Advancing Air Quality Management: A Comprehensive Review of UV Technology, Pyrolysis, and Their Integration

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Abstract

Air pollution is a significant global issue, with pollutants like fine particulate matter (PM2.5), volatile organic compounds (VOCs), nitrogen oxides (NOx), and sulfur oxides (SOx) posing severe health risks. Combining ultraviolet (UV) technologies with pyrolysis has emerged as a promising control strategy, based on a literature review of peer-reviewed journals, industrial documents, and scholarly papers. UV-based technologies like photocatalytic oxidation (PCO), vacuum ultraviolet (VUV), and deep-ultraviolet (deep-UV) use reactive oxygen species (ROS) to break down pollutants. Pyrolysis transforms waste such as plastics, biomass, and medical waste into synthesis gas (syngas) and biochar with less toxic emissions. Integrating UV radiation with pyrolysis forms a hybrid system where photochemical reactions lower activation energies, increase pollutant degradation efficiency, and enable lower-temperature operation. This paper analyzes mechanisms, reactor configurations, and kinetic improvements, along with challenges like residual ozone generation (secondary pollutant), catalytic deactivation, and high energy consumption. Solutions include advanced reactor designs, cost-efficient UV sources, and hybrid catalytic materials. UV-enhanced pyrolysis is a cost-effective, adaptable method for reducing air pollution. Future research should optimize reaction conditions, develop integrated systems for industrial use, and conduct economic feasibility studies.

Keywords: *advanced oxidation processes, industrial air pollution control, reactive oxygen species, UV-assisted pyrolysis*

1. Introduction

Air pollution encompasses a diverse array of substances, including gases such as ozone, nitrogen oxides, sulfur dioxide, carbon monoxide, ammonia and methane, along with particulate matter like soot, lead and biological molecules. Air pollution has become a major global problem. The World Health Organization has estimated that air pollution is responsible for a large number of deaths annually, primarily due to respiratory and cardiovascular diseases (Gongjun & Dongmei, 2024), contributing approximately 7 or 8 million deaths annually and possessing a major risk for various pollution-related illness, including heart disease, stroke, chronic obstructive pulmonary disease (COPD), asthma and lung cancer. Among the six priority pollutants recognized by international air standards is the group of gaseous sulfur oxides (SOx) of which sulfur dioxide (SO_2) is found in much greater concentration. The environment is also affected by high emission of SO_2 mainly through acid rain (Rovira et al., 2022). Organic pollutants primarily consist of Volatile Organic Compounds (VOCs), which includes alkanes, aromatic hydrocarbons, olefins, alcohols, aldehydes, ketones, halogenated hydrocarbons, and various other substances, causing great harm to human health. Most VOCs are generated during the production process, in various industries like pharmaceuticals, printing and petrochemicals, transportation and storage of raw chemicals (Huang et al., 2016).

Atmospheric particulate matter significantly influences climate and precipitation further harming human health beyond direct inhalation. Atmospheric particles include suspended particulate matter, PM_{10} (particles ≤10 µm), $PM_{2.5}$ (particles ≤2.5 µm), ultrafine particles (≤100 nm), and soot (Yao et al., 2018). PM are among the harmful form (other than ultra-fines) of air pollutants, which can penetrate through the blood streams into the lungs and brain which causes various health problems. There is no safe exposure level for particulate matter.

Many studies have been conducted to improve current technologies and find better solutions for air pollution control. The direction is to couple ultraviolet (UV) technology with pyrolysis processes that improve efficiency and efficacy of air pollution control methods. Pyrolysis or thermal destruction allows for converting organic compounds to useful by-products with reduced harmful emissions. Adding UV light to pyrolysis can enhance pollutant destruction and total yield of target products and offer a technologically innovative method of air pollution treatment. Mechanistically, UV-assisted pyrolysis acts by using UV radiation energy to enhance breakdown of complex organic molecules. Research has found that UV irradiation can increase initial C-H bonding cracking and consequently accelerate pyrolysis (Mattonai et al., 2021). For ecologically harmful materials such as plastics, pyrolysis with UV can lead to cleaner fuel and minimize harmful by-product formation (Rajan et al., 2023). Pyrolysis and UV-based methods are used for pollution control and waste management individually, without synergy used. The ability of UV radiation to weaken chemical bonds through advanced oxidation processes by forming reactive oxygen species, when combined with the thermal decomposition capability of pyrolysis at high temperatures can remove more than 90% of pollutants while producing oil, syngas and biochar. UV-assisted pyrolysis promises to be an innovative and efficient solution for existing industrial air pollution problems.

