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Review

An Overview of Electron Accelerator Applications in Environmental Protection with an Emerging Pollutants Decomposing approach

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ABSTRACT

Background: In recent years, problems related to environmental damage and natural resource degradation are receiving increased attention from researchers throughout the world. This occurs mostly, through un-eco-friendly technology used to produce industrial products. Therefore, eco-friendly science and technology (green technology) which can empower and control the existing coal power plant for the virtue of society and the earth is required. **Methods:** A comprehensive literature search was conducted on Electron Accelerator Applications in Environmental Protection with Emerging Pollutants Decomposing. In this regard, relevant studies were retrieved from the international databases of Scopus, Google Scholar, PubMed, Springer, and Science Direct. The search strategy was developed using keywords such as Electron Accelerator, Flue Gas Treatment, Disinfection, Emerging Pollutants, water, wastewater, degradation and treatment. Finally, 20 articles were selected for detailed review in this study. **Results:** The literature addresses various applications of electron accelerators in order to modify the physical, chemical, or biological properties of industrial pollutants in the liquid, solid, and gas phases through treatment by ionizing radiation to control environmental pollution. Many advantages can be achieved through this method, which is known as radiation processing. **Conclusion:** The electronic beam process in the treatment of off-gas, wastewater, and sludge, as well as the decomposition of emerging contaminants, is mentioned as a non-chemical, additive-free process that uses radiolysis to effectively decompose contaminants.

Keywords: Electron Accelerator; Flue Gas Treatment; Treatments; Disinfection, Emerging Pollutants

Introduction

Challenges related to environmental damage and natural resource degradation are receiving increased attention from researchers throughout the world. [1-3]

Therefore, the eco-friendly science and technology (green technology) which can empower and control the existing coal power plant for the virtue of society and the earth is needed. [4] Radiation processing was introduced more than fifty years ago, and many useful applications have been developed since then. [5] However, this was achieved to control environmental pollution in the 1970s. It was when environmental protection organizations were established and standards were set in order to limit emissions. [6]

Radiation processing can be defined as the treatment method of materials and products through radiation or ionizing energy. This processing changes their physical, chemical, or biological properties to

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increase their usefulness and value or reduce their impact on the environment. [7] Accelerated electrons, X-rays (bremsstrahlung) emitted by energetic electrons, and gamma rays emitted by radioactive nuclides are considered proper sources of energy. [8] All of these are capable of ejecting atomic electrons that can ionize other atoms in a collision cascade. Thus, they can have similar molecular effects. [7, 8] The election of energy source is usually based on practical considerations, such as absorbed dose, dose uniformity (max/min) ratio, material thickness, density and configuration, processing rate, and capital and operating costs. [7]

The development of compact and cost-effective accelerators can play an important role in the environmental application of radiation technology. [8] Electron beam technology can successfully treat most of the potentially dangerous toxic substances. Moreover, electron beam plants can transfer much higher amounts of energy into the irradiated objects than other types of facilities including gamma plants. [8] Solving a wide range of environmental protection problems in the gas, liquid and solid phases requires the construction of various accelerators not only in terms of electron energy level, but also beam power, which is directly related to process capacity. [9, 10]

Today, the design and application of the electron accelerator has been well developed due to reliability, larger capacity, greater energy range and cost reduction. This has led to an increase in their use in the refining industry. [11] Among the possible methods for water and wastewater treatment is the radiation method. It is a much more effective way of applying energy to reduce toxic organic compounds and biological compounds. [12] The major goal of irradiation is to initially remove non-biodegradable pollution by converting them into inorganic compounds and biologically degradable organic compounds. Then the microbial pollution caused by bacteria, viruses, etc. is removed. [11, 12] Compactness, high degree of automation of the equipment applied, energy efficiency, high productivity, and excellent compatibility with traditional water treatment methods are important advantages of electron beam technology.

Unlike conventional chemicals in purification, excess radicals produced in the EB process are converted back into water and hydrogen. Therefore, the chemical and corrosive activity of water does not increase. [13]

The present status is suitable for developing and manufacturing high-power electron accelerators for high-capacity beam production. Automatic control, reliability, maintenance reduction, proper use of process conditions, proper electron energy, and beam power are basic features of modern accelerator construction. [11-13] In addition, the technical benefits of applying radiation technology in order to solve many problems of environmental conservation may help overcome negative public opinion regarding this technology. [14]

Technologies that use particle accelerators are considered important in order to advance high-tech processes in various economic fields. They include material processing, sterilization of medical products, environmental protection, medicine (treatment and diagnosis of patients, manufacturing of radiopharmaceuticals), cargo inspection, chemical analysis, nuclear energy (ADS and conversion), etc. [15] The aim of this paper is to address various applications of electron accelerators in order to modify physical, chemical, or biological properties of industrial pollutants regarding the liquid, solid, and gas phases through treatment. It is carried out by ionizing radiation in order to control environmental pollution.

