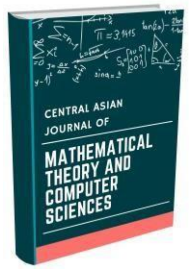

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Article

Environmental Applications of Cold Atmospheric Plasma: Wastewater Treatment, Pollutant Degradation, and Air Purification

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Abstract: Urbanization, agricultural practices and industrial waste have contributed to all environmental pollution, which has become a great concern worldwide, especially when it comes to this air quality aggravated, waste water pollution and constant organic pollutants. Traditional therapeutic techniques, including absorption, ozonation and chlorination, are often associated with high energy costs, inadequate environmental toxins and the production of dangerous underpaths. Given this, cold atmospheric plasma (CAP) has gained popularity in the form of a non-thermal, adaptable and durable technology that can produce a variety of reactive oxygen and nitrogen species (RON) for effective processing. With air purification, wastewater treatment and use of the use in frequent pollutants, this article provides a complete summary of CAP's environmental applications. Advanced oxidation procedures driven by reactive species with short and expanded half -life include the discussion of underlying plasma macology that removes contaminants. In addition, the recent CAP integration is emphasized with hybrid systems as a means of improving efficiency and reducing energy consumption in CAP integration. Relevant problems are strictly investigated, such as security problems, economic viability and scalability. Lastly, future prospects regarding CAP's potential as a game-changing instrument for environmentally sustainable management are discussed.

Keywords: Cold Atmospheric Plasma (CAP), Environmental Remediation, Wastewater Treatment, Advanced Oxidation Processes (AOPs), Pollutant Degradation, Air Purification, Plasma–Catalysis, Sustainable Technology

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1. Introduction

Twenty -sadi is one of the most important issues around the world is environmental pollution, threatening human health, ecosystem and permanent growth. Aquatic systems are constantly exposed to industrial waste, pesticides, medicines, colors and heavy metals, and air quality deteriorates due to increasing urbanization and industry [1]. Chlorination, ozonation and active carved orients are examples of traditional treatment techniques that have been widely used to reduce pollution. These methods often have deficiencies, including high operating costs, falls with insufficient pollution and dangerous for secondary pollution [2.3] under products. Advanced oxidation procedures (AOPS), designed to produce a very reactive hydroxyl radical (• OH), which can create minerals for organic contaminants in spontaneous sub -products such as COA and HAO [4] for organic contaminants. Despite the ability of methods such as phenton oxidation and photo matts, their widespread use is still forced by expenses and operating difficulties. In this connection, cold atmospheric plasma (CAP) has become a flexible and environmentally friendly pollution management method. Partly ionized by an external electric field produces a gas plasma, sometimes known as the fourth location of the fabric, which is a rich mixture of charged particles, UV photons and short and long live reactive oxygen and nitrogen species (ROS and RN) [5].CAP is a possible method of environmental treatment because these reactive species have an extraordinary ability to oxidize inorganic contaminants, degrade organic compounds and neutralize microorganisms [6.7]. This review aims to fully summarize the environmental use of the hood, with emphasis on how it cures waste water, degrades contaminants, and cleans the air. Contaminated removal will all be covered by the original plasma tremema, new development in hybrid plasma systems, and the main obstacles and opportunities for the future.

1.1 Plasma Chemistry in Environmental Systems

Complex chemistry of cold atmospheric plasma (CAP), which produces a wide range of short and long -lasting reactive species in both gaseous and liquid stages, is largely responsible for its efficiency in environmental cleaning. By introducing sophisticated oxidation and reducing processes, these species are constantly destroying organic pollutants, disabling microorganisms and oxidizing inorganic pollutants. The basic understanding of this chemistry is necessary to optimize plasma systems for air purification and treatment of wastewater.

1.1.1 Generation of Reactive Oxygen and Nitrogen Species

Events with stimulation, ionization and separation occur from the transfer of energy from electrons to neutral gas molecules under plasma part. A Wide Range of Caps Reactive Oxygen Species (ROS), Such AS Ozone (O_3), Hydroxyl Radicals (• OH), Singlet Oxygen ($_2$sy ($_2$), and hydrogen peroxide (H_2O_2), as well as reactive nitrogen species (not, not, note, note, note, note, note, note, note, note, note, note, note, note, not, note, Nitrogen (NO), Notrogenide (NO), Notrogenide (NO), Notrogenide (NO) (NO) (NO) (NO), Notrogenide (NO) (NO), Notrogenide (NO), Notrogenide (NO) (NO_3^-) (NO_3^-), Working Gas (wind, oxygen, or mixed). These species have complementary functions: RNS helps with nitration and acid processes in the liquid environment, while praise is largely responsible for oxidative violations of organic molecules.

