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Exploring the Radiation Techniques in Agricultural Wastewater Management

Eksplorasi Teknik-teknik Radiasi dalam Pengelolaan Air Limbah Pertanian

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ABSTRACT

Radiation techniques have gained significant attention in the field of agricultural wastewater management due to their effectiveness in treating diverse contaminants. This review aims to explore the effects and applications of radiation techniques, including ultraviolet (UV), gamma-ray, and electron beam (EB). UV radiation utilizes ultraviolet light to break down organic pollutants, disinfect pathogens, and remove pesticides in agricultural wastewater. Besides, gamma radiation involves the use of ionizing radiation to interact with contaminants and induce degradation processes. Furthermore, EB radiation harnesses high-energy to degrade organic compounds in wastewater. The efficacy of radiation techniques in reducing pesticides, pharmaceutical residues, microorganisms or pathogens, and other organic pollutants has been widely demonstrated. These techniques offer advantages such as versatile applicability, precise targeting of contaminants, and the potential for water reuse in various agricultural sectors, such as crop irrigation, livestock farming, and food processing. However, optimizing process parameters, including radiation dose, dose rate, pH, and temperature, are crucial to maximize treatment efficiency. While radiation techniques have proven beneficial in numerous studies, potential environmental impacts must be addressed. Byproducts generated during radiation and their fate should be studied to evaluate their toxicity and persistence. Proper waste disposal, adherence to safety regulations, and monitoring programs are necessary to minimize risks and ensure the safe use of radiation techniques. In conclusion, UV-C radiation effectively use for surface disinfection, pathogen inactivation, certain pesticides and pharmaceutical residues degradation, while gamma-ray more effective than UV-C for microorganism sterilization and inactivation, pesticide and pharmaceutical residues degradation, as well as EB radiation has high dose rate and selective penetration, and the technique also has speed and precision, feasible for practical application. Thus, advancements in technology will further optimize the efficacy and sustainability of radiation-based wastewater treatment processes in agriculture.

Keywords: agriculture, electron beam, gamma ray, UV, wastewater management

ABSTRAK

Teknik radiasi telah mendapatkan perhatian yang signifikan dalam bidang pengelolaan air limbah pertanian karena efektivitasnya dalam mengolah beragam kontaminan. Tinjauan ini bertujuan untuk mengeksplorasi efek dan penerapan teknik radiasi, termasuk ultraviolet (UV), sinar gamma, dan berkas elektron (EB). Radiasi UV memanfaatkan sinar ultraviolet untuk memecah polutan organik, mendisinfeksi patogen, dan menghilangkan pestisida dalam air limbah pertanian. Selain itu, radiasi gamma melibatkan penggunaan radiasi pengion untuk berinteraksi dengan kontaminan dan menginduksi proses degradasi.

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Selain itu, radiasi EB memanfaatkan energi tinggi untuk mendegradasi senyawa organik dalam air limbah. Kemanjuran teknik radiasi dalam mengurangi pestisida, residu farmasi, mikroorganisme atau patogen, dan polutan organik lainnya telah dibuktikan secara luas. Teknik-teknik ini memiliki kelebihan seperti aplikasi serbaguna, penargetan kontaminan yang tepat, dan potensi penggunaan kembali air di berbagai sektor pertanian, seperti irigasi tanaman, peternakan, dan pengolahan makanan. Namun, mengoptimalkan parameter proses, termasuk dosis radiasi, laju dosis, pH, dan suhu, sangat penting untuk memaksimalkan efisiensi teknik-teknik tersebut. Meskipun teknik radiasi telah terbukti bermanfaat dalam banyak penelitian, potensi dampak lingkungan harus diatasi. Produk sampingan yang dihasilkan selama radiasi dan nasibnya harus dipelajari untuk mengevaluasi toksisitas dan persistensinya. Pembuangan limbah yang benar, kepatuhan terhadap peraturan keselamatan, dan program pemantauan diperlukan untuk meminimalkan risiko dan memastikan penggunaan teknik radiasi yang aman. Kesimpulannya, radiasi UV-C efektif digunakan untuk desinfeksi permukaan, inaktivasi patogen, degradasi pestisida tertentu dan residu farmasi sedangkan sinar gamma lebih efektif dibandingkan UV-C untuk sterilisasi dan inaktivasi mikroorganisme, degradasi residu pestisida dan farmasi, serta radiasi EB memiliki laju dosis dan penetrasi selektif yang tinggi, dan teknik ini juga memiliki kecepatan dan ketepatan, layak untuk penerapan praktis. Dengan demikian, kemajuan teknologi akan semakin mengoptimalkan efektivitas dan keberlanjutan proses pengolahan air limbah berbasis radiasi di bidang pertanian.