Apart from that, there is limited knowledge on UV light and contaminants interaction during pyrolysis and additional studies are needed to gain clear understanding of these mechanisms (Elder & Beste, 2014). Creation of low-cost and efficient UV sources for large-scale use would also be necessary to enable air pollution control to be effective and low-cost (B. Li et al., 2007). Since cities globally are grappling with air quality issues, adoption of new technologies like UV-assisted pyrolysis can supplement conventional pollution control and enable better public health (Zhao et al., 2014; Nebenzal & Fishbain, 2018; Zong et al., 2020). Greater synergy between academies and researchers on one side and industrial players and policymakers on the other side is necessary to enable this technology to realize its potential to the fullest extent (Héroux et al., 2015; Muller & Mendelsohn, 2009).

2. UV-based Technologies

Ultraviolet radiation (UV) is shorter-wavelength radiation ranging from 10 to 400 nanometers, shorter than visible light and longer than X-rays. UV light, about 10% of the Sun's electromagnetic radiation, is also produced by electric arcs, Cherenkov radiation, and specialized lamps like mercury-vapor, tanning, and black lights. In pollution control, UV analyzers monitor nitrogen oxides, sulfur compounds, mercury, and ammonia emissions, especially in flue gas from fossil-fueled power plants. UV irradiation is used in advanced oxidation processes (AOPs) to break down organic contaminants. UV-C light has wide applications to minimize health risks from airborne pathogens and contaminated surroundings. UV-LED water treatment systems in public areas demonstrate efficacy (Kalate, 2021; Oguma & Rattanakul, 2021).

UV technologies are used in air and water pollution control and surface sanitization. UV-C reduces microbial load in air and on surfaces by damaging nucleic acids and proteins, inhibiting microbial growth (Dogu-Baykut & Gunes, 2019; Kitagawa et al., 2021). UV-based systems are applied in air sanitizers and cleaners for public spaces and health centers to improve indoor air quality (Kalate, 2021; X. Li & Blatchley III, 2023). UV/H_2O_2 shows >90% contaminant destruction efficiency under optimal conditions (W. Li et al., 2011). Effectiveness depends on pH, oxidant dosage, and contaminant nature. UV technology is used in environmental monitoring through photodetectors, which convert UV radiation to electronic signals (P. Li et al., 2024). Advanced detectors enable real-time monitoring (Guo et al., 2018). UV-C is used in agriculture as a chemical-free method to enhance post-harvest quality and inhibit decay in fruits and vegetables (Enaki et al., 2022; Khanna, 2023), inducing health-promoting compounds and spoilage inhibition (Sonntag et al., 2023).

UV disinfection disrupts DNA and RNA, creating pyrimidine dimers that prevent microbial replication (Dogu-Baykut & Gunes, 2019). These mechanisms guide disinfection dosages across air, water, and surfaces (Kitagawa et al., 2021; Storm et al., 2020). A catalytic reaction between titanium dioxide and UV-C oxidizes organic matter, neutralizing pathogens, pollen, and mold spores.

2.1 Photocatalytic Removal of Organic and Inorganic Compounds

Photocatalytic UV-based air pollution control involves multi-electron activation where UV radiation on titanium dioxide forms electron-hole pairs that generate reactive oxygen species (ROS) like hydroxyl radicals and super-oxide ions (Talaiekhozani et al., 2021). These ROS oxidize and destroy diverse air pollutants. UV-C activated titanium dioxide breaks down contaminants into carbon dioxide and water (Rouhani & Taghipour, 2023).