2. Material and Methods

Search strategy

A comprehensive literature search was conducted on Electron Accelerator Applications in Environmental Protection with Emerging Pollutants Decomposing. In this regard, relevant studies were retrieved from the international databases of Scopus,

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Google Scholar, PubMed, Springer, and Science Direct. In this literature, we r articles published up to September 2020 were investigated. The search strategy was developed using keywords such as Electron Accelerator, Flue Gas Treatment, Disinfection, Emerging Pollutants, water, wastewater, degradation and treatment. In addition, in order to increase the sensitivity of the search and select a larger number of literatures, additional records were identified by hand searching and reference list review of the retrieved articles. In the first stage, 1200 articles were retrieved from international databases and 320 documents were selected for evaluation by limiting emerging pollutants. In the next step, many articles were removed by examining the titles and abstracts of the articles. Finally, 20 articles were selected for detailed review in this study.

2.1. Electron Accelerators for Environmental Protection

The main purpose of applying this technology is to develop new high-power electron accelerators that could be used to process huge flow streams of liquid or gaseous pollutants. [16] Accelerators are applied for off-gas and wastewater treatment, as well as disinfection testing of biological sludge in a wastewater treatment plant. Besides, they have higher throughput in comparison with gamma sources. [17] A variety of industrial accelerators can now supply electron energy from 0.3MeV to more than 10MeV, with an average beam power of up to 300 kW. [18] In addition, more powerful accelerators are available today.

2.2. Industrial Off-Gas Purification and reducing acid rain

With the development of urban communities as well as industrial activities, the gross emission of pollutants radically increased in most countries of the world. Pollutants are released into the atmosphere along with industrial gases, power plants, residential heating systems, and municipal waste incinerators. [19] These pollutants are present in the atmosphere in conditions in which they can affect people and their environment. Air pollution from particulate matter and other pollutants, not only directly affect the environment, but also lead to contaminated water and soil and degrade them. [19, 20] Fossil fuels including coal, natural gas, oil and bitumen, and etc. are the main sources of heat and electricity.

Power plants that use coal or oil in order to supply energy emit sulfur and nitrogen oxides. These gases are converted to sulfuric and nitric acids in the atmosphere by reaction with water vapor and are activated by ultraviolet (UV) radiation from the sun. These phenomena affect people's health, increase corrosion, and destroy forests and plants. The number of such emissions can be significantly reduced by irradiating combustion gases with energetic electrons. This process forms acid vapors under controlled conditions within the power plant. Then, acidic gases can be neutralized by injecting ammonia vapor in order to produce fine particles of ammonium sulfate and ammonium nitrate. They can be removed from the combustion gas stream by electrostatic precipitators or bag filters. [20]

Many desirable technologies are available to control air pollution. Technologies that treat different pollutants in one step are of particular importance. Electron beam treatment technology (EBFGT) is one example of such processes. [21] Figure 1 represents an example of particulate matter removal by electron beams from a gas stream.

The efficiency and electron energy range suitable for the flue gas treatment process became more important for pilot plants. The energy range is usually considered to be between 0.3 and 0.8 MeV. The beam power is selected to provide the required dose in the full volume of the flue gas stream. Transformer accelerators are considered the most suitable for application regarding electrical efficiency, cost, and compactness. [22] The energy of electrons in industrial facilities is determined by the dimensions of the reaction vessels and the

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accepted flue gas rate. Besides, electron energy of 0.8 MV and beam power of 300-400 KW is the most suitable accelerator parameters. Consequently, total beam power of 600-1200 KW should be applied for a gas flow range 3 of 10000 Nm3/h in order to obtain SO_2 removal efficiency of 70-95%. [22, 23]

2.2.1 Electron accelerators applied for flue gas treatment

There are two common technologies for reducing air pollution from coal-fired power plants emissions. The first conventional technology is wet FGD (flue gas desulfurization), based on SO_2 absorption in lime or limestone slurry; the second one is SCR (selective catalytic reduction), based on NO_x reduction over a catalyst to atmospheric nitrogen with ammonia as a reductant. [24] Moreover, modern technology to reduce air pollution from the coal power plant is electron beam flue gas treatment technology (EBFGT). As mentioned in the previous section, this technology can treat SO_2 and NO_2 pollutants in a one-step process. [21]