Kata kunci: Pertanian, berkas elektron, sinar gamma, UV, pengelolaan air limbah

INTRODUCTION

Agriculture is essential to maintaining the world's food supply and guaranteeing food security. However, these activities frequently result in significant wastewater production that contains a range of pollutants and, if not adequately handled, has a detrimental effect on both the environment and public health. To lessen the detrimental impacts of agricultural wastewater, innovative and effective treatment methods are required. Some prospective methods are using radiation techniques, such as ultraviolet (UV), gamma-ray, and electron beam (EB) have attracted attention recently as useful strategies for treating agricultural wastewater [1] [2] [3]. To break down contaminants and clean wastewater, these techniques use electromagnetic radiation or high-energy electrons [2] [3]. By utilizing certain ionizing radiation wavelengths [4], radiation treatments can target microorganisms [5], and a number of pollutants found in agricultural wastewater, such organic compounds [3] [6], pesticides [2] [7], and pharmaceutical residues [8].

Some mechanisms supporting radiation techniques for the treatment of agricultural wastewater depend on the unique features of each technique. As an illustration, UV radiation primarily employs UV-C wavelengths to generate reactive species, such as hydroxyl radicals [1] [8] [9], that initiate the oxidation processes that result in the breakdown of organic pollutants. The direct effect of radiation corresponds to direct ionization of DNA (one electron ejection) whereas indirect effects are produced by reactive oxygen species generated through water radiolysis, including the highly reactive hydroxyl radicals, which damage DNA. UV-C and to a lesser extend UV-B photons are directly absorbed by DNA bases, generating their excited states that are at the origin of the formation of pyrimidine dimers [10].

Gamma radiation, on the other hand, comes from isotopes like Cobalt-60 (Co-60) or Cesium-137 (Cs-137) and is used in radiation [11] [12]. These powerful rays enter the wastewater, ionizing water molecules and creating free radicals as a result [2] [13]. The primary mechanism of biological damage to macromolecules from ionizing radiation is an indirect interaction that begins with the radiolysis of water. The event is a cascade of chemical transformations that result in the formation of free radicals. Free radicals are highly reactive particles that can indirectly harm DNA and cause cellular damage. These free radicals alter or degrade contaminants when they come into contact with the radiations, turning them into less harmful forms. A relatively new technique called EB radiation also creates reactive species like hydroxyl radicals by bombarding water molecules with accelerated electrons. These radicals' potent oxidizing abilities allow them to effectively remove pathogens and eliminate organic pollutants [14] [15].

The contaminants in agricultural wastewater are significantly affected by radiation methods.

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These techniques have proven to be quite successful at reducing levels of organic pollutants, pesticides, and pharmaceutical residues, which contributes to an overall improvement in the quality of the water [1] [3] [8]. Furthermore, radiation-based approaches have proven to have potent disinfectant characteristics that effectively eradicate dangerous bacteria and reduce the chance of contracting illnesses from contaminated water [5] [11]. Although there is some potential for using radiation techniques to manage agricultural wastewater, it is essential to consider how process variables like radiation dose [2] [16], contact time [5], pH [16], and temperature [2] can be adjusted to improve treatment effectiveness.

In this review, we aim to extensively explore of radiation techniques in agricultural wastewater management. By looking into the scientific tenets, benefits, and drawbacks of radiation techniques as unique methods for treating agricultural wastewater, as well as case studies and recent advancements in the field, we hope to provide readers a complete understanding of their potential.

THE RADIATION PROCESSING CONCEPT

The radiation process is a versatile technique that harnesses the interaction of ionizing or non-ionizing radiation with materials to modify their properties. This concept revolves around the diverse ways in which radiation energy interacts with matter. Thus, there are different types of ionizing radiation (gamma-ray and electron beam) and non-ionizing radiation (UV), as illustrated in **Figure 1**.

Gamma-ray

Ionizing radiation, including gamma-ray, engages in a fascinating interaction with matter, resulting in ionization and the creation of positive ions and free electrons. The process begins with the incident photon, a high-energy particle with a short wavelength. As this photon encounters atoms within a material, it primarily interacts with the electrons that surround the atomic nucleus [17]. One of the key mechanisms involved is the photoelectric effect, where the photon transfers its entire energy to an inner-shell electron. This energy transfer is potent enough to overcome the binding energy that holds the electron in its orbit, leading to the ejection of the electron from the atom. Additionally, Compton scattering occurs when the incident photon collides with an outer-shell electron. In this process, the collision imparts some of the photon's energy to the electron, causing the photon to scatter in a different direction, and the electron is ejected with lower energy [17] [18].

Gamma radiation utilizes ionizing radiation [13] [4], typically generated by isotopes such as Co-60 or Cs-137. These isotopes emit high-energy gamma-ray that penetrate the wastewater [2] [3]. When gamma-ray interact with water molecules, ionization occurs, resulting in the formation of free radicals, including hydroxyl radicals (•OH). These radicals exhibit strong oxidative properties and can initiate the degradation of organic pollutants by breaking chemical bonds. Gamma radiation also effectively sterilizes the wastewater by damaging the DNA/RNA of pathogens, thus preventing their proliferation [14] [19]. Thus, this radiation has an advantage, such as offering excellent penetration through the wastewater, enabling treatment of large volumes. It is effective in both contaminant degradation and pathogen inactivation [14] [20] [21]. However, the use of isotopes and the associated safety considerations and waste management can present challenges [22] [23].