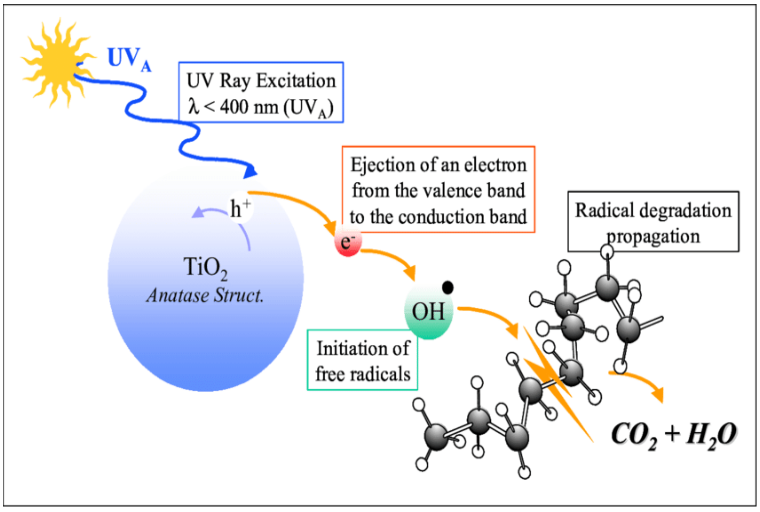

Fig. 1: Schematic diagram of photocatalytic oxidation in presence of UV (Saint-Gobain Isover SA, 2000).

Air quality management must consider inorganic contaminants like CO, SOx, NOx, and H_2S in both indoor and outdoor settings (S. Li, 2024). Photocatalytic oxidation, which uses photo-catalysts activated by solar or UV light, is an effective method for degrading these pollutants. Visible-light-active TiO_2 with oxygen-deficit states can enhance adsorption energy, enabling efficient nitric oxide removal. Similarly, SOx can be oxidized to sulfates and sulfides through reactive oxygen species (Talaiekhozani et al., 2021).

2.2 UV and VUV Irradiation

Ultraviolet (UV) light spans wavelengths from 1–380 nm, divided into five subcategories: UV-A (315–380 nm), UV-B (280–315 nm), UV-C (200–280 nm), vacuum UV (100–200 nm), and extreme UV (1–100 nm). Standard mercury lamps efficiently produce UV-A through UV-C, while vacuum UV requires specialized equipment like xenon excimer lamps due to its strong absorption by ordinary materials (Huang et al., 2016; Lei et al., 2022). VUV light (185 nm) effectively purifies air and water through multiple mechanisms by directly breaking down pollutants and creating powerful oxidants. When interacting with water, VUV generates hydroxyl radicals (•OH), and with oxygen it produces ozone (O_3), while reactive species including atomic oxygen [$O(^1D)$ and $O(^3P)$] work together to destroy contaminants.

The integration of VUV photolysis with ozone-assisted catalytic oxidation enhances pollutant degradation while converting residual ozone into active oxidants. This process, known as VUV-OZCO, improves treatment efficiency and prevents ozone accumulation by utilizing it in catalytic reactions, creating a pollution control cycle through ozone produced during VUV photolysis (Rovira et al., 2022). Although ozone can decompose VOCs, most photocatalysts have limited capability in ozone decomposition, leading to partial utilization and persistent residual ozone. Compared to UV-PCO and VUV, VUV-PCO offers superior VOC degradation performance with fewer byproducts and better stability, though catalytic deactivation still occurs due to organic buildup and water vapor (Huang et al., 2016).

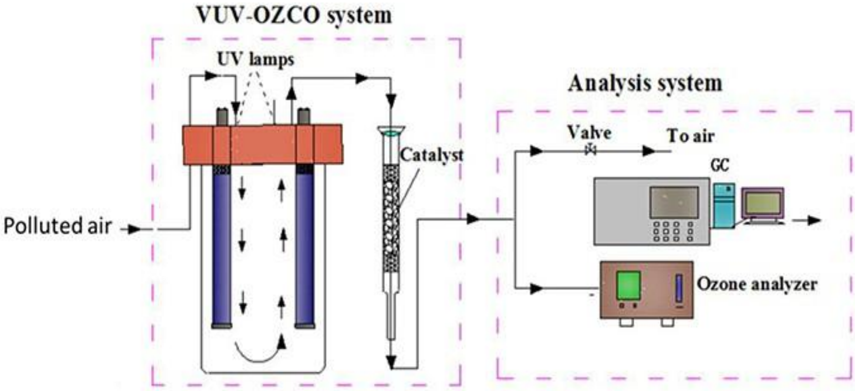

Fig. 2: The schematic diagram of VUV-OZCO system (Huang, 2015).