Coal-fired power plants are a type of power plant that uses coal combustion in order to generate electricity. The flue gas is discharged into the air. It is from the combustion of coal contains major components of carbon dioxide (CO_2), water vapor (H_2O), nitrogen (N_2), oxygen (O_2), nitrogen oxides (NO_x = NO_2 and NO), and sulfur oxides (SO_x = SO_2 and SO) with a much lower concentration, and also fly ash (contain trace elements of heavy metals). The diagram of the operating principle of EBFGT is depicted in Figure 2. (25)SO_2 and NO_x are irradiated under the energetic electron beam along with water vapor in the chamber, and ammonium gas is injected into the chamber simultaneously. The flue gas will react with radicals of water vapor in order to form sulfuric and nitric acid. Then, these acids undergo a reaction with ammonium to produce an aerosol of ammonium sulfate and nitrate. The reaction process of the EBFGT is in a very short time. It is because converting flue gas in the form of gas phase into solid phase (aerosol) is in the order microsecond. [21] Figure 2 indicates the principals of flue gas purification with E-Beam process.[21]

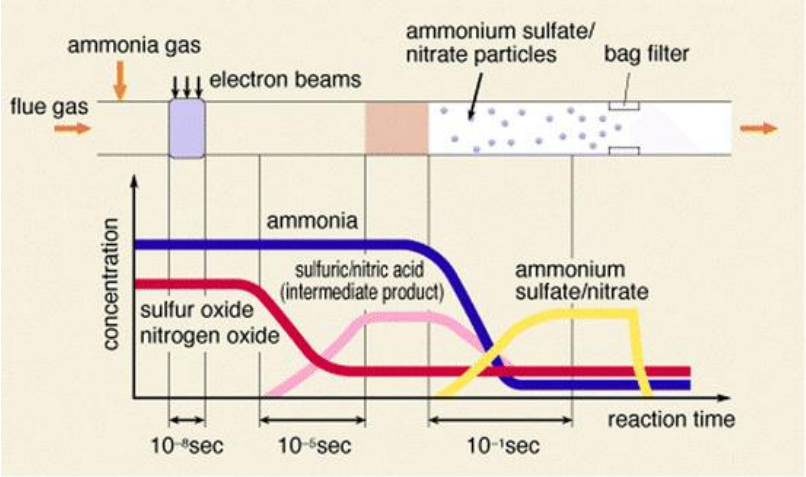

Figure 1. Sequences of Physicochemical Reactions Leading to Acidic Pollutant Removal and Solid Fertilizer Particle Formation [20]

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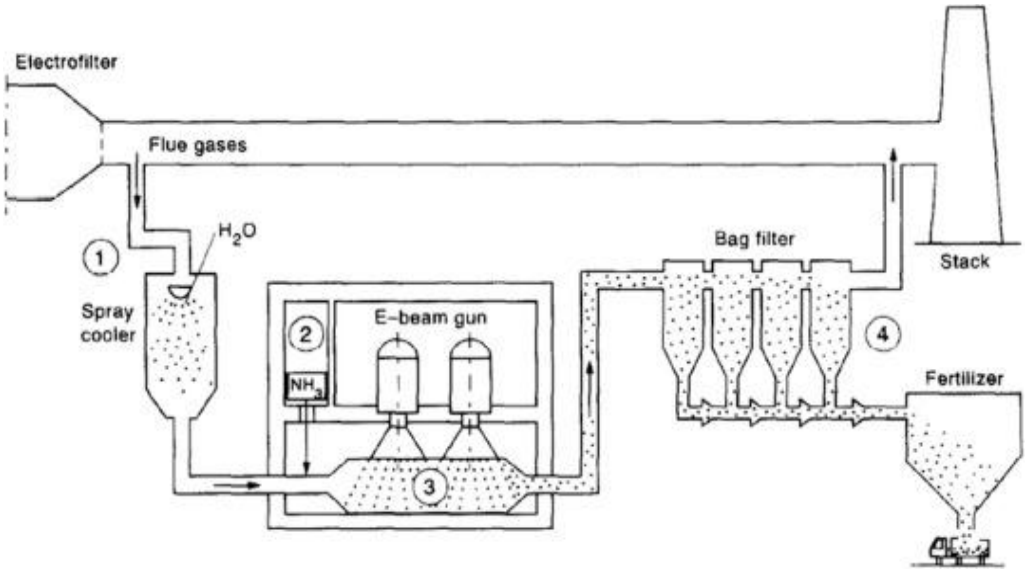

Figure 2. The Diagram of Working Principle of EBFGT [21]