Electron beam (EB)

EB is a form of ionizing radiation that is characterized by having sufficient energy to remove tightly bound electrons from atoms, resulting in the formation of ions (atoms with a net electrical charge) and free electrons. The energy of an EB is high enough to cause ionization when it interacts with matter. In the context of EB processing, a high-energy EB is generated and directed towards a material. When the electrons in the beam collide with the atoms of the material, they can impart enough energy to eject electrons from the inner shells of the atoms, leading to ionization. This ionization process introduces positive ions and free electrons within the material, modifying its properties.

EB radiation involves the use of high-energy electrons generated by an electron accelerator [3] [16]. These accelerated electrons collide with water molecules, producing reactive species, notably hydroxyl radicals (•OH), through a process called radiolysis [16] [19]. The hydroxyl radicals generated during EB radiation are powerful oxidizing agents that can rapidly degrade various organic pollutants present in agricultural

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wastewater. Further, during EB irradiation of water, hydroxyl radical (•OH), hydrated electron (eaq−) and hydrogen atom (H•) intermediates form with yields of 0.28, 0.27 and 0.06 μmol J^{-1}, respectively [24]. Moreover, the high-energy electrons have sufficient penetrating power to effectively disinfect the water and inactivate pathogens [3] [14]. It offers precise control over the energy and dose delivered, making it suitable for tailored treatments. However, it requires specialized equipment and energy-intensive operations [1] [8] [25]. Furthermore, EB processing can be found in various industries, including sterilization of medical equipment, cross-linking of polymers, and modification of material surfaces. The ionizing nature of the electron beam plays a crucial role in these applications by inducing controlled changes in the target materials.

Ultraviolet (UV)

Non-ionizing radiation, like UV rays, lacks the energy to cause ionization but can still bring about changes in molecular and atomic structures, such as vibrational energy alterations or bond stretching. When UV radiation encounters a substance, it imparts energy to the material. This energy aligns with the vibrational frequencies of chemical bonds within molecules. As a result, the absorbed UV energy induces increased molecular vibrations, influencing the kinetic movement of atoms. Additionally, UV radiation promotes bond stretching, where the distances between atoms in a molecule undergo alterations. These changes in bond length can impact the stability and reactivity of the molecular structure.

UV radiation is able to damage the RNA and DNA of microorganisms in a way that prevents them from multiplying. As a result, these germs are eliminated because they can no longer multiply and spread. The least effective wavelengths for disinfection are UV-A waves (315-400 nanometers or nm). Some minor bacteria can be cleaned out by UV-B (280-315 nm), which is a little more potent. But even though UV-C is still harmful, it is thought to be the most potent and effective UV wavelength for disinfection in wavelength range (200-280 nm) [20] [5]. UV-C light possesses the ability to generate reactive species, such as hydroxyl radicals (•OH), through a process known as photolysis [1] [26]. These radicals are highly oxidizing and capable of breaking down organic pollutants into simpler, less harmful compounds [27]. Additionally, UV-C and UV-B light can directly damage the genetic material (DNA/RNA) or by pyrimidine dimer formation of microorganisms [20] [11], rendering them incapable of reproduction and effectively disinfecting the wastewater [5]. According to Ravanat and Douki [10], pyrimidine dimers can cause structural distortions in the DNA helix and interfere with DNA replication and transcription, leading to mutations and other DNA damage. The advantage of this radiation is widely used for its ability to degrade organic pollutants and disinfect water without the need for chemical additives. However, it is limited by its reduced penetration depth and the presence of certain compounds that can absorb or block UV light [9].

DEGRADATION TYPES OF POLLUTANTS

Under radiation, whether through UV, gamma, or EB radiation (**Figure 1**), pollutants undergo degradation and transformation through various mechanisms or process, such as photolysis, radiolysis, oxidation, polymerization and cross-linking. The specific mechanisms depend on the type of radiation and the characteristic of the pollutants, as shown in **Table 1 and 2**.

Photolysis

In UV radiation, photons with specific wavelengths interact with pollutants. The energy from UV photons can break chemical bonds within the pollutants, leading to their degradation. This process is known as photolysis. Zhu et al [28] investigated the degradation kinetics and pathways of three commonly-used Calcium Channel Blockers (CCBs), such as amlodipine (AML), diltiazem (DIL), and verapamil (VER) under UV (254 nm) irradiation. In other case, for the breakdown of a wide variety of chemical substances, including halogenated hydrocarbons, pentachlorophenol, insecticides, herbicides, aromatic compounds, and more recently medicines, advanced oxidation processes (AOPs) generate a significant amount of OH radicals [29] [30] [31]. A series of chemical processes can be used to decompose complicated toxin complexes employing OH radicals because of their high reactivity. When water molecules decay due to processes like radiation and photolysis, reactive oxygen and nitrogen species (RONS) are created. These RONS subsequently attack the molecules of