3. Pyrolysis in Pollution Control

Pyrolysis enables the conversion of methane-rich natural gas into hydrogen and solid carbon, with recent industrial-scale success. It also shows potential for biomass transformation into syngas or biochar, plastic waste upcycling to liquid fuels, and safe waste valorization into inert byproducts. Maximizing the process requires understanding initial decomposition, primary reactions, and charring. Microwave catalytic pyrolysis improves efficiency by overcoming biomass's poor dielectric properties (Ke et al., 2024).

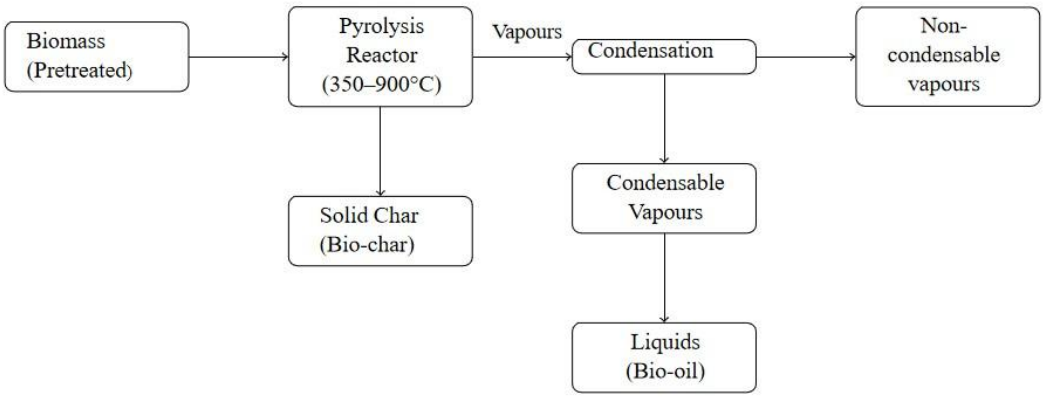

Fig. 3: Typical pyrolysis process in pollution control

3.1 Pyrolysis of Plastic Waste

The process is carried out through several necessary steps: First, different forms of waste plastics are collected and processed, perhaps through shredding for acquiring more consistency. Prepared feed is then fed to a pyrolysis reactor that is made air-free to provide a thermally driven rather than oxidation-based process. External heat is supplied to the reactor, typically ranging between 350 and 900°C, resulting in thermal cracking of complex hydrocarbons contained in plastics. This produces vaporisation and breakdown of plastic polymers with help of the lack of air to repress combustion reactions, yielding oil, syngas, and solid char for different applications (Devi et al., 2021; Hasan et al., 2025).

The pyrolysis products serve distinct sustainable applications: the liquid fraction (bio-oil) functions as a renewable fuel alternative; syngas provides feedstock for chemical production; and the solid char residue demonstrates value in agricultural soil enhancement or specialized industrial uses. If quick pyrolysis is used, formed vapours are quenched instantly to condense oil separated by non-condensable gases. Slow pyrolysis preferentially produces higher yields of solid char, necessitating subsequent separation processes to isolate the desired product. Overall, pyrolysis is a productive method for treatment of rubbish plastic to useful products that avoid environmental problems and help in material recovery through sustainable means (Hasan et al., 2025).

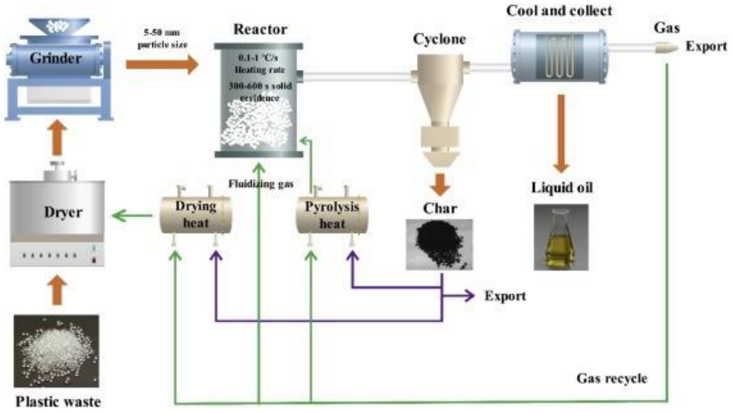

Fig. 4: Pyrolysis of Plastic Waste (Maqsood, 2021)