Table 1. The List of Accelerators Applied at Test Sites

Size	Accelerator (MeV, KW)	System (Nm^3/h)
Tokyo 1970 - 71	2-12;1.2 linear	*20 l;batch*
Takasaki 1972-74	-;15 Cocroft-Walton	*60*
Ebara 1974-77	0.3 -0.75:30	*1000*
Uni Tokyo 1974 -78	1; 90-120 Dynamitron	*36 - 84*
Ebara 1974-78	0.6 – 0.75 ; 2× 10-45	*3000 - 10000*
JAERI 1981	1.5;30	*0.09*
Res.Cottrell 1984-85	2× 0.8 ; 80	*5300*
Indianapolis 1984-88	2× 0.88 ; 160	*8000 – 24,000*
Karlsruhe 1984	190 – 200 ; 22	*100 - 1000*
Karlsruhe 1984	150 – 300 ;36	*60 - 1000*
Badenwerk 1985	260 – 300 ; 2 × 90	*10,000 – 20,000*
Warsaw 1990 now	1 ; 20	*1 - 400*
Kawęczyn 1990 - 94	700 ; 2 × 50	*20,000*
Fujisawa 1991	500 ; 15	*1500*
Matsudo 1992	900;15	*1000*
Nagoya 1992	800 ; 3 × 36	*12,000*
Tokyo 1992	500 ; 2 × 12.5	*50,000*
Mianyang 1999	800 ; 36	*3000 – 12,000*
Chengdu 1999-2004	800 ; 2 × 320	*270,000*
Bejing 2000		
Pomorzany 2002 - now	700 ; 4 × 268	*270,000*
Maritza East 2003 - 05	700 ; 3 × 12.5	*10,000*

As shown in Table 1,Electron accelerators were applied from a very early stage of the development of the flue gas treatment process. In Table 1, accelerators applied in a different laboratory, pilot, and industrial-size installations are listed. [23]

The most popular accelerators, due to electron energy requirements (up to 1MeV), were transformer accelerators as presented in Figure 3. These are the most economical units with high energy efficiency. Their preference for applications is connected with the fact that the density of flue gas is close to 1.25kg/Nm3, which assures good penetration of the medium treated by electrons. It is much deeper in comparison with the liquid or solid phases. [24]

Figure 4 indicates the pilot of a treatment plant using electron beam technology. [24, 26]

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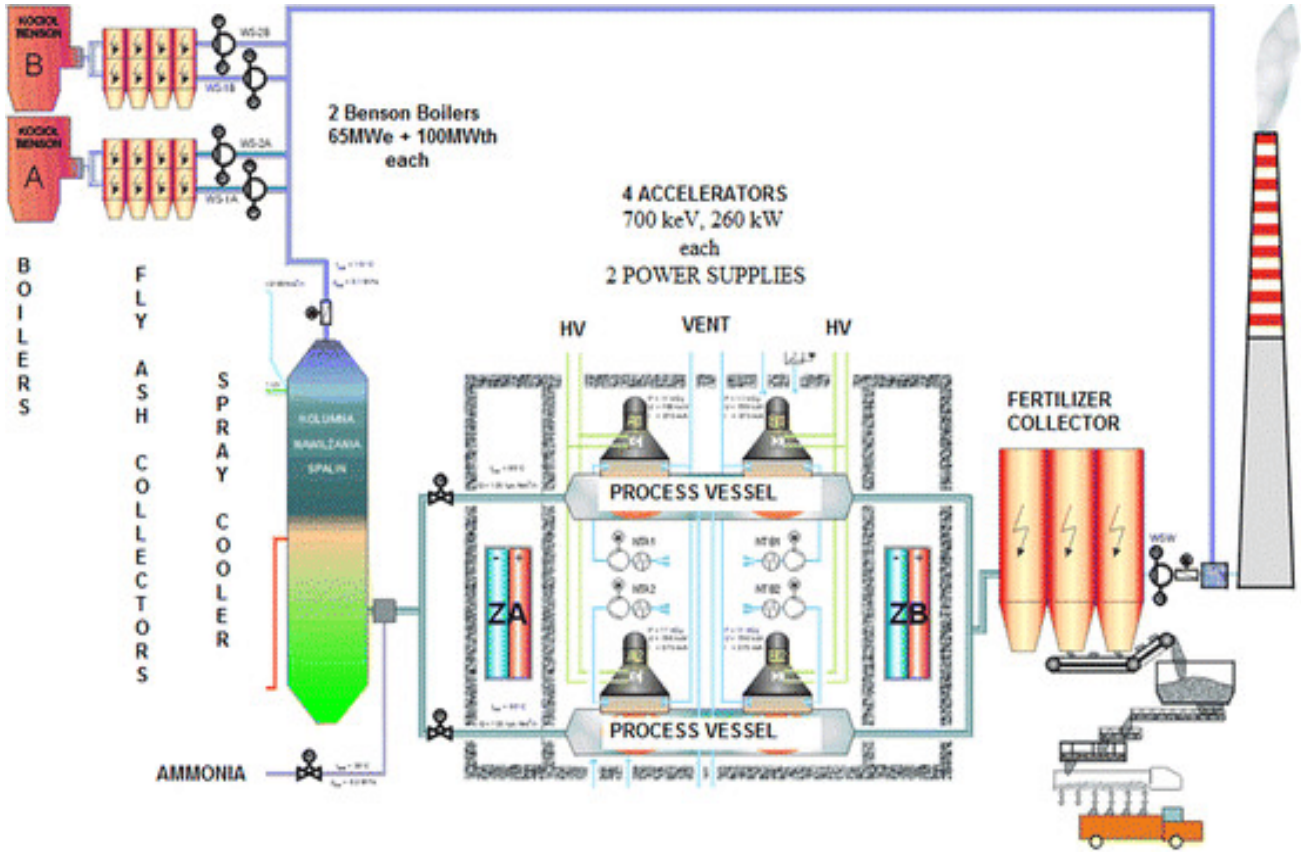