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the pollutant [27]. In addition, the research by Bustos et al. [32] combined UV-C direct photolysis and reactive oxygen species (ROS)-mediated photooxidation, leading to a greater degradation of the chemical species present in the reaction medium and potentially in charge of the sample toxicity. The degradation conditions were less effective in the absence of dissolved oxygen (i.e. in trials with nitrogen bubbling), since the indirect photodegradation's contribution was suppressed. Additionally, in the presence of hydrogen peroxide, the overall degradation of pharmaceutically active compounds (PhACs) will be contributed to by both UV photolysis and UV/H_2O_2 oxidation. In other case like Quinoline, an organic contaminant, was successfully UV-photodegraded using TiO_2/SiO_2 powders [33]. In the presence of UV irradiation, TiO_2 (mainly anatase) generates electron-hole pairs when exposed to UV radiation, which diffuse and react with H_2O/O_2 to produce OH/O_2 radicals that aid in the breakdown of organic molecules in wastewater. Because its charge carriers have a higher recombination time, anatase is the most preferred crystalline phase for this purpose [33] [34]. In other case, Zhuang et al. [54] described that for UV disinfection of selected genes, generally, the genes of microorganisms decreased greatly as the UV irradiation doses increased. Besides, to reduce antibiotic resistance genes (ARGs), including intI1 and 16S rRNA genes, it can be successfully reduced by AOPs such the UV/H_2O_2 method [55].

Radiolysis

Radiolysis is a chemical reaction that occurs when a substance is exposed to ionizing radiation. This radiation, which can be in the form of high-energy particles or electromagnetic waves, such as gamma-ray and EB radiation, has enough energy to break chemical bonds in the substance it interacts with. As a result, radiolysis leads to the formation of free radicals and other reactive chemical species. These free radicals can then initiate various chemical reactions, including oxidation, reduction, and the formation of new chemical compounds. Radiolysis is a well-studied phenomenon and is often used in various scientific and industrial processes, including radiation sterilization, wastewater treatment, and understanding the effects of radiation on materials and biological systems [35] [36].

Ionizing radiation can break down organic pollutants that are not biodegradable, such as pesticides, medicine residues, and other pollutants in aquatic environments, either directly or indirectly. Water radiolysis has the notable benefit over other advanced oxidation processes (AOPs) in that pollutant molecules can be broken down in both oxidative and reductive modes since it produces both potent oxidizing and reducing species. For example, reducing agents include hydrogen atom H, superoxide radical anion O_2, and hydrated electron e_{aq}^-, while oxidizing species include hydrogen peroxide (H_2O_2) and hydroxyl radical OH [63].

Oxidation

Oxidation is a chemical process in which a substance loses electrons, resulting in an increase in its oxidation state. The oxidation of indole as an illustration refers to the conversion of indole into intermediate products during its degradation process. This oxidation is facilitated by reactive species generated by ionizing radiation, such as hydroxyl radicals, hydrated electrons, and hydrogen radicals. The generation of ROS is a crucial mechanism in the degradation and transformation of pollutants under radiation [37]. UV, gamma, and EB radiation all contribute to the formation of ROS [38] [15] [35]. ROS, such as hydroxyl radicals, have strong oxidative properties and can react with pollutants. They break chemical bonds within the pollutants, leading to the formation of simpler and less harmful compounds. He et al. [49] stated that ionizing radiation (gamma and EB) was effective to reduce the contaminant, like indole, in chemical wastewater. Some reactive species react with indole molecules, leading to the formation of various intermediate products, including 3-methylindole, 3-methylinodle radicals, hydroxylation inodole, anilinoethanol, and isatoic acid [39]. This oxidation process facilitates the degradation of pollutants by transforming complex molecules into smaller fragments or completely mineralizing them into carbon dioxide (CO_2), water (H_2O), and other simple inorganic compounds [37] [35] [40]. Like UV, ionizing radiation also can reduce antibiotic and inactivation of ARGs in cephalosporin C fermentation (CEPF) residues [41]

Polymerization and cross-linking

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In certain conditions, radiation can also induce polymerization or cross-linking reactions in pollutants [15] [42]. This is especially relevant for organic compounds that have reactive functional groups or multiple bonds [18]. The high-energy radiation such as gamma-ray and EB can trigger the formation of polymer chains of molecules or the cross-linking of molecules [15] [43], resulting in the transformation of pollutants into more stable and less reactive forms. On the other hand, while exposure to high dose rates of radiation, such as EBs, enhances the crosslinking processes of these free radicals in the presence of oxygen, exposure to low dose rates of radiation, such as Co-60 gamma-ray, encourages the degradation reactions through oxidations. The crosslinking events of these C-centered free radicals and their reactivity with oxygen are established as competitive reactions at low dose rates. The equivalent peroxyl radicals are created when the C-centered free radicals combine with molecular oxygen. Finally, a variety of processes involving these peroxyl radicals cause the polymers to degrade [18]. Yet, in the other study, Ranković et al. [44] checked that the used dose rate was high enough not to cause degradation of the polymeric chain of the flocculant and lead to the formation of carcinogenic acrylamide monomer. The concentration of acrylamide, both before and after radiation, was below the limit of measurability of the method, and far below the limit value for sludge to be used as fertilizer.

DIRECT AND INDIRECT ENERGY DEPOSITION

Direct energy deposition and indirect energy deposition are two essential mechanisms in the realm of radiation processing, a versatile technique harnessed for various applications such as pollutant treatment and material modification.

