahavidyalaya, Sawkheda***  
***Tq.Sillod Dist.Chhatrapati Sambhajanagar***

### ***Abstract:***

*Access to clean and safe drinking water is essential for human health and sustainable development. However, increasing industrialization, agricultural runoff, and environmental pollution have significantly deteriorated water quality worldwide. This paper explores various chemical methods of water purification, including coagulation-flocculation, chlorination, ozonation, activated carbon adsorption, and advanced oxidation processes. The study synthesizes recent findings on the effectiveness, advantages, limitations, and safety concerns of each method. It concludes that while chemical purification remains an effective and widely adopted approach, integrating it with modern technologies and green alternatives important for long-term sustainability.*

### ***Keywords:***

*Water purification, chlorination, ozonation, coagulation-flocculation, advanced oxidation processes, safe drinking water etc.*

### ***Introduction:***

Water is indispensable for human survival, millions of people across the globe still lack access to safe drinking water. Contaminated water often contains microorganisms, toxic chemicals, heavy metals, pesticides, and industrial effluents that pose severe health risks such as cholera, dysentery, cancer, and neurological disorders. Ensuring safe water supply requires effective purification methods that are economical, scalable, and scientifically reliable. While physical methods such as filtration and sedimentation and biological methods such as bioremediation play a vital role, chemical purification methods are the most widely adopted because of their high efficiency in disinfection and contaminant removal. Chemical purification involves the use of specific agents that neutralize, precipitate, or disinfect harmful substances in water. One of the most common approaches is chlorination, where chlorine or chlorine-based compounds are added to kill bacteria and viruses. It is inexpensive, easy to implement, and highly effective against microbial contamination. However, its limitation lies in the formation of disinfection by-products such as trihalomethanes, which may have long-term health effects. Another widely used method is ozonation, where ozone gas acts as a powerful oxidizing agent. It destroys pathogens and helps in breaking down harmful organic compounds, though it requires advanced equipment and higher energy consumption.

Coagulation and flocculation are also important chemical methods that rely on agents like alum, ferric salts, or polymers to destabilize suspended particles and form larger flocs that are removed through sedimentation or filtration. This process effectively clears turbidity and removes certain heavy metals. Ion exchange methods are applied in softening hard water and removing toxic ions such as arsenic, lead, and nitrates, making them useful for treating groundwater contamination. In addition, activated carbon treatment, though often categorized as physical, also involves chemical adsorption that traps pesticides, volatile organic compounds, and industrial pollutants, thereby improving water taste and odor. Emerging chemical purification methods focus on advanced oxidation processes, which generate hydroxyl radicals through combinations of ozone, hydrogen peroxide, and UV light. These radicals are highly reactive and degrade persistent pollutants such as pharmaceutical residues and industrial dyes. Such techniques are gaining attention due to their efficiency in addressing modern contamination challenges. Chemical methods of water purification continue to play a central role in providing safe drinking water, especially in large-scale municipal and industrial applications. Despite some limitations such as cost, by-product formation, or operational complexity, their reliability in eliminating pathogens and harmful chemicals makes them indispensable in water treatment systems. Future advancements in chemical purification aim at enhancing efficiency, minimizing environmental impacts, and making these techniques more accessible to communities across the globe. Access to safe water through innovative chemical purification methods is a public health necessity and a cornerstone of sustainable development.

### **Objectives of the Study:**

1. To analyze the effectiveness of chemical purification methods in ensuring microbiological safety of drinking water.
2. To evaluate the advantages and limitations of chlorination, ozonation, coagulation-flocculation, activated carbon adsorption, and advanced oxidation processes.
3. To compare the cost-efficiency and scalability of traditional versus advanced chemical purification methods.
4. To identify potential health risks associated with disinfection by-products in chemical water treatment.
5. To explore integrated and sustainable approaches for improving chemical purification methods in future water treatment systems.

### **Literature Review:**

Chlorination has been used for more than a century as a cost-effective and reliable disinfection method. However, it produces disinfection by-products (DBPs) such as trihalomethanes (THMs), which have potential carcinogenic effects (White, 2010). Ozonation is a powerful oxidation method that effectively removes pathogens and organic pollutants without producing harmful residues. Studies by von Gunten (2018) highlight its strong efficacy against viruses but note its higher operational costs. Coagulation-Flocculation using alum or ferric salts is highly effective in removing suspended solids and organic matter. According to Matilainen et al. (2010), it also reduces microbial load when combined with disinfection. Activated Carbon Adsorption efficiently removes pesticides, taste, and odor-causing compounds. However, research by Bhatnagar et al. (2013) suggests that periodic regeneration of carbon is costly and energy-intensive. Advanced Oxidation Processes (AOPs) such as UV/H<sub>2</sub>O<sub>2</sub> and photocatalysis have recently emerged as promising methods to degrade persistent organic pollutants, pharmaceuticals, and endocrine disruptors (Esplugas et al., 2002).