Figure 3. An Industrial Plant for EBFGT: EPS Pomorzany, Szczecin, Poland.(24)

Table 2. Basic Parameters of Electron Accelerators Applied in Facilities for Liquid Solid Phase Treatment [27]

Type of treated object	Electron energy (MeV)	Beam power (kW)	Company and country of development	Remarks
Liquid sewage sludge	0.85	50	Deer Island ,Boston,USA	Capacity 400 m^3/day ICT accelerator
Wastewater/sludge	1.5	75	Florida International University, University of Miami,USA	ICT accelerator,5000 m^3/day
Sludge	1.0	50	Wedel, near Hamburge, Germany	500 m^3/day
Sewage sludge	0.4	34	Stuttgart-Hohnheim,Germany	Batch operation
Wastewater	1.5	37.5	IPEN,Brazil	Dynamitron
Sewage/drinking water	0.5	12.5	Seibersdorf Research Center, Austria	
Composted sludge			JAERI,Takasaki,Hapan	
Wastewater (wastes from nekal)	0.7-1.0	50 × 2	Voronezh, Russia	Continuously operated facility with capacity 12000 m^3/day

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2.3. Municipal and industrial wastes treatment

It is estimated that the amount of fresh water available to people for daily consumption is about 9000 cubic kilometers per year. Another 3500 cubic kilometers stored by dams and reservoirs can be added. [25] Harnessing the remaining water resources to meet human needs is increasingly costly due to topography, distance, and environmental impacts. Furthermore, providing a clean water supply is one of the goals of sustainable development which has been discussed by many countries. [28] Because of increasing levels of pollution and the complexity of polluted effluents from urban and industrial activities, conventional wastewater treatment technologies often fail to remediate and disinfect polluted water. Therefore, municipal and industrial wastewater treatment is becoming an important issue in the field of environmental engineering. [29] The application of radiation technology in the liquid phase treatment process is usually related to wastewater (communal and industrial), dung waste, groundwater, and drinking water treatment. This is to remove organic and pathogenic contamination of those media. While the application of gamma rays used to be very common in the past, experts are now implementing accelerator facilities more widely (Table2). [28, 29] Explains the Basic Parameters of Electron Accelerators Applied in Facilities for Liquid Solid Phase Treatment)

Electron beam treatment of wastewater often leads to their purification from various pollutants.(30)This is due to the decomposition of contaminants as a result of their reaction with highly reactive species. They, in turn, result from water radiolysis (hydrated electrons, OH free radicals, and H atoms).The main processes applied for the treatment of water by accelerated electrons are as follows [31]:

- Radiation oxidation
- Radiation polymerization and copolymerization
- Radiation coagulation
- Radiation transformation of biologically -non degradable compounds to a biodegradable state
- Radiation disinfection and distinction of helminths
- Thermoradiation purification

Sludge from municipal wastewater treatment plants is a proper fertilizer for the soil. It is not possible to use them due to the presence of pathogenic microorganisms, parasites, and parasitic eggs allowed in the agricultural industry. However, it was without any disinfection process. [28] As a result, a lot of research has been carried out in many countries to prove the effectiveness of electron beam purification in such environmental processes. They will be discussed in more detail in the next section. [28, 30]

On the other hand, a mobile electron injection water treatment system was developed by Raychem, USA. It was to use the electron beam for environmental remediation of ground and wastewater. The electron injection system made it possible to purify water using a relatively low-energy electron beam through its special design. It is possible to install a trailer easily with all the necessary equipment on the site. Furthermore, this system is fully automatic and designed to operate unattended. [27] Figure 5. Represents a Simplified Technological Map of Industrial E-beam Wastewater Treatment Plant; F1–F4 Air Fans, P1–P2 Water Pumps, D1–D2 Diffusers, An Accelerator, R Reactor, B1 and B2 Primary and Secondary Basins.