Direct energy deposition

In direct energy deposition, ionizing radiation, such as gamma-ray and electron beam, directly interacts with target molecules. This interaction results in processes like ionization and excitation, where electrons are either ejected or move to higher energy levels. Direct energy deposition is particularly effective in inducing chemical changes, breaking bonds, and generating free radicals within the target material. It plays a significant role in achieving specific modifications and transformations desired in the treated substances.

In gamma and EB radiation, high-energy radiation directly transfers its energy to the pollutants, causing the breaking of chemical bonds. This direct energy deposition leads to the fragmentation of pollutants into smaller molecules [18]. The high-energy electrons in EB and the ionizing radiation in gamma interact directly with the pollutants [13], inducing chemical changes and structural modifications [4]. In living cells, the irradiation effects through the induction of genomic, biochemical, physiological and morphogenetic changes [45]. One of the main effects is the direct energy dissipation and damage to macromolecules such as nucleotides by breaking single and double bonds and inducing the cell apoptosis [46], showing in **Figure 2**.

On the other hand, in UV radiation processes, energy deposition occurs primarily through indirect mechanisms rather than direct ionization. Unlike ionizing radiation gamma-ray and EB), UV radiation does not have sufficient energy to directly ionize atoms or molecules. Instead, it primarily operates through indirect processes like the photoelectric effect and excitation of electrons to higher energy states. While these processes can lead to chemical reactions and alterations in molecular structures, the energy deposition is considered indirect in the context of UV radiation.

Indirect effects

Indirect energy deposition involves an intermediate step in which molecules known as sensitizers absorb the ionizing radiation. These sensitizers, often present in the material being processed, subsequently transfer the absorbed energy to the target molecules. The application of non-ionizing radiation, such as UV light, is explicitly covered by photolysis. Sensitizers can also be involved in absorbing non-ionizing light and starting photochemical reactions, which is why photolysis and indirect energy deposition are associated even if they are not directly related to ionization. For the purpose of material modification, pollutant degradation, or other uses, it is important to comprehend these interactions while developing radiation processing systems. This process can contribute to the formation of ROS and other secondary reactions.

In ionizing radiation, including gamma-ray and EB radiation, indirect energy deposition is

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crucial in biological systems, where water molecules frequently act as sensitizers. Understanding the interplay between direct and indirect mechanisms is fundamental in tailoring radiation processing techniques to achieve optimal results, whether it is pollutant degradation or material enhancement. For example, in gamma radiation and EB radiation, ionization of water molecules occurs, leading to the formation of hydroxyl radicals (•OH), hydrogen radicals (•H), and hydrated electrons [36] [47] [35]. Additionally, indirect radiochemical effects play role in cell inactivation, for example, the formed free radicals and reactive oxygen species can damage nucleic acids (**Figure 2**) and other cellular material or compartments [46]. On irradiating polymers in dilute or semi-dilute solutions, the effects of ionizing radiation are minor importance and can be neglected when in mechanistic considerations. It means that water absorbs practically all of the energy, and that the reactive byproducts of water radiolysis can then attack the macromolecules, causing reactions in the system's polymer component. Consequently, radiation has an indirect influence on the polymer [45]. In addition, through indirect and/or direct means, ionizing radiation can degrade non-biodegradable organic pollutants like pesticides, pharmaceuticals residues, and other pollutants in aquatic environments. Since both potent oxidizing and reducing species are produced during water radiolysis, this technology has the remarkable advantage over other advanced oxidation processes (AOPs) in that pollutant molecules can be broken down in both oxidative and reductive ways [61]. For instance, hydrogen peroxide (H_2O_2) and hydroxyl radical radical OH are oxidizing species, while hydrogen atom H, superoxide radical anion O_2^- and hydrated electron e_{aq}^- are reducing agents [62] [63].

$$H_2O \rightarrow \bullet OH\ (2.7) + e_{aq}^-\ (2.6) + \bullet H\ (0.55) + H_2\ (0.45) + H_2O_2\ (0.71) + H_3O^+\ (2.6) \qquad (1)$$

In Eq. (1), the number in brackets refers to chemical yield (G-value), presenting the number of species formed per 100 eV of energy absorbed, at a pH ranged from 6.0 to 8.5 [64].

TYPES OF CONTAMINANTS AND THE EFFICACY OF RADIATION

The radiation techniques, such as UV, gamma, and EB radiation influence a number of microrganisms and a variety of pollutants found in agricultural wastewater, as illustrated in **Table 1 and 2**. These methods can successfully target and address several groups of contaminants, including pesticides, pharmaceutical residues, microorganisms, and other organic pollutants.

