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Research article

Separation processes for the treatment of industrial flue gases – Effective methods for global industrial air pollution control

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ABSTRACT

The treatment of flue gases has become a crucial area of interest with the increasing air emissions into the atmosphere from industries involved in combustion of fossil fuels in their operations. In essence, there is a critical need for effective methods of treatment more than ever. Treatment and separation are now a demand for the overall industrial operations to control the rate of flue gas emissions. The major culprit in this wise is power generating industry. The major associated air pollutants are carbon dioxide, sulfur oxides, trace metals, volatile organic compounds, particulate matters, and nitrogen oxides. However, the choice of technologies to be utilized requires more than just knowledge of the separation process, but also a good understanding of the properties of the pollutants. This review explored and evaluated the various separation processes and technologies for the treatment of industrial flue gases for the control of the associated air pollutants. It also analyzed the performance with references to cost and efficiency, the advantages and disadvantages, principles for selection, research direction, and/or potential opportunities in existing separation processes and technologies.

1. Introduction

One of the major challenges resulting from industries, involved in the combustion fossils for their operations, is the release of flue gases, into the atmospheric space. Some of the inherent air pollutants in these flue gases, cause global warming and climate change [1]. With the rapid growth of the industrial and economic sectors, pollutants associated with flue gases have continued to threaten the environment and human well-being. Among the pollutants inherent in flue gases from combustion operations in coal-fired powered plants are Sulfur oxides, Nitrogen oxides, particulate matter, and trace heavy metals. Sulfur dioxide and nitric oxides are two gases from which acid rain and photochemical smog are formed [2]. It is important to note that the emission of air pollutants in large amounts is a product of fossil fuel combustion, solid waste, and biomass [3,4]. The emitted pollutants when in contact with each other lead to environmental complications like mist, photochemical smog, and acid rain amongst others. They are not just risky to human health but also to the ecosystems [5]. These pollutants come from diverse sources, including moving sources such as the exhaust of motor vehicles, fixed sources, and marine exhaust i.e. boilers in industries, furnaces with high temperatures, and power plants [6].

Globally, gaseous air pollutants have led to altercation of the planet, and this is evident in climate change and global warming.

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List of the acronyms

PM -	Particulate matter
FGD -	Flue gas desulfurization
WFGD -	Wet flue gas desulfurization
SCR -	Selective catalytic reduction
ACI -	Activated carbon injection
FGDG -	Flue Gas Desulfurization Gypsum
CFFG -	Coal-fire flue gas
ESP -	Electrostatic precipitators
GHG -	Greenhouse gas
HVAC -	Heating, Ventilating, and Air-conditioning
MDEA -	Methyl di-ethanolamine
VOCs -	Volatile Organic Compounds
HPR -	Hyper-crosslinked polymeric resins
MOFs -	Metal-organic frameworks
PFAS -	Per/poly-fluoroalkyl substances
MSW –	Municipal solid waste
APC-R -	Air pollution control residue
IAPs -	Indoor air pollutants
SVOCs -	Semi-volatile organic compounds

These pollutants amongst others include CH_4, SO_2, CO_2, surface O_3, and NO_2. Due to the increase in combustion operation and other industrial processes, these gases have been continually released into the atmosphere. Statistics show that by 2050, surface O_3 will increase by 20 % [7]. CO_2 reached 412 ppm in 2019 from 312 ppm which took about a century to 1958 [8], it is projected to reach 550 ppm by 2050 with the increasing demand for energy across the globe [9]. In the case of SO_2, the rate of emission across different sources from developed countries to developing countries was measured between 1960 and 2014 to be 61 % to 83/% respectively, and the global emission as of 2014 was 103 Tg [10]. With the continuous dependency on the industrial process that involves combustion to meet the global energy demand, this number will only increase except a mitigation strategy is put in place for treatment and separation of these pollutants [10]. NO_2 amongst others is also released into the atmosphere from different sources and this was pointed out by Munsif et al. [11].

There are advanced technologies for the control of air pollutants such as sulfur dioxide SO_2, mercury, organic pollutants, and nitrogen oxides (NO_X), emitted by industries involved in fuel combustion for their operations. The techniques are based on various

Table 1
Flue gas compositions.

Composition	Description
Nitrogen	This is one of the major components with (79 %) by volume of air; is introduced into the combustion reaction as a functional or integral part of the combustion air of which its activity wasn't straightforward in the process. Part of the combustion air including nitrogen removal out of fuel is accountable for the yield of oxides of nitrogen.
CO_2	It is described as an odorless and colorless gas and has a slightly vinegary taste; It's always released during the respiration and combustion process.
Water vapor	Hydrogen present in fuel combined with O_2 and produces water (H_2O); including the vapor content released from the combustion air, they all are present as either flue gas humidity (at high temperatures) or as condensate (at low temperatures)
O_2	An incomplete combustion reaction remains an integral portion of the flue gas and is also used to quantify the effectiveness of the process of combustion.
CO	This is a toxic, odorless gas, and colorless; that is largely a result of the half-finished combustion of carbonic fuels
Oxides of nitrogen	This kind is produced at high temperatures, with nitrogen from the combustion air, and also from the fuel that reacts in a certain proportion to first give nitric oxide (Thermal-NO, and fuel-NO)
Sulfur dioxide	Another toxic and colorless gas that has a strong foul smell. That is produced from the oxidation process with the presence of sulfur in the fuel; a reaction with condensate or water yields sulfuric acid.
Hydrocarbons	A chemical compound that generally consists of carbon and hydrogen; and occurs in natural gas, coal, and crude oil; generated through an incomplete process of combustion.
Hydrogen sulfide	This is a toxic gas, with a crude oil and natural gas component that exists in refineries plants; H_2S is produced during other processes in the industries
Hydrogen-halides	Flue gas that is a product of the combustion of waste material and/or coal includes; the formation of hydrogen fluoride, hydrogen halides, and hydrogen chloride, thereby forming acids that are aggressive in humid atmospheres
Hydrocyanic acid	This is a liquid that is very harmful and has a boiling point of 25.6 °C; it is present in flue gases of burning plants
Ammonia	It is present and very vital in flue gases that have a relationship with de-nitrification plants
Solids e.g. dust, soot	Solid pollutants are also formed in flue gas as a result of incombustible components of the liquid or solid fuels; and some other compositions including aluminum, calcium, and oxides of silica in the case of coal

Source: [28].

stages to reduce the concentrations of the targeted pollutants. The stages include fuel pretreatment to eliminate impurities, combustion optimization in the process of the combustion, and post-combustion process to capture pollutants intrinsic in flue gases [12]. It is imperative to have the understanding that the treatment of flue gases must be of high efficiency to meet the strict standards of emissions. For instance, flue gas desulfurization (FGD) methods comprises seawater FGD, wet flue gas desulfurization (WFGD), electron-beam FGD, and spray dry FGD [13]. [14]. The methods of removing organic pollutants are electrochemical degradation, photochemical degradation, adsorption, biological remediation, and catalytic combustion [15,16]. [17,18].

In addition, key investigations reveal that some of these technologies are effective for the treatment of specific pollutants. Electrostatic precipitation, which is for the treatment of the particulate matter, especially trace metals [19]. Adsorption techniques for trapping on adsorbents. This works for CO, CO_2 and volatile organic compounds [20]. Treatment of industrial flue gases laden with SO_2, NO_X can be obtained using wet scrubbers [21]. There are also membrane technologies for gaseous pollutants separation from flue gases [22]. Plasma technologies is effective for the decomposition of hazardous pollutants into harmless substances [23]. Thermal incineration and catalytic oxidation are applicable for the destruction of hazardous air pollutants especially gaseous pollutants that are combustible [24,25]. Bio-filtration technology is excellent for the removal of odors and particulate matter [26,27]. It is expected that industries burn carbonaceous fuels especially power plants are equipped with systems meant for cleaning their flue gases [28,29].