3.2 Plasma Pyrolysis of Medical Waste

Plasma represents a state of matter where atoms are partially or fully ionized, creating a conductive medium of charged particles and neutral species. Plasma pyrolysis treats hazardous waste using ultra-high temperatures (3000–5000°C) to decompose organic materials into reusable byproducts like syngas and vitrified slag. It outperforms incineration by eliminating toxic emissions and enabling resource recovery, especially for medical waste. Plasma heat safely disposes of municipal, biomedical, and hazardous waste. Medical waste exposed to plasma arc breaks down into CO, H2, and hydrocarbons. The system uses a multi-stage thermal process, with initial combustion producing gases at ~1200°C (Nema & Ganeshprasad, 2002). A rapid quenching mechanism cools gases from 500°C to 70°C, suppressing dioxin formation. The method combines plasma arcs (over 3000°C) with oxygen-deprived conditions for complete molecular dissociation.

Research shows its effectiveness in treating contaminated solid wastes and hazardous organics via thermal decomposition (Nema & Ganeshprasad, 2002). It meets dioxin/furan emission standards, handles mixed waste without sorting, inactivates pathogens, and allows energy recovery through syngas.

Fig. 5: Commercial Plasma Pyrolysis Plant at Gujarat Institute, India (Tribune India, 2020)

3.3 Co-pyrolysis of Biomass

Co-pyrolysis, which involves the simultaneous thermal treatment of two or more feedstocks, has been shown to significantly enhance the quality and yield of pyrolysis oil. Studies demonstrate that this process not only increases oil production but also reduces water content while improving its energy density, making the resulting bio-oil more suitable for fuel applications (Abnisa & Daud, 2014). Additionally, co-pyrolysis offers economic and waste management advantages by lowering processing costs and enabling the valorization of mixed waste streams that would otherwise be difficult to treat.

The process is typically carried out in an oxygen-free, closed reactor at moderate temperatures (400–600°C), with optimal conditions depending on feedstock composition. Prior to pyrolysis, materials are dried (e.g., 105°C for 24 hours) and ground for efficient decomposition. Industrially, drying heat can come from integrated heat recovery systems, improving energy efficiency. Despite benefits, upgrading pyrolysis oil often requires costly steps like catalytic treatment, solvent addition, or hydrogenation, which may outweigh the oil's economic value (Abnisa & Daud, 2014).

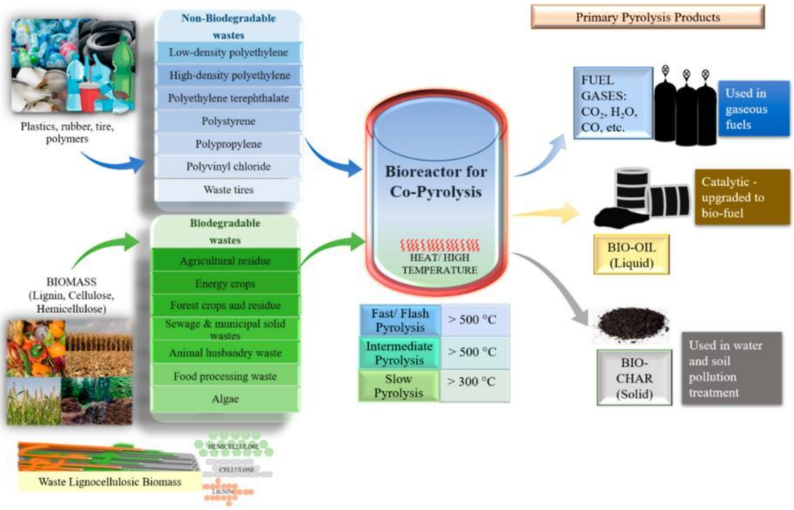

Fig. 6: Mechanism of Co-pyrolysis (Ghai, 2022).