Pesticides

The radiation procedures are an efficient way to deal with the presence of pesticides, a prevalent class of toxins present in agricultural wastewater [2] [8]. Pesticide residues can be broken down and degraded by oxidation and chemical reactions by UV, gamma, and EB radiation. High-energy radiation fragments and degrades pesticide molecules by rupturing the chemical links that hold them together [3] [9]. The reactive species produced during radiation, like hydroxyl radicals, aid in the oxidation and decomposition of pesticide chemicals. Ferhi et al. [48] use UV-C to remove and reduce herbicide and insecticide, such as atrazine (ATR), malathion (MAL) and glyphosate (GLY) in wastewater. The possible environmental impact of pesticide residues in agricultural wastewater is minimized as a result of this technique. It is significant to remember that the efficacy of radiation procedures for pesticides may differ depending on elements like the particular pesticide molecule, its chemical makeup, and the presence of other elements in the wastewater that may compete for the absorption of radiation energy [9] [7] [49].

Some research reported that radiation techniques have been demonstrated to effectively reduce pesticide residues in water systems [2] [8] [16]. Pesticides are often persistent and can pose environmental risks if not properly removed. Radiation methods offer an efficient approach for their degradation. The oxidative properties of radiation, particularly through the generation of hydroxyl radicals, facilitate the breakdown of pesticide molecules [7] [50]. UV-C, for instance, was removed 70-80% MAL in 25 min from the groundwater, 75% of GLY was eliminated after 10 min irradiation at concentrations higher than those found in natural groundwater [48]. Ferhi et al [48] also was completely eliminated ATR after 15 min photodegradation while more than 75% was reduced from the turbid wastewater after 25 min. Dichlorvos (2,2-dichlorovinyl dimethyl phosphate, DDVP) is an organophosphorus

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pesticide that has been classified as highly hazardous chemical that photodegradation DDVP could occur under simulated sunlight in the presence of dissolved oxygen providing an alternative degradation mechanism to the typically suggested partial hydrolysis in water [32]. Radiation disrupts the chemical bonds within the pesticides, leading to their degradation into simpler and less toxic forms [51] [49].

In another study, the photocatalytic degradation of organophosphorus pesticides such as methyl parathion (MP) and parathion (PA) under UV irradiation is investigated using synthesized Zinc oxide (ZnO) nanocatalyst at 85 mg/L, required oxygen demand of 40% with rate constants [52]. Under such conditions, a 93 ± 2.5% degradation of MP and PA was achieved. It also proves more efficient photonanocatalyst for the oxidation and decomposition of the pesticides proceeded at higher reaction rates. Sharma et al. [52] explain when ZnO nanoparticles are added to a photocatalytic system, it can enhances the reaction rate and acts as catalyst. It is attributed to the photogenerated electron being trapped, which prevents electrons and holes from recombining. It is necessary to ascertain the ideal catalyst dosage for the highly efficient degradation of organophosphorus (OP) pesticides in wastewater.

Pharmaceutical residues

The pharmaceutical residues also found in agricultural wastewater. These residues can enter wastewater through various pathways, including the disposal of unused pharmaceuticals, excretion by humans and animals [6] [8], and runoff from areas where pharmaceuticals are applied [9] [8]. Sources of this pollutant primarily originate from the use of pharmaceutical products in human healthcare [1] [20], veterinary medicine [6] [53] [19], and aquaculture [14] [54]. According to research of Al-Qaim et al [55], there are 11 pharmaceutical residues, such as caffeine, prazosin, enalapril, carbamazepine, nifedipine, levonorgestrel, simvastatin, hydrochlorothiazide, gliclazide, diclofenac-Na, and mefenamic acid. Vymazal et al [56] described that only seven substances (ibuprofen, diclofenac, metoprolol, furosemide, hydrochlorothiazide, paracetamol, and caffeine) were found in all samples of inflowing water, and seven substances (clarithromycin, gabapentin, ketoprofen, triclocarban, triclosan, warfarin, and tramadol) were found in more than 75% of samples of inflowing wastewater. Besides, ibuprofen (IBU) which is a pharmaceutical drug that is classified as a non-steroidal anti-inflammatory drug (NSAID) that investigated in agricultural soil and IBU has been detected in Gran Canaria in reclaimed water for irrigation and in groundwater, recently [57] [58]. In addition, three regularly used CCBs, a class of pharmaceuticals that includes AML, DIL, and VER, were the subject of an investigation by Zhu et al [28]. Furthermore, in human excretion, improper disposal of unused medications, and wastewater from hospitals and pharmaceutical manufacturing also facilities such as patient urine and excrement as well as hospital liquid waste contribute to the presence in the soil, surface waters, and wastewater collecting system [22]. Furthermore, in the case of animal farming, the use of veterinary medicine and growth promoters can also produce the pharmaceutical residues [53].

Pharmaceuticals, which can enter water sources through various pathways, pose concerns due to their potential environmental impact and risks to human health [59] [50]. The mechanisms involved in radiation (UV or solar light radiation), such as oxidation and degradation, can effectively break down pharmaceutical compounds [60], including CCBs (AML, DIL, and VER) [28]. The removal efficiencies of AML, DIL and VER in the wastewater treatment plant (WWTP) effluent were 100%, 21% and 32% at 100 mJ/cm^2, respectively [28]. Besides, a medium-pressure (MP) ultraviolet (UV) system proved to be more efficient to maximize the bench-scale degradation of the selected group of compounds (ketoprofen, naproxen, carbamazepine, ciprofloxacin, clofibric acid, and iohexol) by both UV photolysis and UV/H_2O_2 oxidation [61]. At UV fluences of 100mJ/cm^2, the contaminants (such as ciprofloxacin and ketoprofen) were surprisingly well removed by LP-UV photolysis, while other contaminants were also removed, albeit to a lesser extent, by low-pressure (LP) UV photolysis and the UV/H_2O_2 AOP. However, in the MP-UV system, the removal of iohexol and clofibric acid at low UV fluences (40 and 100 mJ/cm^2) did not increase considerably, except the MP removal of carbamazepine, clofibric acid and naproxen will increase to 13%, more than 30%, and 52%, respectively [61].