This review compiled the various separation processes and technologies for the treatment of industrial flue gases for air pollution control. The advantages and disadvantages, principles for selecting technologies, and development direction are delt with. It also analyzes the performance with references to cost-effectiveness, efficiency, and potential opportunities in existing methods of separation. A typical flue gas has compositions as represented in Table 1. The constituents usually are hydrogen halides, water vapor, nitrogen, carbon monoxide, sulfur dioxide, hydrocarbons, carbon dioxide, oxygen, hydrocyanic acid, hydrogen sulfide, ammonia, solids, and oxides of nitrogen, dust, and soot [28].

2. Methodology

To achieve this goal, the authors systematically considered contemporary practices for revision and literature from different resources. Research articles were evaluated from several databases and platforms including Science Direct, Web of Science, ResearchGate, Scopus and Google Scholar were carefully selected. The search encompassed a recent publication such as journals, conferences, and term papers, all written in English. Initial analysis of the literature obtained from the keyword search was performed by the authors as shown in Table 2.

3. Recent advances in separation processes for industrial treatment of flue gases

3.1. Flue gas desulfurization (FGD)

The flue gas desulfurization (FGD) process is among the recent advances made, and it has led to the formation of modern Flue Gas Desulfurization Gypsum (FGDG) (see Table 3). FGDG possesses low environmental risk and could be reused for different relevant applications with variables and optimum conditions. Yan et al. [47] pointed out in their research, that centered on the process of desulfurization of the flue gas from coal-fired power plants. FGDG is produced in abundance as a by-product during industrial operation because of its properties both physical and chemical (Fig. 1). It is important to note that during the last decade, production of FGDG has drastically increased while the rate of beneficial usage has reduced slowly.

The adsorption of FGD as depicted in Fig. 1 illustrates one of the adsorption mechanisms for FGD. The use of a modern and recently developed flue gas desulfurization process increases the value of the products and makes them appealing as they contain a lesser number of harmful elements. Recent investigation also shows that novel and traditional FGDG applications cause minimal environmental concerns [48]. Among the recent advances in the beneficial application for material synthesis include wallboard production, concrete/cement, and asphalt production [49,50], It also finds application in other construction materials: production of $CACO_3$, production of calcium sulfate, soil amendment, reduction of soil erosion, water treatment etc. [51].

3.2. Mercury removal from coal-fired flue gas using mineral absorbents

Combustion in coal-fired power engenders the release of gaseous and solid impurities. Mercury is a very toxic trace element that forms part of coal-fire flue gas (CFFG) [52]. It does not just threaten the environment but also human health, which is why it has gained researchers' attention over the years and the Environmental Protection Department. Mercury primarily occurs in three main types:

Table 2
Suitability measures.

Criterion	Inclusion	Exclusion
Article Topic	Incorporate flue gases and their constituents	Do not incorporate flue gases and their constituents
Article Type	Empirical Studies	Non-empirical studies, not related studies
Article Publication	Published and peer-reviewed	Unpublished or pre-printed
Article Availability	Available as full text	Not Available
Language	English	Non-English

Table 3
Advantages and disadvantages of the different separation technologies.

S/N	Technology	Advantages	Disadvantages	References
1	Electrostatic Precipitators	High efficiency for dust removal. Cost-effective based on diameter. Low energy usage. High automation and efficient collection of dust from flue gas in large quantities at high temperatures. Low operating cost.	They require regular cleaning to maintain efficiency.	[30,31]
2	Cyclonic process	Highly efficient in removing particles larger than 20 μm. Cost-effective for industries. Potentially reduces maintenance and treatment cost	Decreased effectiveness with smaller particles. Equipment wear. Relatively low efficiency of collection for fine dust particles	[32,33,34]
3.	Adsorption	It has an above 85 % efficiency Possess a high selectivity rate The adsorbent can be recycled The capacity for CO_2 capture is strong	The material for adsorbent must be one with high temperature. The two control stages must be with thermodynamic balance.	[19,35]
4	Wet scrubber	Capable of simultaneously removing multiple gases. Lower cost. Appropriate for systems with high volumes of air.	Results in secondary pollution. Ineffective.	[36,37]
5	Membrane technology	This method has an efficiency of above 80 % It is utilized for the separation of other gases The cost of investment is relatively low It saves energy and space and it is easy to install No secondary pollution	The lifespan of the membrane is short The purity of the product is average Little preparation in the research phase but the commercial phase is mature. High-pressure drop. Material is difficult to prepare.	[38,37]
6	Plasma technology	Speed of operation. Large Operating capacity.	High rate of energy consumption. No secondary pollution	[39,40]
7.	Thermal incineration	Low energy consumption. Effective and stable with heavy metals. Simplicity of operation.	Capacity to withstand corrosion and pressure. Generation of liquid waste.	[41,42]
8.	Catalytic oxidation process	Good selectivity Durability of catalytic materials	High energy consumption. Lower degradation efficiency.	[43,44]
9	Bio-filtration unit	Efficient for growth Effective for water pollutant removal and removal of heavy metals. Low capital and operation costs. Simple to fabricate Easy to operate.	Requires large surface area. Periodic replacement of filter bed. Compaction of packing materials	[45,46]

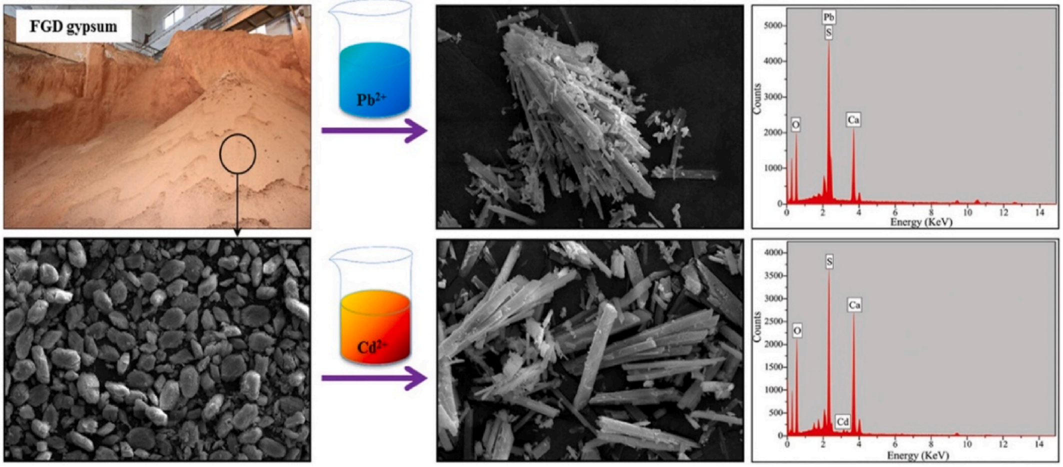

Fig. 1. FGD gypsum of Pb (II) and Cd (II) Adsorption Mechanism [47].

oxidized mercury Hg^{2+}, particle-bound mercury Hg^{P}, and elemental mercury Hg^{0}. Research, as illustrated in Fig. 2 shows that mineral absorbent performs well at capturing mercury extensively. Devices that include fabric filters (FF), electrostatic precipitators (ESP), and wet flue gas desulfurization (WFGD) have proven to be effective at capturing Hg^{P} and Hg^{2+} except for Hg^{0} [53].