2.4. Biological sludge disinfection

Nowadays, the problem of water pollution by chemicals and biology is well known. Due to water shortage regarding municipal, agricultural, and industrial purposes in many regions, reservoir water, mainly rivers, is often reused. Thus, suitable remediation and disinfection are necessary in order to protect the consumers' health. [32-35]

The sludge resulting from municipal or industrial wastewater treatment is usually in the form of a liquid or semisolid liquid that typically contains 0.25–12 % solids by weight, depending on operations and processes used. [33]

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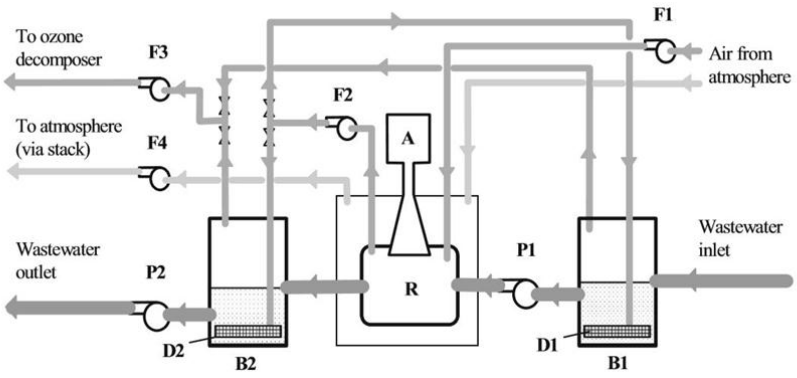

Figure 4. Simplified Technological Map of Industrial E-beam Wastewater Treatment Plant; F1–F4 Air Fans, P1–P2 Water Pumps, D1–D2 Diffusers, An Accelerator, R Reactor, B1 and B2 Primary and Secondary Basins

Among the components removed in the wastewater treatment process, the sludge is more voluminous and the problems related to its processing and disposal are more complex.[34] Radiation technology can be also effectively applied in treatment of sewage sludge, airport and hospital wastes. Environmental regulations have the tendency to increase the difficulties and cost of disposing toxic and contaminated materials. [36] This technology applied to solid material and objects, requires higher energy of electrons (5 to 10 MeV) to achieve positive results. Findings based on various studies revealed that sewage sludge can be successfully disinfected by exposure to high-energy radiation. Doses of 2–3 kGy destroy more than 99.9% of bacteria present in sewage sludge. This is while higher doses (up to 10 kGy) are required to inactivate organisms resistant to radiation. For this purpose, sludge irradiation plant by composting process with a capacity of 50 tons per day requires an electron accelerator with a beam power of 15 kW. [30] Beside disinfection, irradiation has a beneficial effect on physicochemical properties of sewage sludge such as specific resistance to filtration, water separation and sedimentation. [35, 36]

2.5. Degrading of emerging pollutants

Emerging pollutants can be understood as any synthetic or naturally-occurring chemical or any microorganism. They are not commonly monitored or regulated in the environment with potentially known or suspected adverse ecological and human health effects. These contaminants mainly include chemicals found in pharmaceuticals, personal care products, pesticides, industrial and household products, metals, surfactants, industrial additives and solvents. [37] Many of them are applied and released continuously into the environment even in very low quantities. Some may cause chronic toxicity, endocrine disruption in humans and aquatic wildlife and the development of bacterial pathogen resistance. [38]

These residues have been suspected to be associated with altered reproductive function in human, such as breast cancer, abnormal growth patterns, neuro-developmental delays in children and changes in immune function. [37, 38] Several processes have been investigated in order to remove these contaminants. They include ferric chloride coagulation, powdered activated carbon, magnetic ion exchange combined with microfiltration or ultrafiltration, as well as nanofiltration and reverse osmosis. While each of these methods presents specific limitations in the removal of EDCs in aqueous solution, EB has the ability to treat EDCs and drug residues with a very high degree of reliability and in a very efficient manner. Radiolysis

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products from water in the formation of highly reactive intermediates, which then react with the target molecules, culminate in structural changes.[35]