4. UV-assisted Pyrolysis

The hybrid system combining UV photocatalysis with pyrolysis can form a sophisticated system of pollution control that can utilize multiple modes of degradation. UV-induced photo- catalytic reactions generate reactive species that can initiate degradation reactions with lower temperatures compared to traditional thermal reactions alone. UV-created reactive species can destabilize chemical bonds that can become susceptible to thermal breakdown. Further, Pyrolysis temperature has the potential to enhance mass transfer rates and mobility of reactive species and hence efficient pollutant breakdown (Devi et al., 2021; Liu et al., 2019). UV-Pyrolysis has great potential for control of a broad spectrum of air pollutants. Combined action of thermal breakdown and photo-catalytic oxidation can lead to high efficiencies of removal for simple and complex molecules of VOC_s under optimized conditions. Treatment of Nitrogen Oxides (NO_x) and Sulfur Oxides (SO_x) is special. Photocatalytic oxidation leads to oxidation of NO to NO_2 and thermal reactions can convert these compounds to atomic form of nitrogen. Similarly, sul- fur compounds can be subjected to both reprocesses to yield more manageable products (Rovira et al., 2022). Particulates can be reduced by combining mechanical particulate collectors with pyrolysis units. Plasma Pyrolysis with UV radiation has vast potential (Yao et al., 2018)

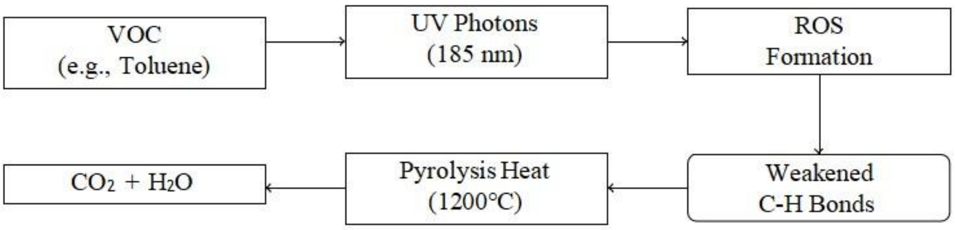

Fig. 7: Theoretical process flow for UV-assisted pyrolysis

Integrating conventional pyrolysis with advanced oxidation processes such as those catalyzed by UV, further improves the process efficiency in pollutant degradation. The synergy between UV-technology and pyrolysis not only facilitates breakdown of pollutants but also results in reduced activation energy requirements with enhanced oxidation rates. UV-assisted pyrolysis promises to be a great technology for effective control of industrial air pollution but with limitations in equipment and energy requirements, formation of some byproducts and lack of large scale implementations.

5. Conclusion

The integration of pyrolysis and UV technologies is a promising air pollution control strategy, enhancing pollutant degradation and process efficiency. Its success depends on large-scale implementation supported by focused research and development. This review explores current UV-based and pyrolysis technologies, their mechanisms, limitations, and combined potential for sustainable air pollution control. As air pollution worsens, innovative solutions like UV pyrolysis are emerging, especially for urban areas. It reduces harmful emissions and complements existing control methods by breaking down complex pollutants into less harmful or useful by-products, while improving waste management efficiency.

Studies show UV pyrolysis effectively removes compounds such as sulfur oxides (SOx), volatile organic compounds (VOCs), and pathogens, making it a strong option for reducing urban air pollution. Recent research also highlights the potential of combining laser-induced breakdown spectroscopy (LIBS) with plastic recycling via pyrolysis at the molecular level (Nabi et al., 2024). Furthermore, secondary organic aerosol (SOA) formation complicates pollutant reactions, reinforcing the need for methods like UV pyrolysis to prevent environmental harm (Ahern et al., 2019). Pairing UV light with ozone reactors boosts efficiency, offering an energy- and eco-friendly alternative to traditional incineration.

However, challenges such as secondary pollutant formation (ozone, NOx), scalability, and UV equipment costs need resolution. Continued research should focus on enhancing efficiency, scalability, and photochemistry to broaden application—from industrial pollution control to municipal air cleaning. Its ability to treat mixed pollutant streams and support sustainable practices positions UV pyrolysis as a viable air quality management solution, with potential for significant environmental improvement and long-term industrial adoption.

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