1.1.2 Advanced Oxidation Processes (AOPs)

One of the most important chemical mechanisms in plasma-assisted environmental treatment is the generation of hydroxyl radicals (•OH), which possess a redox potential of 2.8 V—one of the highest among oxidants [10]. Hydroxyl radicals can non-selectively attack organic molecules, breaking chemical bonds and leading to their mineralization into carbon dioxide and water. In aqueous systems, plasma–liquid interactions promote the continuous generation of •OH radicals, H_2O_2, and peroxynitrite ($ONOO^-$), which together form a powerful oxidative environment [11].

1.1.3 Degradation of Organic Pollutants Persistent

Organic pollutants such as dyes, pharmaceuticals, and pesticides often resist conventional treatment methods due to their complex molecular structures. Plasma-generated ROS and RNS attack these molecules through electron transfer, hydrogen abstraction, and bond cleavage pathways, leading to fragmentation and eventual mineralization [12]. For example, azo dyes undergo cleavage of their –N=N– bonds, while antibiotics such as tetracycline are degraded into smaller, less toxic intermediates [13]. Compared to traditional oxidants like chlorine, CAP achieves more complete degradation with reduced risk of forming harmful chlorinated by-products.

1.1.4 Inactivation of Microorganisms In addition to chemical degradation,

CAP is highly effective in inactivating microorganisms present in wastewater and air. Reactive species penetrate microbial membranes, induce oxidative stress, and damage nucleic acids and proteins [14]. Plasma also produces UV photons and shockwaves that contribute to microbial decontamination. Importantly, CAP inactivates antibiotic-resistant bacteria and biofilms more effectively than many conventional disinfection processes, making it a valuable alternative for modern sanitation challenges [15].

1.1.5 Role of Plasma–Liquid Interactions

When plasma interacts directly with liquid water, unique plasma–liquid interfacial processes occur. Short-lived species (•OH, O_2^-) generated at the interface rapidly react, while longer-lived species such as H_2O_2, NO_2^-, and NO_3^- diffuse into the bulk liquid and maintain residual antimicrobial and oxidative effects [16]. This dual chemistry—surface-localized fast reactions and bulk-phase sustained activity—provides CAP-treated water with extended remediation capabilities even after treatment has ceased.

2. Plasma for Wastewater Treatment

Wastewater from industrial, agricultural, and municipal sources contains a complex mixture of contaminants, including dyes, pharmaceuticals, pesticides, heavy metals, and microbial pathogens. These pollutants are often resistant to conventional treatment methods and may accumulate in aquatic systems, posing long-term risks to ecosystems and human health. Cold atmospheric plasma (CAP) has gained attention as a versatile and effective approach for wastewater treatment due to its ability to generate reactive species capable of degrading organic molecules, oxidizing inorganic compounds, and inactivating microorganisms simultaneously.

2.1 Removal of Industrial Dyes

Synthetic dyes, especially azo dyes widely used in the textile industry, are among the most persistent and toxic pollutants in wastewater. CAP has demonstrated strong degradation capabilities through cleavage of azo bonds (–N=N–) and breakdown of aromatic rings [17]. Plasma-generated hydroxyl radicals (•OH) and ozone (O_3) attack dye molecules, leading to decolorization and mineralization into less harmful end products such as CO_2 and H_2O. Studies have reported decolorization efficiencies exceeding 90% within short treatment times, highlighting CAP as a competitive alternative to ozonation and photocatalysis [18].

2.2 Degradation of Pharmaceuticals and Personal Care Products

Pharmaceuticals and personal care products (PPCPs) are emerging contaminants that often resist biodegradation and persist in the aquatic environment. Antibiotics such as tetracycline, ciprofloxacin, and sulfamethoxazole have been successfully degraded using CAP, with hydroxyl radicals and peroxynitrite acting as the primary oxidants [19]. Importantly, plasma treatment not only reduces parent compound concentrations but also transforms toxic intermediates into less harmful products. In several cases, toxicity assays with aquatic organisms showed significantly lower toxicity of plasma-treated effluents compared to untreated samples [20].

2.3 Removal of Pesticides and Agrochemicals

Agricultural runoff introduces a wide range of pesticides and herbicides into water bodies, many of which are persistent organic pollutants. CAP treatment has been reported to efficiently degrade organophosphates, chlorinated pesticides, and carbamates [21]. For example, plasma-generated •OH radicals rapidly break down organophosphate esters, reducing their neurotoxic potential. Unlike conventional chlorination, plasma does not introduce secondary chlorinated by-products, making it a safer alternative for agricultural wastewater treatment.