The convenient option is adsorbent injection technology because it prevents the addition of major new plants. Other developed

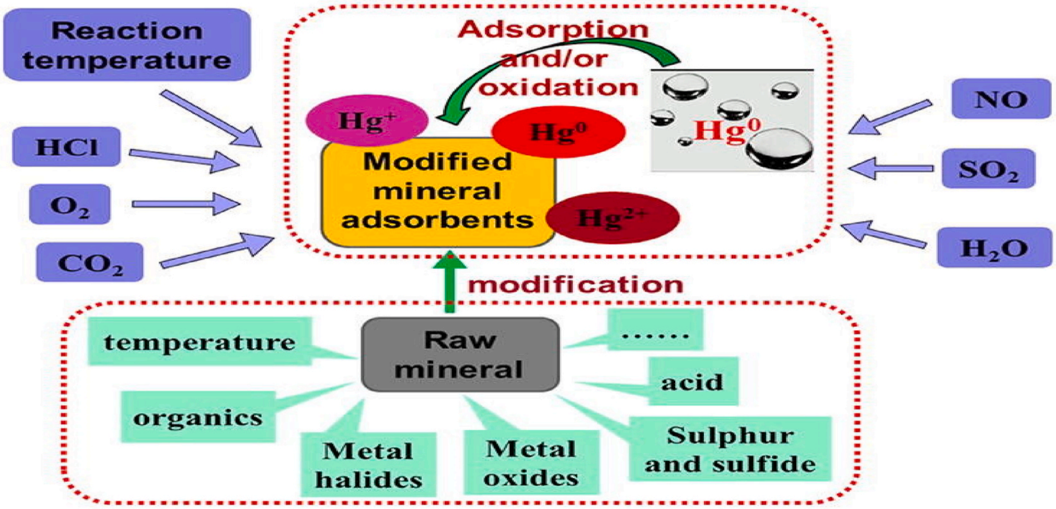

Fig. 2. Mercury Capturing Mechanism [52].

injection species include calcium-based adsorbents, fly ash absorbents, mineral absorbents, and carbon-based adsorbents [54].

3.3. *Technologies for post-combustion carbon-dioxide capture with the aid of activated carbon*

In post-combustion capture, CO_2 is captured from the flue gas which is usually released into the atmosphere from the combustion of fossil fuels. These processes for the capture of carbon include pre-combustion, post-combustion, direct air capture, and oxy-fuel combustion. Among the technologies for carbon capture are chemical looping, absorption, and cryogenic distillation [55]. The principal anthropogenic greenhouse gas (GHG) causing warming globally as well as climate change is CO_2 as shown in Fig. 3. Large stationary emission sources contribute about 65 % of CO_2 around the globe and they include fossil-fuel power plants which are primarily thermo-electric power plants, iron and steel mills, petrochemical and cement industries, industrial power plants, industries for processing gas, refineries that help in transportation and electricity generation [56]. In other to trap CO_2 from flue gases, three

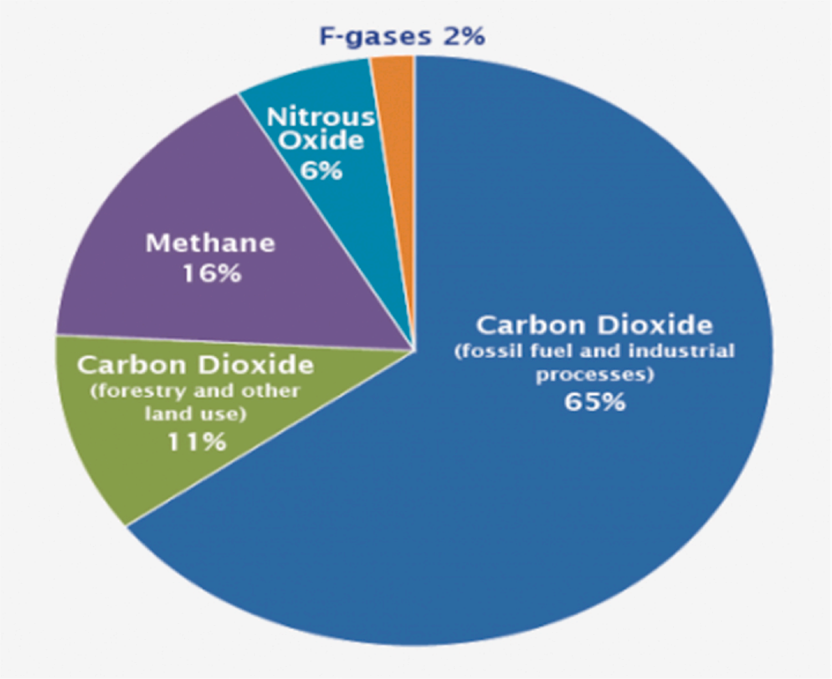

Fig. 3. Proportions of global air emissions [58].

capture technologies are known; pre-combustion, post-combustion, and oxy-fuel combustion. One of the most popular of the three which is widely used is the post-combustion, it can be a substitute or added for a short period without facing existing technologically significant changes or risks. A universal medium for the separation with better advantages than the first-generation processes used for the capture depends on amine-based scrubbing that is naturally energy intensive [57]. This is illustrated n Fig. 4.

3.4. Selective catalytic technology for the reduction of nitrogen oxides from flue gases

NO_X are among the contaminants from industrial processes, power plants, and stationary fuel combustion operations. They exist in different forms: NO, NO_2 , N_2O and N_2O_3. Combustion of fossil fuels produces nearly 5 % of NO_2 and 95 % of NO. Emission of NO_X is classified into thermal NO_X, produced from high-temperature oxidation of atmospheric nitrogen by oxygen. Secondly, they can also be produced from the oxidation of fuel-N when compounds consisting of N are removed at low temperatures in the form of volatile organic compounds and partly transformed to NO. Finally, prompt NO_X, which is a product of the hydrocarbon (HC) reaction with molecular nitrogen at low temperatures rate under fuel-rich conditions [59,60]. NO_X Emissions pose a series of risks to human health, climate change and depletion of the ozone layer.

4. Some technologies for the treatment flue gases

Some of the technologies which are discussed in this review include but are not limited to electrostatic precipitation, cyclonic process, adsorption techniques, wet scrubbing, membrane and plasma technologies, thermal incineration, catalytic oxidation, bio-filtration, photocatalytic oxidation.

4.1. Electrostatic precipitation (ESP)

Electrostatic precipitation techniques can be classified by structure and design such as plate-wire ESP, flat-plate ESP, and tubular ESP. It can also be classified based on the operational temperature which includes cold-side ESP, and hot-side ESP; and the methods by which particles are removed from the collection surface: Dry ESP, Wet ESP [61]. The plate-wire ESP is a particle removal method whose operation is by the charging of particles coming into the system, in a high-voltage environment (Fig. 5). Primarily, there are two configurations available when it comes to ESP: single-stage and two-stage collections. Typically, in a single-stage collector, there is the movement of particle-laden flue gas in a very charged string of wires between grounded plates in series. The electric fields then charge the particles generating ions from the wires that are charged, and then move in a direction and are received on the plates that are grounded. For a two-stage collector, the particles are typically charged in a first-stage section used for charging. In the second stage, the particles are then collected on the plates that are grounded. The efficiency of the collection of single-stage ESP is lower than that of two-stage ESP [62]. Hence, the plates used for collection can be operated closely together since the two-stage method of ESP is most likely higher than single-stage ESP.