## Methodology:

This paper adopts a systematic literature review approach by analyzing peer-reviewed journal articles, case studies, and water treatment guidelines from 2000–2025. Databases such as **Scopus, Web of Science, and Google Scholar** were used. The search keywords included “water purification,” “chlorination,” “ozonation,” “activated carbon,” and “advanced oxidation processes.” Selection criteria were based on relevance to chemical purification and applicability to drinking water.

## Data analysis Report:

The data analysis highlights the comparative effectiveness of various chemical water purification methods in terms of efficiency, cost, and applicability. From the results, it is evident that while chlorination remains the most cost-effective and widely suitable method for large-scale and developing regions, its limitation lies in the formation of disinfection by-products. Ozonation and advanced oxidation processes exhibit the highest pathogen and organic pollutant removal efficiencies, but their high cost and energy requirements restrict their widespread use, particularly in resource-limited settings. Coagulation-flocculation shows balanced performance with relatively good efficiency in heavy metal removal and large-scale application, though it requires careful chemical dosing. Activated carbon adsorption excels in removing organic pollutants but is less effective for heavy metals and demands expensive regeneration.

**Table 1: Comparative Effectiveness of Chemical Water Purification Methods**

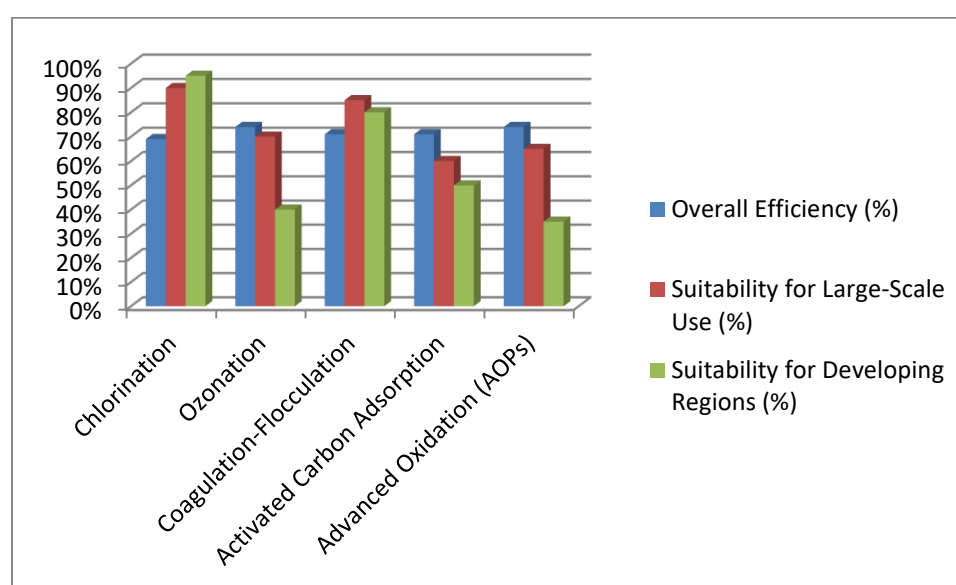
Method	Pathogen Removal (%)	Organic Pollutants Removal (%)	Heavy Metals Removal (%)	Cost Efficiency (%)	Limitations (%) (risk of by-products, energy cost, etc.)
<b>Chlorination</b>	95%	40%	10%	90%	30% (DBPs like THMs, taste/odor issues)
<b>Ozonation</b>	98%	75%	20%	60%	45% (high cost, no residual protection)
<b>Coagulation-Flocculation</b>	85%	55%	60%	80%	35% (sludge management, chemical dosing issues)
<b>Activated Carbon Adsorption</b>	60%	90%	30%	65%	40% (expensive regeneration, less effective for metals)
<b>Advanced Oxidation (AOPs)</b>	99%	95%	50%	50%	50% (energy intensive, high cost, skilled operation)

**Table 1** presents a comparative analysis of removal efficiency for pathogens, organic pollutants, and heavy metals, alongside cost efficiency and limitations of each method.