2.4 Microbial Inactivation in Wastewater

Wastewater often harbors pathogenic microorganisms, including bacteria, viruses, and protozoa. CAP treatment provides effective microbial inactivation by combining oxidative damage with UV radiation and electric fields [22]. Unlike chemical disinfectants such as chlorine, CAP can disrupt biofilms and inactivate antibiotic-resistant bacteria, which are increasingly prevalent in hospital and municipal wastewater [23]. Additionally, plasma-treated water retains residual antimicrobial activity due to the presence of long-lived species such as H_2O_2 and NO_3^-, extending its disinfecting effect beyond immediate treatment.

2.5 Heavy Metal Oxidation and Precipitation

Although CAP is primarily recognized for organic pollutant degradation, it also affects inorganic contaminants. Plasma-generated radicals can oxidize certain heavy metals (e.g., Fe^{2+} to Fe^{3+}, As^{3+} to As^{5+}), facilitating their removal through precipitation or adsorption [24]. This ability to combine organic degradation with inorganic remediation makes CAP uniquely suited for complex wastewater streams.

2.6 Comparison with Conventional Methods

CAP has a number of benefits over conventional wastewater treatment methods including UV disinfection, ozonation, and chlorination. It prevents the production of persistent byproducts, speeds up rates of degradation, and doesn't require extra chemicals. Moreover, plasma systems may be included as pre-treatment or polishing stages into already-existing treatment facilities, boosting overall effectiveness [25]. For industrial use, energy efficiency and scale-up are still problems that need to be solved.

3. Plasma for Air Purification

Air pollution, arising from industrial emissions, vehicular exhaust, and indoor contaminants, is a major environmental and health concern worldwide. Pollutants such as nitrogen oxides (NO_x), sulfur oxides (SO_x), volatile organic compounds (VOCs), and airborne microorganisms contribute to respiratory diseases, climate change, and ecological degradation. Traditional air purification methods, such as adsorption, filtration, and catalytic converters, are sometimes constrained by high operating costs, frequent regeneration requirements, or inadequate elimination. By creating a reactive environment that may oxidize gaseous contaminants and inactivate airborne pathogens in ambient settings, cold atmospheric plasma (CAP) offers a possible substitute.

3.1 Removal of Nitrogen Oxides (NO_x) and Sulfur Oxides (SO_x)

Among the most dangerous air pollutants are nitrogen oxides (NO and NO_2), which cause respiratory ailments, acid rain, and smog production. Through plasma-induced oxidation, CAP efficiently transforms NO into NO_2 and then generates nitric acid (HNO_3) or nitrates [26]. In a similar manner, sulfur dioxide (SO_2) may be converted into sulfates or sulfuric acid (H_2SO_4), which are easier to neutralize or trap [27]. With the extra advantage of working at lower temperatures, these reactions show that CAP has the potential to be a clean substitute for traditional flue-gas desulfurization and denitrification systems.

3.2 Degradation of Volatile Organic Compounds (VOCs)

Benzene, toluene, formaldehyde, and acetaldehyde are examples of volatile organic compounds (VOCs) that are a major source of air pollution both inside and outdoors. VOCs are oxidized into smaller, less dangerous molecules like CO_2 and H_2O by CAP, which also produces ozone, excited oxygen species, and hydroxyl radicals [28]. Plasma can effectively break down volatile organic compounds (VOCs) at room temperature, which makes it appropriate for interior air filtration in contrast to catalytic systems that need high temperatures. One drawback, though, is the potential for the production of intermediate byproducts such organic acids or aldehydes, which calls for catalytic system coupling or optimization [29].

3.3 Inactivation of Airborne Microorganisms

In healthcare institutions, public transit, and food processing facilities, airborne transmission of germs, viruses, and fungus presents significant dangers. By rupturing microbial membranes, destroying nucleic acids, and deactivating bioaerosols, CAP has shown potent antibacterial properties [30]. Studies have demonstrated that plasma may render Staphylococcus aureus, influenza viruses, and even SARS-CoV-2 surrogates in air streams inactive [31]. This demonstrates how plasma-based disinfection systems may enhance air quality, especially in high-risk indoor settings.

3.4 Hybrid Plasma–Catalyst Systems

To improve efficiency and minimize the formation of undesired by-products, CAP is often combined with catalysts, creating plasma–catalyst hybrid systems. For example, coupling plasma with TiO_2, MnO_2, or zeolite catalysts enhances VOC mineralization while reducing secondary pollutants [32]. Plasma generates reactive intermediates that activate the catalyst surface, leading to synergistic effects beyond those achievable by either plasma or catalysis alone. This hybrid approach has been successfully tested for both industrial flue-gas cleaning and indoor air purification [33].