Cost limits single-stage systems application to power plants, while two-stage systems are seen where heating, ventilating, and air conditioning (HVAC) units exist, and these units are solely for the collection of pollutants. Hence, according to research, the two-stage

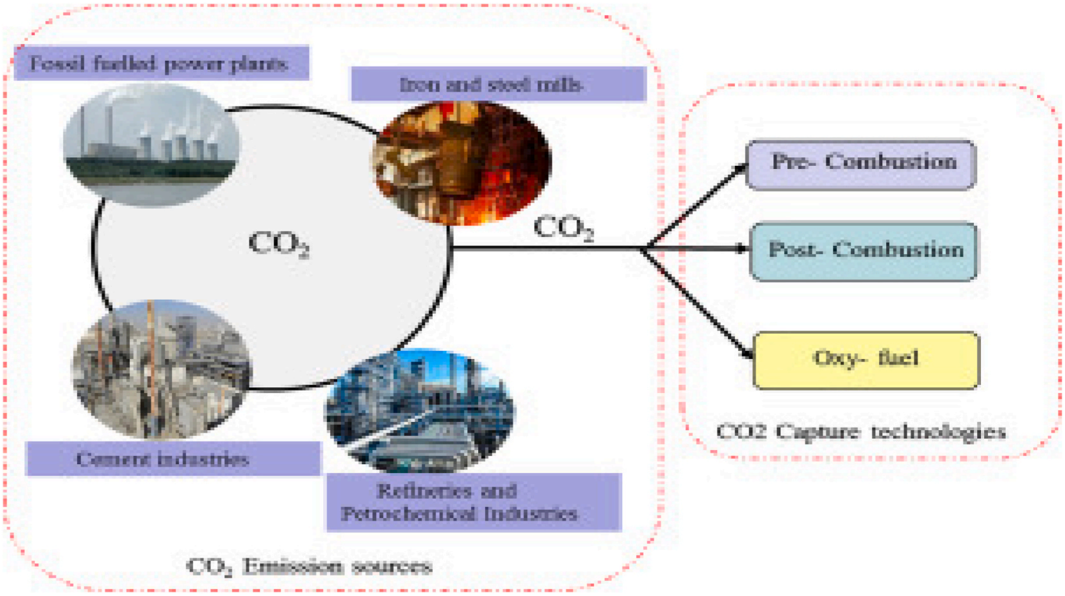

Fig. 4. CO_2 Emission sources [57].

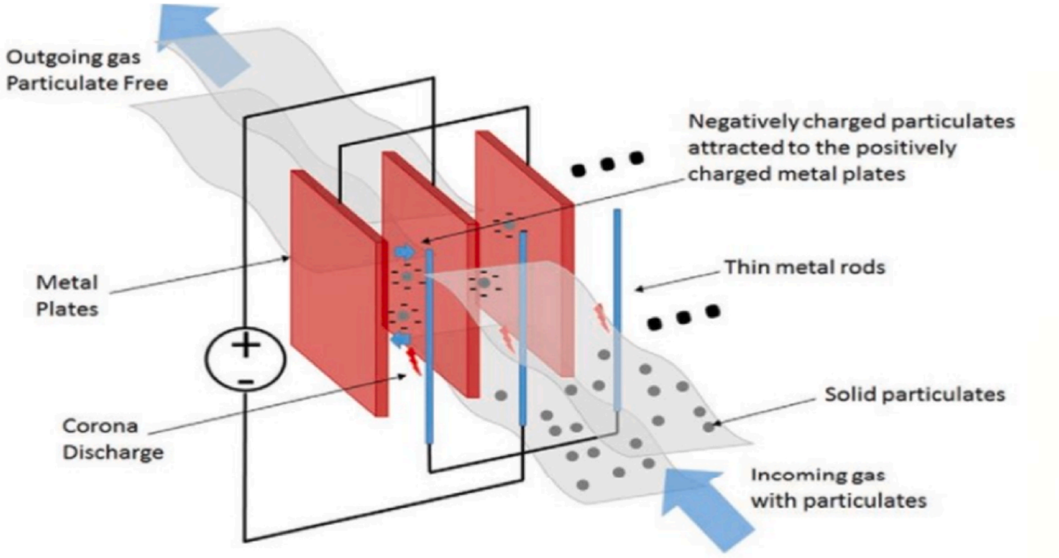

Fig. 5. A typical electrostatic precipitator [62].

ESP is more cost-effective in particle collection with a diameter larger than 16 nm, and the single-stage ESP unit is more efficient for particles that have a smaller diameter [63].

When it comes to the combustion of solid fuels that are biomass-based, one major challenge is the increasing production and emission of the solid part of particulate matter which constitutes flue gas. This emission is on the increase because biomass is largely used as a renewable source [64]. Research has shown the importance of electrostatic precipitators, and it is preferred because of their simplicity of installation requiring little space, higher efficiency, and cost-effectiveness. Also, when the single-pipe tubes are increased to four-pipe chimney ESPs, particulate matter emission decreases significantly, and separation efficiency increases [65]. Other advantages of ESPs; are high efficiency for dust removal, low energy usage, high automation, and efficient collection of dust from flue gas in large quantities at high temperatures [30,31]. The only drawback of ESP is regular cleaning of collection plates to avoid loss of efficiency. This is difficult because nanoparticles stick to the system's surfaces.

4.2. Cyclonic processes

Cyclones are separation technology used for waste gas treatment in industries for solid and gas material (Fig. 6). It is known to be

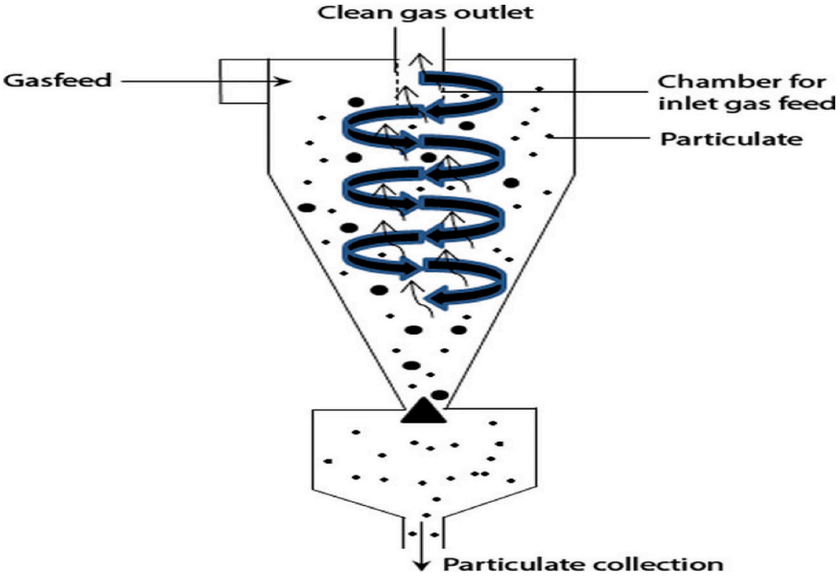

Fig. 6. Typical Cyclone system used in the treatment of flue gases [67].

more efficient at higher pressure and temperature and more so, for fine particle sizes of 2–3 μm in diameter, making them more economical for industrial use. This technology relies on the weights of the particles for removal. The centrifugal force is used to carry these particles that are fed into the cylinder tangentially to reach the required rotation and take them in the direction of the cylindrical wall then through the vortex and ultimately into the collection box where the particles are received [32]. When the size of the emitted particles reduces, the efficiency of the collection decreases considerably. Research has shown that the simultaneous desulfurization and de-nitrification of flue gas using hydro-jet cyclone is achievable. In general, this technology can potentially assist companies in saving on the cost of maintenance and treatment and safeguard nature by preventing the damage initiated by flue gas contamination [66].

Another investigation on the intrusive sampling of dust deposition in a granular bed filter-cyclone coupled separator shows that cyclones are frequently used in industries as a purported method for flue gas treatment. There is optimism that cyclone equipment is a piece of popular equipment among other equipment due to its simple geometry, high efficiency of separation, and the ability to adapt to extremely volatile conditions [68,69]. However, its efficiency of collection is relatively low for fine dust particles which is the major drawback preventing it from further usage in futuristic cases with high demand for purification [70]. Hence the model of a granular bed filter-cyclone combined separator, a collector unit regeneration method, a selection unit, and a dust-loaded flue gas.