Conclusion

Overpopulation combined with industrialization, urbanization, and an energetic lifestyle have given rise to serious environmental problems, especially in large cities. In many industrial urban areas, there are problems because of high air and water pollution. Therefore, pollution control has become the main issue in the field of environmental engineering. EB is considered an important technique for environmental protection. Advances in accelerator technology not only mean an increase in number of units, but also lower costs, higher doses, more compact size suitable for production lines, enough beams for the process, reliability and other important parameters in radiation processing. Ionizing radiations in the form of energetic electrons and X-rays (bremsstrahlung) are being used for many practical applications. High-energy and high-power beams have the ability to alter the physical, chemical and biological properties of materials on an industrial scale. This technology has received more attention than other conventional treatment methods due to the need for smaller area, high electrical efficiency and production of by-products such as fertilizer. EB process in the treatment of off-gas, wastewater, and sludge, as well as the decomposition of emerging contaminants, is a non-chemical, additive-free process that uses radiolysis to effectively decompose contaminants.

Conflict of interest

Authors declares no conflict of interest.

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Authors contribution

Research design : E.A.M

Data collection : O.A.M

Data analysis : N.B.Y

Writing and editing the article : N.B.Y ,E.A.M , O,A,M.

References

1. Mead I. International energy outlook 2017. US Energy InformationAdministration. 2017.
2. Basfar AA, Fageeha OI, Kunnummal N, Chmielewski AG, Licki J, Pawelec A, et al. A review on electron beam flue gas treatment (EBFGT) as a multicomponent air pollution control technology. Nukleonika. 2010;55:271-7.
3. Kim J, Han B, Kim Y, Doutzkinov N, Nikolov K. E-Beam Flue Gas Treatment Plant for "Sviloza Power Station" AD. 2009.
4. Kim J, Kim Y, Han B, Doutzkinov N, Jeong K-Y. Electron-beam Flue-gas Treatment Plant for Thermal Power Station. Journal of the Korean Physical Society. 2011;59(6):3494-8.
5. Son Y-S. Decomposition of VOCs and odorous compounds by radiolysis: a critical review. Chemical Engineering Journal. 2017;316:609-22.
6. Ighigeanu D, Martin D, Zissulescu E, Macarie R, Oproiu C, Cirstea E, et al. SO2 and NOx removal by electron beam and electrical discharge induced non-thermal plasmas. Vacuum. 2005;77(4):493-500.
7. Kwon YK, Han DH. Microwave Effect in the Simultaneous Removal of NO x and SO2 under Electron Beam Irradiation and Kinetic Investigation of NO x Removal Rate. Industrial & Engineering Chemistry Research. 2010;49(17):8147-56.
8. Standardization IOf, Standardization IOf. ISO 11137: Sterilization of health care products-Radiation-Part 2: Establishing the sterilization dose. ISO Geneva; 2013.
9. Chung BY, Kim J-S, Lee MH, Lee KS, Hwang SA, Cho JY. Degradation of ampicillin in pig manure slurry and an aqueous ampicillin solution using electron beam irradiation. Radiation Physics and Chemistry. 2009;78(7-8):711-3.
10. Kim J, Han B, Kim Y, Yaacov NB, editors. Economics of electron beam sludge hygenization plant. International Meeting on Radiation Processing; 2008.
11. Kim J-C, Kim K-H, Armendariz A, Al-Sheikhly M. Electron beam irradiation for mercury oxidation and mercury emissions control. Journal of Environmental Engineering. 2010;136(5):554-9.
12. Chu L, Wang J, Wang B. Effect of gamma irradiation on activities and physicochemical characteristics of sewage sludge. Biochemical engineering journal. 2011;54(1):34-9.

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[DOI: 10.18502/aoh.v6i4.11729]