3.5 Energy Efficiency and Practical Applications

Although CAP is highly effective, its energy efficiency remains a concern for large-scale air purification. Research is currently focused on optimizing reactor designs (e.g., dielectric barrier discharges, packed-bed reactors) and minimizing power consumption [34]. Pilot-scale plasma systems have already been tested in factories, hospitals, and office spaces, demonstrating practical feasibility. With further improvements in energy utilization and integration with renewable energy sources, plasma-based air purification could become a mainstream solution for both industrial and domestic applications.

4. Combined and Hybrid Plasma Systems

Although cold atmospheric plasma (CAP) has shown strong potential for environmental remediation, its standalone application is sometimes limited by energy efficiency, incomplete mineralization of pollutants, or the formation of intermediate by-products. To address these issues, researchers have increasingly focused on hybrid systems that combine plasma with complementary technologies such as photocatalysis, ozonation, and membrane filtration. These synergistic approaches enhance pollutant degradation, reduce energy demand, and minimize secondary pollution.

4.1 Plasma–Photocatalysis

The combination of CAP with semiconductor photocatalysts, most notably titanium dioxide (TiO_2), has received significant attention. Plasma generates UV photons and reactive species that activate the photocatalyst surface, promoting the generation of electron–hole pairs and additional hydroxyl radicals [35]. This results in enhanced mineralization of volatile organic compounds (VOCs), dyes, and pharmaceuticals compared to plasma or photocatalysis alone. For instance, CAP–TiO_2 systems have been reported to achieve nearly complete VOC removal at lower energy costs while reducing the formation of aldehyde by-products [36]. Other photocatalysts, such as ZnO and g-C_3N_4, have also been successfully integrated with plasma for wastewater and air purification.

4.2 Plasma–Ozonation

Ozone (O_3) is one of the long-lived reactive species generated by plasma discharges, and it can be further enhanced through plasma–ozone hybrid systems. When combined, plasma provides additional radicals (•OH, O_2^-) that accelerate ozone decomposition into highly reactive intermediates [37]. This synergy increases the efficiency of organic pollutant degradation, particularly for pharmaceuticals and pesticides. Plasma–ozonation has also demonstrated improved microbial inactivation in wastewater, outperforming ozonation alone due to the broader spectrum of reactive species [38].

4.3 Plasma–Membrane Filtration

Another promising hybrid approach is the integration of CAP with membrane-based separation systems. Membranes are widely used for desalination and wastewater treatment but are prone to fouling and biofilm formation. Plasma pre-treatment of feed water or plasma modification of membrane surfaces significantly reduces fouling and enhances antimicrobial properties [39]. CAP can also alter membrane surface chemistry, increasing hydrophilicity and permeability. Such hybrid systems extend membrane lifespan while improving pollutant removal efficiency.

4.4 Plasma with Biological Processes

Recent studies have explored combining CAP with biological treatment methods. Plasma pre-treatment breaks down complex organic molecules into smaller intermediates that are more biodegradable, thus improving the performance of downstream biological processes [40]. This combined approach reduces energy requirements by leveraging microbial activity while ensuring more complete pollutant degradation.

5. Conclusion

Especially air purification, polluting decline and wastewater treatment, some of the most important environmental issues in areas with cold atmospheric plasma (CAP) have become a playing technology. Organic pollutants, microorganisms and even some inorganic pollutants can be removed simultaneously because reactive oxygen and nitrogen species (RON), UV photons and a wide range of charged particles have their special ability to produce. Unlike traditional treatment techniques, CAP provides a multi -use method for environmental school, works in ambient settings and requires some chemical input.Understanding the underlying decrease in plasma macology and proving cap's effect against different types of environmental toxins, such as dyes, medicines, pesticides, volatile organic compounds (VOC) and airborne pathogens have upgraded over the last ten years. In addition, the adaptability is shown to plasma -based techniques in the manufacture of hybrid plasma systems, which combine cap with photo night, ozonation or membrane filtration to provide efficiency to increase efficiency, reduce urban preachers and improve energy consumption. There are some obstacles that require legislative permission before scalability, energy efficiency, long -term security evaluation and mass placement that still have to be overcome despite these advances. However, an optimistic future is indicated by the inclusion of plasma technologies in relevant treatment systems, continuous progress in reactor design and the use of renewable energy sources. Making yoga, cap is a creative, adaptable and durable way to restore environmental restoration. Plasma -based technologies are ready to become an important component of future plans to achieve cleaner air and water, which will promote the stability of the global environment with human health and more research, industry investments and regulatory support.

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