4.3. Adsorption techniques

The mass transfer process of adsorption involves the contact of a liquid or gaseous stream with a porous solid, then the selection and removal of pollutants by adsorbing the adsorbate on the adsorbent as illustrated in Fig. 7. The adsorption technique is one of the widely accepted methods for reducing volatile organic compounds (VOCs). It has proven to be an effective technology to combat VOCs that harm human lives and the ecosystems [20]. The major factors in the technology are the cost of investment, cost of operation, and safety. Among the factors influencing the adsorption of VOCs which are principally the properties both physical and chemical of the materials required for the adsorption process include pore size distribution, chemical functional group, and specific surface area.

Activated carbons (ACs) and Zeolites are microporous structures used in adsorption processes. Hyper-crosslinked polymeric resins (HPR) are more beneficial with the restriction of ACs and zeolites for use in industries. The three, are materials for adsorption used in controlling VOCs. The metal-organic frameworks (MOFs) are an extensive classification of crystalline material that is characterized by large surface and rich surface chemical functional group which makes it suitable for VOCs adsorption. They are adsorbent that possess ultrahigh porosity, and each adsorbent is deployed for different targeted gases [20]. According to research, adsorption is described as an effective method and the most frequently adopted technique for purification of water [35]. The factors influencing the capacity of adsorption include concentration, time of contact, kinetics, dosage, conditions for the reactions, and isotherm model. One key factor that helps in the capture of pollutants is the porous structure [71]. [72].

Due to the augmentation in the population of the world, there has also been high pressure in the demand for food. Hence, increasing the rate at which pesticides are used to make a profit and meet production. One key area of research, as a result, is the elimination of these toxic substances using adsorption [73–75]. Syeda et al. [76] investigated the use of cyclodextrin-based adsorbents to treat hazardous pollutants from water using the adsorption techniques and pointed out several techniques that are useful in the treatment of wastewater such as activated sludge, membrane filtration, active oxidation process amongst others.

4.4. Wet scrubbing

The wet scrubber is a device used for the control and capturing of fine particulate matter. A redesigned wet scrubber incorporates multi-sand filter technology which has been evaluated with software to authenticate it dependability [77]. Wet scrubber technology, as

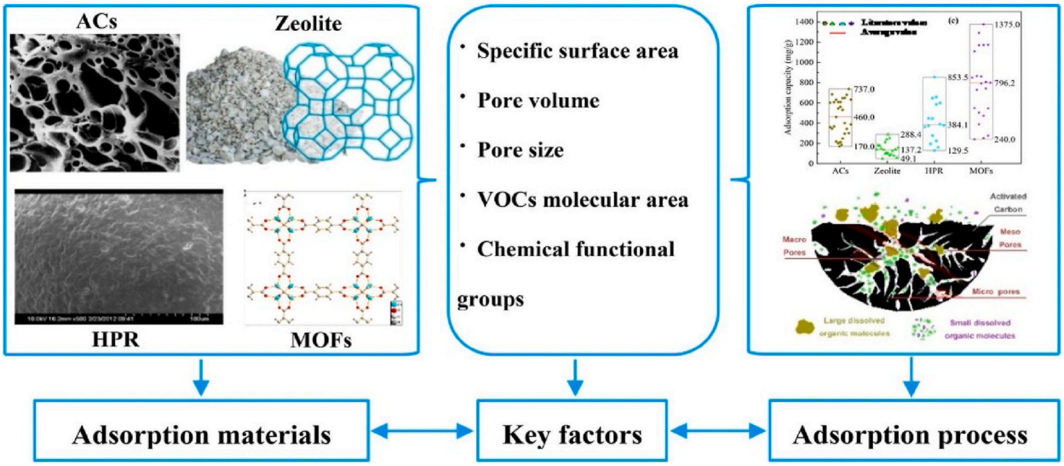

Fig. 7. Materials for adsorption, key factors, and adsorption process [20].

shown in Fig. 8, is known for high purification efficiency, and high dust adaptability [78]. When it comes to the performance of the wet scrubber, the size of the particles to be scrubbed is put into consideration. Due to the compact nature, operation, and maintenance costs amongst others, wet scrubbing has advantages over ESP [79]. The wet scrubber technology is now aided with absorption to remove gases and particulate matter by making the gaseous pollutants from flue gas become absorbed in a liquid stream. The gas transfer rate to liquid is dependent on the mechanism of transfer of masses, solubility, and concentration of the gas in a solution at equilibrium [80].

Typically, a venturi scrubber type, as shown in Fig. 8, is considered the preferred type of wet scrubbing because it performs at high collection efficiency in the control of fine particulate matter. It has a lower initial cost, capacity to neutralize dust and gas that are corrosive, and cool down hot gases [80]. Hence, there is a need for further treatment of wastewater produced.

4.5. Membrane technology

Membrane technology is one of the up-to-date pollution control methods for trapping gases that include hydrocarbon, oxides of sulfur, oxides of nitrogen, and carbon monoxides [24,81,82]. A typical set-up process is illustrated in Fig. 9. For the control of pollutants using this technology, several membranes are constructed from polymeric materials: polysulfone, polyimide, polyurethane, polypropylene, and polyacrylonitrile [38,83]. Others include a nanofibrous membrane which is for the filtration of air and can remove micron particulates from nanoparticles. There are membrane filters that can remove ultrafine pollutants, and aerosols. Vapor-permeation membranes are used for dealing with volatile organic compounds (VOCs). Bioreactor membranes are sued for biological treatment. Among the many advantages of membranes include adjustible porosity, low-pressure drop, high surface area per unit mass, and high particle capturing efficiency [84].

4.6. Plasma technology

This is an advanced technology for degenerating a wide range of Per/poly-fluoroalkyl substances (PFAS). PFAS compounds (a class of anthropogenic chemicals that are drawing the attention of researchers owing to their omnipresence and adverse environmental impact) [85]. There are two types of plasma technology: thermal and non-thermal. The latter being more selective requiring lower energy when compared with the thermal plasma technology [86]. Typical plasma separation processes are illustrated in Figs. 10 and 11.

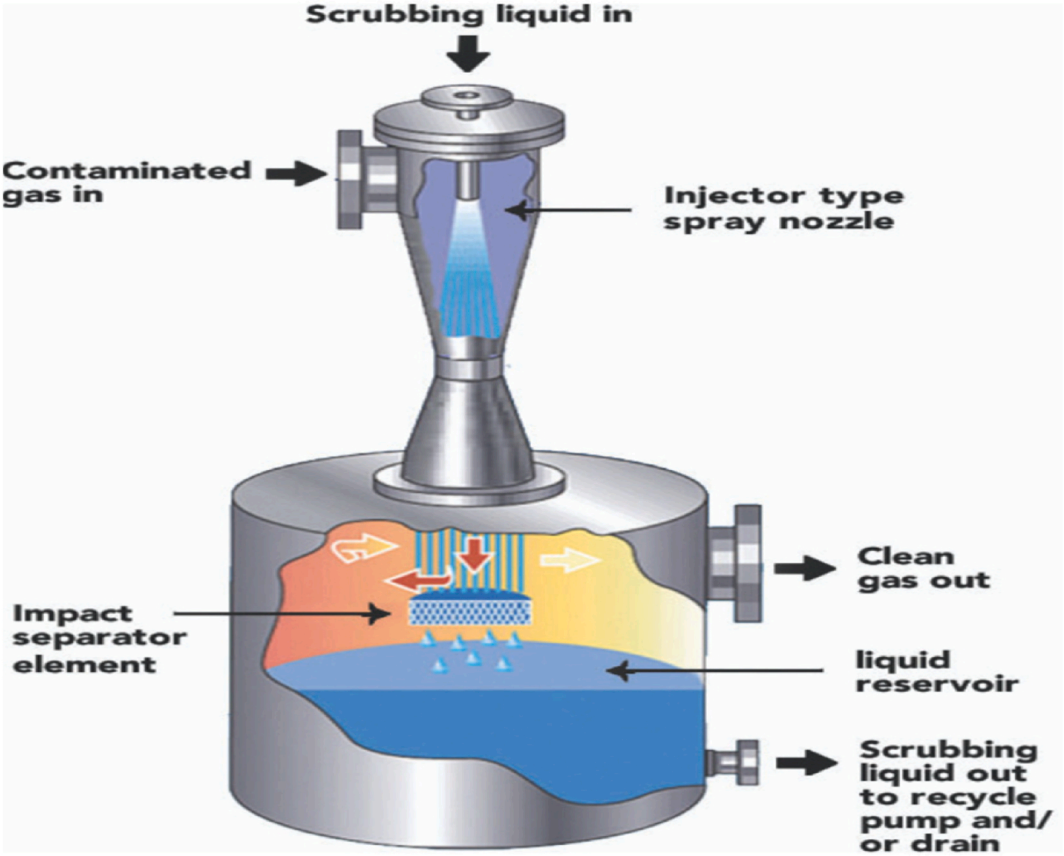

Fig. 8. Typical Venturi Scrubber [80].