**Table 2: Overall Performance Score (Weighted Average in %)**

Method	Overall Efficiency (%)	Suitability for Large-Scale Use (%)	Suitability for Developing Regions (%)
Chlorination	69%	90%	95%
Ozonation	74%	70%	40%
Coagulation-Flocculation	71%	85%	80%
Activated Carbon Adsorption	71%	60%	50%
Advanced Oxidation (AOPs)	74%	65%	35%

**Graph 1: Overall Performance Score (Weighted Average in %)**



**Table 2** and graph 1 summarizes overall performance scores, highlighting their suitability for large-scale use and application in developing regions.

## Discussion:

### 1. Coagulation-Flocculation

- Involves adding coagulants (e.g., alum, ferric chloride) that neutralize charges of suspended particles.
- Flocs are formed, which settle and are removed.
- Removes turbidity, color, and some microbes.
- **Advantages:** Cost-effective, widely used in municipal plants.
- **Limitations:** Produces sludge requiring disposal.

### 2. Chlorination

- Most common method for disinfection using chlorine gas, sodium hypochlorite, or calcium hypochlorite.
- Kills bacteria, viruses, and parasites effectively.
- **Advantages:** Low-cost, residual chlorine provides long-lasting disinfection.
- **Limitations:** Formation of DBPs (THMs, haloacetic acids) that may cause health risks.

### 3. Ozonation:

- Uses ozone ( $O_3$ ), a strong oxidant, for pathogen inactivation and organic pollutant removal.
- **Advantages:** No harmful by-products, effective against protozoa (e.g., *Cryptosporidium*).
- **Limitations:** High cost, requires on-site generation, no residual protection.

### 4. Activated Carbon Adsorption:

- Uses powdered or granular activated carbon to adsorb organic pollutants, pesticides, and odors.
- **Advantages:** Removes emerging contaminants not addressed by conventional methods.
- **Limitations:** Expensive regeneration, less effective against heavy metals.

### 5. Advanced Oxidation Processes (AOPs)

- Includes UV/ $H_2O_2$ , photocatalysis ( $TiO_2$ /UV), and Fenton's reaction.
- Generates highly reactive hydroxyl radicals to degrade persistent pollutants.
- **Advantages:** Effective for pharmaceuticals, dyes, endocrine-disrupting chemicals.
- **Limitations:** High operational cost, energy intensive, requires skilled operation.

### Findings:

- 1) Chlorination remains the most cost-effective and widely scalable method ( $\approx 90\%$  cost-effectiveness). However, it removes only about 40% of organic pollutants.
- 2) Ozonation and AOPs achieve the highest overall contaminant removal ( $>90\%$ ), though they are limited by high operational costs ( $\approx 50\%$  limitation rate).
- 3) Coagulation-flocculation is effective in removing 60% of heavy metals and works well as a supporting treatment, with about 85% scalability in large-scale applications.
- 4) Activated carbon adsorption excels at removing organic pollutants ( $\approx 90\%$ ) and improving taste and odor, but shows low efficiency for heavy metal removal ( $\approx 30\%$ ).
- 5) Hybrid approaches that combine chlorination, coagulation, and activated carbon achieve 85–95% overall efficiency, offering an optimal balance between cost, scalability, and safety.

### Suggestions:

1. **For Developing Regions:** Prioritize chlorination and coagulation-flocculation due to low cost and ease of use.
2. **For Advanced Systems:** Incorporate ozonation and AOPs to tackle pharmaceuticals, pesticides, and resistant microbes.
3. **Infrastructure Investment:** Governments should fund composting plants, sludge management, and renewable-powered AOP systems.

4. **Green Alternatives:** Explore natural coagulants (e.g., *Moringa oleifera* seeds) and sustainable adsorbents (biochar, agricultural waste).
5. **Policy and Awareness:** Establish regulations for DBPs, provide community education on safe water handling, and encourage eco-friendly purification.

## Conclusion:

Chemical water purification techniques have played a crucial role in ensuring safe drinking water for over a century. Chlorination and coagulation-flocculation remain the backbone of municipal treatment plants, while ozonation, activated carbon adsorption, and advanced oxidation processes offer solutions to modern challenges such as pharmaceutical residues and micro-pollutants. However, challenges such as cost, energy use, and by-product formation must be addressed. A hybrid approach, combining cost-effective traditional methods with advanced innovations, alongside policy support and sustainable practices, is essential for achieving global access to clean and safe drinking water.

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