It has been studied how gamma radiation can cause the anti-inflammatory drug diclofenac to break down in aqueous media. The findings demonstrated that as the absorbed dose increased,

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the concentration of diclofenac gradually decreased. Nearly 97% of the diclofenac in a 4.5 mg L-1 aqueous solution was degraded after exposure to radiation at an absorbed dose of 1015 Gy [36]. In the research of Chu et al. [41] use irradiation technique to degrade cephalosporin C, a β-lactam type of antibiotic [62], with the removal efficiency of 85.5% for radiation at dose of 100 kGy [41]. Similarly, Chen et al [63] reveal that ionizing radiation was effective to degrade cephalosporin C at concentration 0.02–0.2 mM in aqueous solution, at 0.4 - 2.0 kGy. Total organic carbon (TOC) reduction reached 5–28% at 2.0 kGy. In EB technique, can degrade two fluoroquinolone antibiotics (ciprofloxacin and norfloxacin) which investigated in 0.1 mmol dm^{-3} aqueous solutions.

Pathogens or microorganisms

The microbiological pollutants, such as bacteria, viruses, parasites, and other diseases that can be effectively removed using radiation procedures [10] [19]. Ravanat and Douki [10] stated that ionizing radiation, including UV radiation, can damage the DNA of microorganisms and viruses, leading to their inactivation or death. Additionally, Chu et al. [19] added that the combined treatment of gamma radiation and persulfate resulted in no antimicrobial activity against *E. coli* and *S. aureus*, suggesting that radiation alone may not be sufficient to eliminate microorganisms in different water metrics. Waterborne diseases are less likely because radiation-induced damage to DNA and RNA limits the ability of germs to spread and cause infections. It is unnecessary to use conventional disinfectants and there is low risk of the production of disinfection byproducts because using radiation techniques for microbial disinfection [7] [4]. In addition, these methods provide broad-spectrum disinfection, successfully eradicating a variety of microbiological pollutants [14] [5] [20].

The high-energy radiation damages the genetic material (DNA/RNA) of pathogens, preventing their replication and rendering them non-infectious. UV, gamma, and EB radiation exhibit strong disinfection capabilities. UV radiation, for instance, has been reported as an appropriate technique for inactivating coliforms and *Salmonella* spp. destroying the genetic material of the bacterial cell [11]. In another study comparing low-pressure mercury arc lamps and ultraviolet light-emitting diodes (UV LEDs) for water disinfection, it was found that LP UV achieved a 4-log10 reduction in pathogens with the following doses: *E. coli* B at 6.5 mJ/cm^2, a non-enveloped virus 2 at 59.3 mJ/cm^2, and *Bacillus atrophaeus* at 30.0 mJ/cm^2. For UV LEDs, the 4-log_{10} reduction doses were 6.2 mJ/cm^2 for *E. coli* B, 58 mJ/cm^2 for non-enveloped virus, and 18.7 mJ/cm^2 for *B. atrophaeus* [64].

UV-C and to a lesser extend UV-B photons are directly absorbed by DNA bases, generating their excited states that are at the origin of the formation of pyrimidine dimers [10]. The pyrimidine dimers are a type of DNA damage that can be induced by UV radiation. They are formed when two adjacent pyrimidine bases (thymine or cytosine) in the DNA strand become covalently linked, forming a dimer structure, such as cyclobutane pyrimidine dimers (CPDs), are the most frequent type of pyrimidine dimers formed in DNA exposed to UV radiation. CPDs can be produced by absorption of UV-B and UV-C radiation, as well as UV-A radiation. Another type is the pyrimidine (6-4) pyrimidone photoproducts (64PPs), which are produced by UV-C and UV-B radiation but not UV-A radiation. The formation of pyrimidine dimers is often explained in terms of a photoreaction involving the double bond of one pyrimidine base and the keto or imino group of an adjacent base. The dimers can cause structural distortions in the DNA helix and interfere with DNA replication and transcription, leading to mutations and other DNA damage [10].

Radiation has an impact on living cells, such as yeasts, moulds, bacteria, and virues by inducing changes in the genome, the body's biochemistry, its physiology and morphology [45]. Ionising radiation's mode of action is therefore widely acknowledged to involve a more or less severe denaturation of cellular components. Direct energy loss, damage to macromolecules like nucleotides by breaking single and double strand, and cell death are a few of the main impacts (**Figure 2**). Additionally, indirect radiochemical effects contribute to cell inactivation. For instance, free radicals and ROS produced during radiochemical reactions can harm nucleic acids and other cellular components like membranes and important enzymes. The hydroxyl •OH radical is the most common disruptor due to its strong oxidizing power. This radical is responsible for irreversible damage to the

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biological molecules near its formation. In addition, produced during the radiolysis of water are other extremely reactive substances such H_3O^+, H•, HO•, and e-hydrated (the hydrated electron), which are crucial in cellular destruction [18] [46].