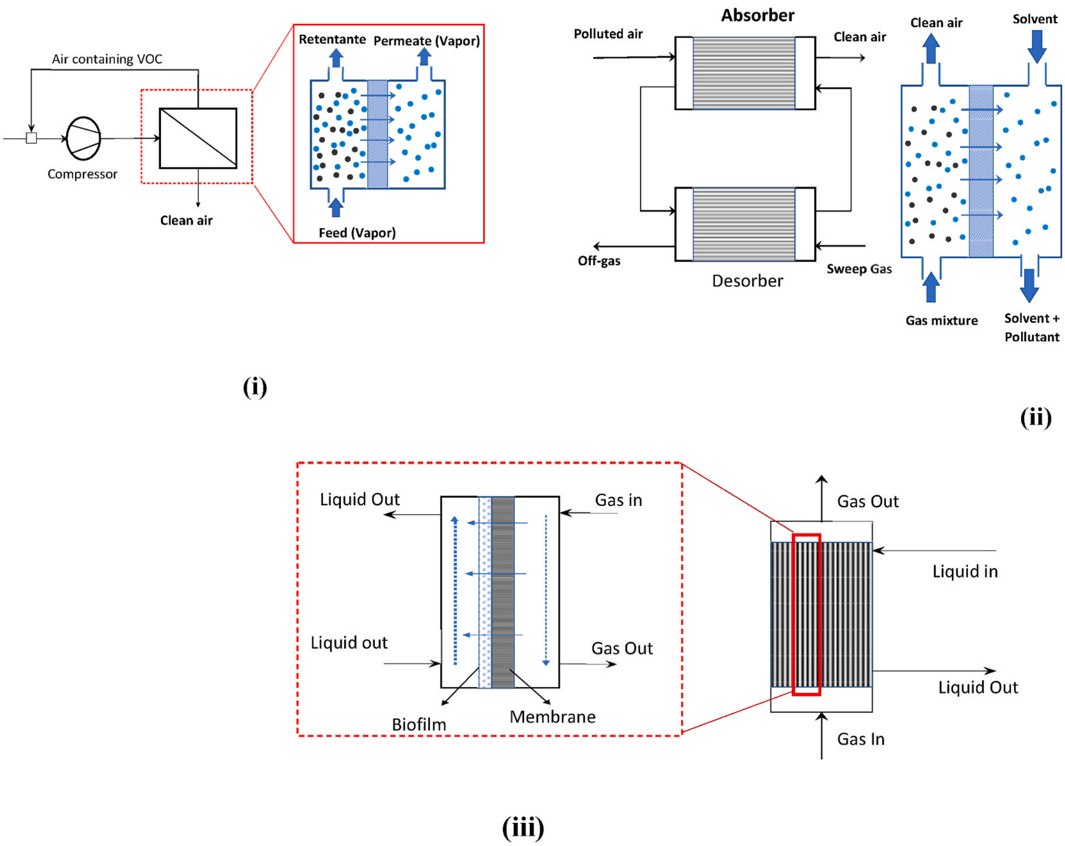

Fig. 9. Membrane technologies for air filtration (i) Pervaporation (ii) membrane Contactor, and (iii) membrane bioreactor [38].

This technology is applied in cleaning flue gases of their associate pollutants. It has demonstrated great promise in dealing with VOCs which are industrial contaminants, dyes, and recalcitrant organic compounds [89,90]. A good understanding of the reactive species is required to achieve better performance when contaminants are being treated using plasma technology [91]. This technology is now finding application in e-waste treatment and its classifications which are growing and are generated from electronic devices.

4.7. *Thermal incineration*

This technology is one of the two main thermal treatment technologies that is used to treat municipal solid wastes (MSW) that cannot be further recycled and direct combustion of flue gases laden with combustible gaseous pollutant in an incineration plant [92] as shown in Fig. 12. It is regarded as efficient when dealing with MSW and degradation of the combustibles in flue gases [93]. High-temperature thermal treatment of flue gases is a chemical process that breaks down organic materials to make new chemicals with a unique chemical composition that have little or no effect on human well-being and the environment [94].

4.8. *Catalytic oxidation process*

This technology is used for solving the problems related to oxides of nitrogen and sulfur oxides. Yuan et al. [95] explored the efficiency of NO oxidation by a novel unaltered Fenton unit as a catalyst. A typical set-up process is shown in Fig. 13. The experiments were carried out with the independent variables: reagent temperature, start-up pH, Fe^{2+}/H_2O_2 molar ratio, and gas flow rate. A high efficiency was achieved. This approach is implicitly meant for the treatment of NO present the flue gases. Ettireddy et al. [96] considered the mechanism for the treatment of NO and NH_3 with the use of $MnOx/TiO_2$ catalysts. While the major advantages are allocated to MnOx/TiO2 catalysts, non-ignorable is a fly in the ointment of N_2O formation which is known as a strong greenhouse gas [97]. In addition, Hao et al. [98] employed a cost-efficient and cooperative means of removing SO_2, NO, and Hg^0 in a flue gas. The research exploited a combined system that involves a dual-absorption scheme and an oxidation system for vapor, in which Na_2CO_3 and $H_2O_2/Na_2S_2O_8$ were deployed as the oxidant and absorbent. The outcomes showed that the efficacies of SO_2 exclusion and NO transition attained 99.5 % and 93 % proportionately.

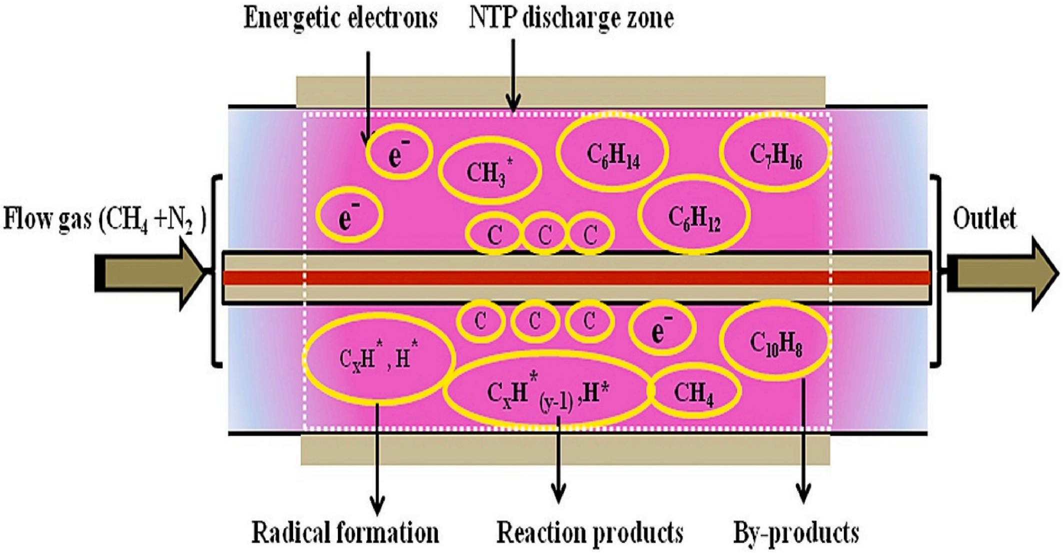

Fig. 10. Non-thermal plasma technology [87].