13. Abdou L, Hakeim O, Mahmoud M, El-Naggar A. Comparative study between the efficiency of electron beam and gamma irradiation for treatment of dye solutions. Chemical Engineering Journal. 2011;168(2):752-8.
14. Paul J, Rawat K, Sarma K, Sabharwal S. Decoloration and degradation of Reactive Red-120 dye by electron beam irradiation in aqueous solution. Applied Radiation and Isotopes. 2011;69(7):982-7.
15. Thomaidis NS, Asimakopoulos AG, Bletsou A. Emerging contaminants: a tutorial mini-review. Global NEST Journal. 2012;14(1):72-9.
16. Chmielewski AG. Reviews of Accelerator Science and Technology Vol. 4 (2011) 149–161 c World Scientific Publishing Company. Reviews of Accelerator Science and Technology. 2011;4:149-61.
17. Han B, Kim J, Kim Y, Kim S. High power accelerator for environmental application. 2011.
18. Doutzkinov N, Nikolov K, editors. The Possibility for Implementation of E-Beam Technology in TPS "Svilosa," Bulgaria. IAEA Meeting on Electron Beam Flue Gas Treatment; 2007.
19. Masjedi MR, Taghizadeh F, Hamzehali S, Ghaffari S, Fazlzadeh M, Jafari AJ, et al. Air pollutants associated with smoking in indoor/outdoor of waterpipe cafés in Tehran, Iran: concentrations, affecting factors and health risk assessment. Scientific reports. 2019;9(1):1-11.
20. Khusravi R, Khodadadi M, Gholizadeh A, Mehrizi EA, Shahriary T, Shahnia A. BOD5 removal kinetics and wastewater flow pattern of stabilization pond system in Birjand. European Journal of Experimental Biology. 2013;3(2):430-6.
21. Park J-H, Ahn J-W, Kim K-H, Son Y-S. Historic and futuristic review of electron beam technology for the treatment of SO2 and NOx in flue gas. Chemical Engineering Journal. 2019;355:351-66.
22. Alonso JR. Accelerators for America's future workshop: medicine and biology. Health Physics. 2012;103(5):667-73.
23. Basfar AA, Fageeha OI, Kunnummal N, Al-Ghamdi S, Chmielewski AG, Licki J, et al. Electron beam flue gas treatment (EBFGT) technology for simultaneous removal of SO2 and NOx from combustion of liquid fuels. Fuel. 2008;87(8-9):1446-52.
24. Hocking MB. Handbook of chemical technology and pollution control: Elsevier; 2016.
25. Nichipor H, Sun Y, Chmielewski AG. Kinetic modelling of NO heterogeneous radiation-catalytic oxidation on the TiO surface in humid air under the electron beam irradiation. Nukleonika. 2017;62(3):235-40.
26. Chmielewski AG, Han B. Electron Beam Technology for Environmental Pollution Control. Topics in current chemistry (Cham). 2016;374(5):68.
27. Dillon L, Sellers C, Underhill V, Shapiro N, Ohayon JL, Sullivan M, et al. The Environmental Protection Agency in the early Trump administration: Prelude to regulatory capture. American Journal of Public Health. 2018;108(S2):S89-S94.
28. Mehrizi E, Sadani M, Farzadkia M, Kermani M, Ghahremani E, Nadafi K. Discussion and Comparison of Efficiency Natural Systems for Wastewater Treatment in Stabilization Pond and Artificial Wetland about Removal Organic Materials and Solids (TSS, BOD5, and COD) in Yazd's Sewage at 2009-2010. Journal of Basic and Applied Scientific Research. 2012;2:1270-7.
29. Zarei A, Biglari H, Mobini M, Dargahi A, Ebrahimzadeh G, Reza Narooie M, et al. Disinfecting Poultry Slaughterhouse Wastewater Using Copper Electrodes in the Electrocoagulation Process. Polish Journal of Environmental Studies. 2018;27(4).
30. Calvo WAP, Duarte CL, Machado LDB, Manzoli JE, Geraldo ABC, Kodama Y, et al. Electron beam accelerators—trends in radiation processing technology for industrial and environmental applications in Latin America and the Caribbean. Radiation Physics and Chemistry. 2012;81(8):1276-81.
31. Han B, Kim J, Kang W, Choi JS, Jeong K-Y. Development of mobile electron beam plant for environmental applications. Radiation Physics and Chemistry. 2016;124:174-8.
32. Sudlitz M, Chmielewski AG. A Method for WWTP Sludge Valorization through Hygienization by Electron Beam Treatment. Fermentation. 2021;7(4):302.
33. Choi J-S, Park J-H, Kim Y, Kim J, Jung S, Han B, et al. Removal of nonylphenol from industrial sludge by using an electron beam. Journal of the Korean Physical Society. 2016;69(6):1029-34.
34. Homlok R, Takács E, Wojnárovits L. Degradation of organic molecules in advanced oxidation processes: relation between chemical structure and degradability. Chemosphere. 2013;91(3):383-9.
35. Venturi M, D'Angelantonio M. Applications of radiation chemistry in the fields of industry, biotechnology and environment: Springer; 2017.
36. Lafitte-Trouqué S, Forster C. The use of ultrasound and γ-irradiation as pre-treatments for the anaerobic digestion of waste activated sludge at mesophilic and thermophilic temperatures. Bioresource technology. 2002;84(2):113-8.
37. Cukierman AL, Nunell GV, Bonelli PR. Removal of emerging pollutants from water through adsorption onto carbon-based materials. Emerging and Nanomaterial Contaminants in Wastewater: Elsevier; 2019. p. 159-213.
38. Kümmerer K. The presence of pharmaceuticals in the environment due to human use–present knowledge and future challenges. Journal of environmental management. 2009;90(8):2354-66.

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