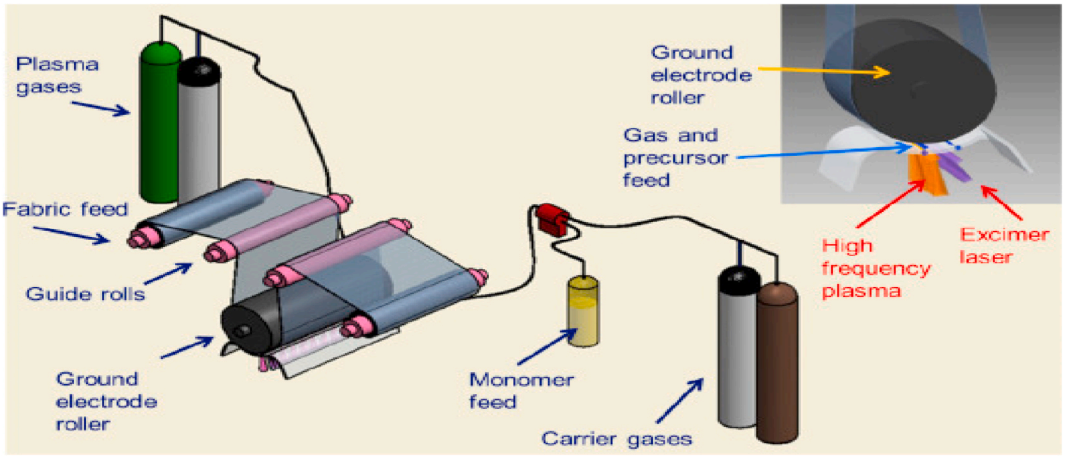

Fig. 11. Plasma Technology [88].

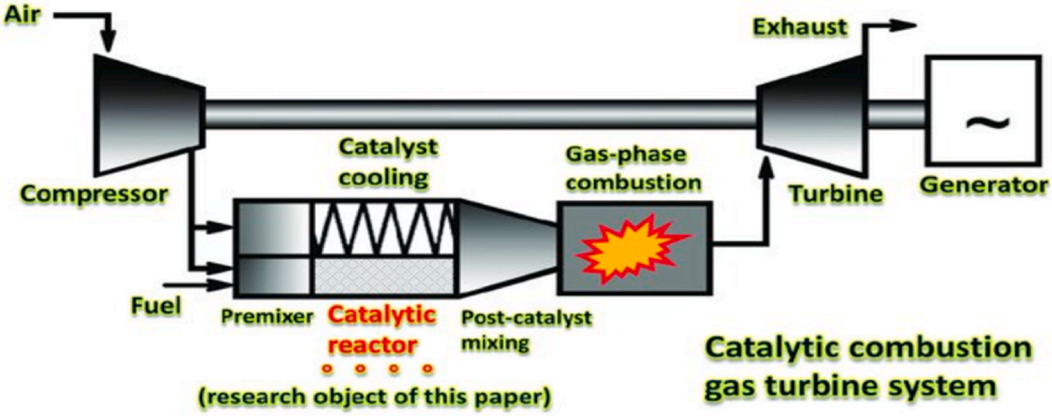

Fig. 12. Schematic of thermal incinerator using a catalyst [53].

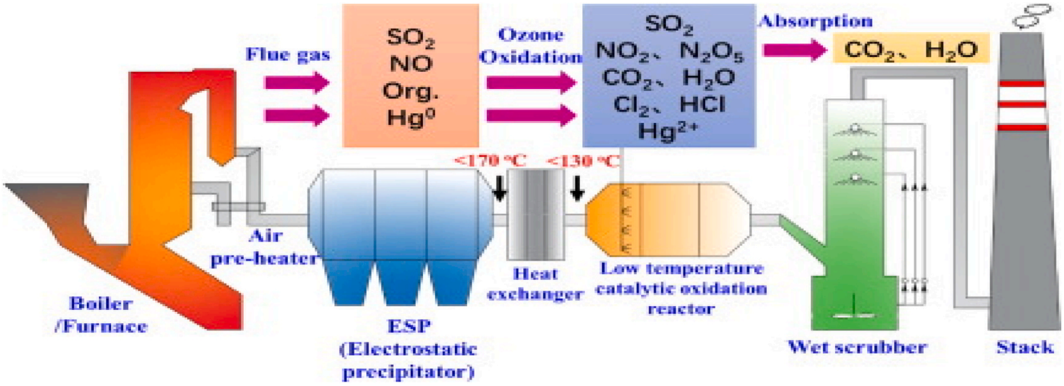

Fig. 13. Catalytic oxidation removal of SO_2, NO, and Hg^0 [12].

4.9. Bio-filtration

Bio-filtration is a recent pollution management technology that has been established for treating odor, volatile organic compounds (VOCs), and some other impurities in the air (Fig. 14). This method has received worldwide attention because of its low budget, ease of operation, high efficiency, and low energy consumption. In overseeing these several forms of pollutant reduction, bio-filtration methods have been employed. The pollutants are adsorbed on the medium exterior and are metabolized to non-threatening substances through microbes that are immobile. Bio-filtration is highly beneficial in removing toxins from flue gases. Bio-filtration takes advantage of the opportunities of microbial tactics (fungi and bacteria tactics) to decrease the wider range of pollutants [99]. Xie et al. [100] examined the elimination process of CO_2, SO_2, and NO_x in a flue gas as well as nitric and sulfur compounds in the liquid phase in a bio-filter. Simulated industrial wastewater was engaged as spray fluid. Mutually, this bio-filter system attained a better flue gas handling performance through the right procedure scheme, which gives an efficient reasonable approach to improve the purification of flue gases and the potential for industries.

4.10. Photo-catalytic oxidation

With the recent development that has led to many people working from homes and spending most of their time indoors, has engendered exposure to indoor air pollutants: Volatile organic compounds VOCs and Semi-volatile organic compounds (SVOCs). VOCs and SVOCs are from sources such as combustion and building materials electronic facilities, gas from indoor fuel, smoking, consumer products and combustion of coal and oil [10,102]. Hence the quality of indoor air has become an important factor [103,104]. One

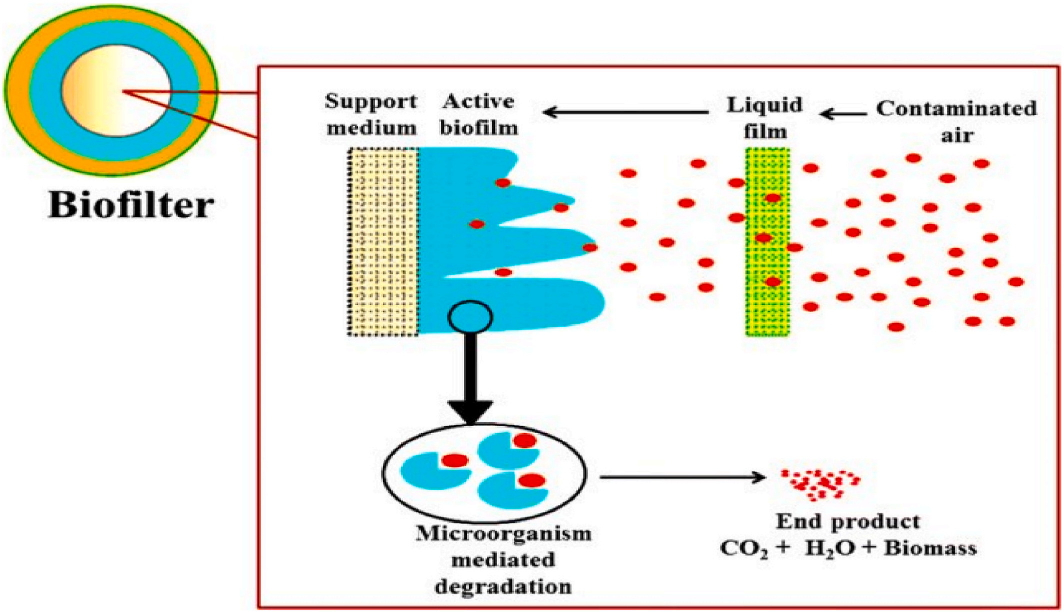

Fig. 14. Bio-filtration process with bio-filter for treatment of flue gas [101].

technological approach for the efficient elimination of these indoor air pollutants is photocatalytic oxidation. Photocatalytic reactors such as packed-bed reactors, optical fiber reactors, monolithic reactors, and micro-reactors is the answer. A typical photo-catalysis process is shown in Fig. 15. Other technologies proposed to minimize the effect of these contaminants include non-thermal plasma, electrochemical oxidation, adsorption and ozonation [105,106].

5. Advantages and disadvantages of flue gas treatment technologies

Tabe 3 gives the pros and cons of different separation technologies for the reduction and removal of air emissions from flue gases.

6. Selection principle of flue gas treatment technologies

In selecting a suitable technique for the treatment of pollutants in flue gases, the efficiency and effectiveness of the technologies are vital after analyzing the composition of the pollutants present in the flue gases. Analysis of the flue gas composition is critical for choosing the required technologies that would be effective for the treatment of the flue gas pollutants. There are also environmental requirements to be met when it comes to the amount of emission from different industrial process plants. This would also be a guide in selecting the techniques that will match the environmental regulations required.

Some crucial factors to be considered when selecting a technique (s) for the treatment or removal of pollutants from flue gases include the cost of operation, the efficiency of removal, the requirement for maintenance, and the rate of energy consumption. Some facilities are better for smaller plants while others are ideal for larger plants that release greater amounts of flue gases. In considering the cost, the availability of technology/technologies is also important as well as the integration into major plant facilities.

7. Different research areas and directions for development of treatment technologies

To combat the pollutants, present in flue gases, several technologies are being developed and improved upon for power plant emissions and industrial processes. Among the advanced control technologies utilized are the electrostatic precipitators. The efficiency of this technique has continuously been improved with a target of decreasing the rate of energy consumption. Renewable energy sources are a major area being sought after for adoption toward net-zero emission from industrial processes. The integration will reduce the rate of emissions of flue gases from fossil fuels. Outright utilization renewable energy sources would eliminate fossil fuels in the generation of energy.

The method of carbon capture is also another technique for reducing one of the major contributors to climate change and global warming. The CO_2 captured could find application in industrial process and oil recovery processes. This technology is being implemented in power plants. Another area is control and monitoring systems which are aimed at optimization of the system's performance. This will enhance the efficiency and provide real-time data on emissions that would facilitate the identification of problems, reduce emissions, and improve performance.

In other to maximize efficiency, and decrease the rate of emissions by automation, one other area under consideration is the integration of artificial intelligence (AI) and machine learning which can aid optimization of the systems for the treatment of flue gases. AI is capable of predicting future emission rates and levels. The major focus is the reduction of emissions, improving the efficiencies of systems and power generation for a sustainable energy and environment.

8. Short discussion

Air pollution is one of the major challenges resulting from industrial reactions and processes and this has gained the attention of

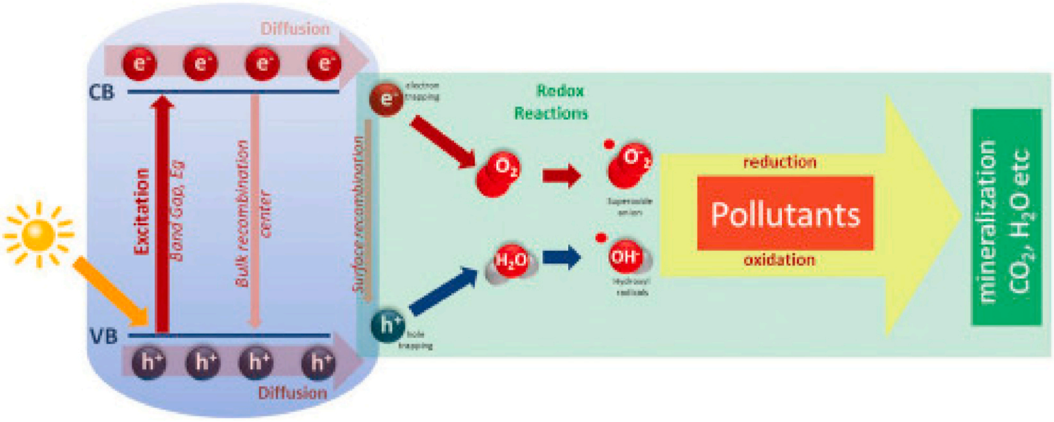

Fig. 15. Process of photo-catalysis [107].

governments, policy makers and researchers across the globe. which is a crucial area of operation, and the increasingly stringent pollutant discharge ethics, There are arrays of new challenges in managing and of controlling air pollutants emanating from flue gases, especially in the industrial sector involving in combustion fossil fuels for their operations. So, this review has descriptively explored the treatment of flue gases by separation processes and technologies.

It is evident that, there is a critical need for more effective methods of separation than ever. As pollution transmission line standards are being raised, separation is now an integral part of the overall field of mitigation necessary to control flue gases. The advanced technological methods for the control of air pollutants via separation processes have been herein highlighted. However, the choice of gas separation technologies requires more than just knowledge of the separation process and the key conditions, but also a good understanding of the features of the pollutants. The performance with references to costs, efficiencies, and potential opportunities in existing methods of separation is also discussed.

However, some possess a few disadvantages and limitations such as high costs of purchase, high energy required for operation, and low life span of the catalysts. Different research areas and directions for development of treatment technologies show that different technologies need improvement on their installations, durability, efficiencies, and cost of operations. These can be addressed by the concerted efforts of the regulators in governments, the researchers in the academia, and investors in the industrial sectors.

9. Conclusion

It has been emphasized that air pollution is one of the major challenges bedeviling the globe. This review shows the advancements made for treating different pollutants resulting from industrial flue gases with available technologies. The pros and cons of the different technologies identified, as well as research direction and principles for selection are highlighted. In other to control and mitigate the rate of emission of these pollutants that are emitted through the combustion of fossil fuels, effective and efficient methods or technologies are required. The technologies highlighted are based on their benefits such as simple installations, efficiencies, and low cost of operations. However, some possess a few limitations such as high cost of equipment and catalysts, low life span of the catalysts and high energy consumption. There is therefore a need to look into a variety of combinations that will help leverage on these methods to maximize the resultant output from utilization and reduce the cost of operations.

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Data availability statement

The authors declare that the associated data with the study has not been deposited into a publicly available repository. All the data reported in this work will be made available upon request.

CRediT authorship contribution statement

Francis B. Elehinafe: Validation, Conceptualization. **Ephraim A. Aondoakaa:** Writing – original draft. **Akinnike F. Akinyemi:** Supervision. **Oluranti Agboola:** Writing – review & editing. **Oyetunji B. Okedere:** Writing – review & editing.

Declaration of competing interest

The authors do not have conflicts of intersts.

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