Other organic pollutants

Radiation techniques, such as UV, gamma, and EB radiation, have proven to be highly effective in reducing organic pollutants in water systems [35] [65] [50]. Pyridine, indole, and quinoline are organic compounds, all belonging to the class of heterocyclic aromatic compounds, which incorporate carbon atoms into their molecular structure. Pyridine is characterized by a six-membered ring featuring five carbon atoms and one nitrogen atom, while indole exhibits a five-membered ring comprising four carbon atoms and one nitrogen atom. Quinoline, on the other hand, is distinguished by a fused ring structure composed of both a benzene ring and a pyridine ring [66]. These compounds, originating from diverse sources, including coal tar and agricultural activities employing pesticides, fertilizers, and other chemicals, can find their way into wastewater systems. The presence of pyridine, indole, and quinoline in agricultural wastewater is particularly significant, as it can give rise to environmental concerns stemming from their potential toxicity and persistence [66] [67].

The mechanisms of degradation, such as photolysis and oxidation, break down complex organic molecules into simpler and less harmful compounds. For example, five intermediate products were investigated during indole degradation, including 3-methylindole, 3-methylinodle radicals, hydroxylation inodole, anilinoethanol and isatoic acid. The possible pathway of indole degradation was proposed by [39]. He et al [39] reveal that both acute toxicity and chronic toxicity of intermediate products of indole degradation were significantly reduced with results that showed the removal efficiency of indole was 99.2%, except for 3-methylindole [39]. However, in other research, He et al [68] stated that 3-methylindole were investigated with results showed that the removal efficiency of 3-methylindole was 96.2% when initial concentration was 20 mg/L, absorbed dose was 3 kGy, and pH was 3. Furthermore, under UV irradiation (= 365 nm), Jing et al. [69] achieved 91.5% quinoline removal in aqueous solution with suspended TiO2 nanoparticles (average size of 16 nm). Thus, By exposing water containing organic pollutants to UV radiation, the energy from UV photons disrupts the chemical bonds in the pollutants, leading to their degradation [50].

KEY PROCESS PARAMETERS

Radiation Dose

The amount of radiation energy provided to the wastewater throughout the treatment process is referred to as the radiation dose. The radiation dose varies significantly depending on the application [2] [3] [70]. Moreover, it can be industry-specific. The ideal or most effective radiation dose varies based on the specific industrial application or process. In other words, the optimal radiation dose may differ from one industry to another, depending on the materials being treated, the desired outcomes, and safety considerations. This variability is determined by the specific needs and requirements of a particular industry or application. In wastewater management, with an initial concentration of 10 mg/L and an absorbed dose of 2 kGy, He et al. [39] demonstrated almost 100% removal efficiency for indole, and 3 kGy with initial concentration 20 mg/L of 3-methylindole was 96.2%. Chu et al. [71] also used gamma radiation (7.0 kGy) to obtain more than 90% of quinoline removal and, after combining it with TiO_2 nanoparticles, the degradation rate increased 1.5 times. On the other hand, Verde et al. [72] employed gamma radiation in the dose range of 5.3 to 40.2 kGy to investigate two wastewater samples (from municipal and slaughterhouse treatment plant), and their research successfully contributed to the inactivation and biodegradation processes. However, to reconcile the desired therapeutic outcomes with cost considerations, the dose must be carefully calibrated. Inadequate radiation dose may lead to insufficient contaminant breakdown, leaving behind persistent pollutants or diseases. On the other side, excessive doses might result in energy waste, the possibility of treated water degradation, or the production of toxic byproducts [7]. The individual pollutants, their radiation resistance, and the intended level of treatment must all be taken into account when determining the proper radiation dose by UV [73], gamma [11] [65], or EB radiation [18].

Dose Rate

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The radiation time is yet another important factor affecting the effectiveness of the treatment [73] [65] [74]. Higher degradation rates and greater disinfection effectiveness are often brought on by longer radiation periods. Depending on the particular pollutants, their concentration, and the needed level of treatment, the ideal radiation time will vary. In UV-C radiation, the required exposure time typically ranges from seconds to minutes [48] [49], or minutes [75], and in some cases, it may extend from minutes to hours [33]. Conversely, in gamma-ray, the exposure time varies from seconds to hours [76], minutes [71] [39], and even hours [2] [72]. Similarly, in EB radiation, the exposure time spans from seconds to hours [76] [44].

The degradation and disinfection processes are improved by longer exposure intervals because they allow for a more comprehensive interaction between the radiation and pollutants. When establishing the ideal radiation period, practical factors like treatment capacity, energy consumption, and overall system performance should also be taken [77] [78]. In ionizing radiation, Tegze et al [24] use two samples of pharmaceutical residues (ciprofloxacin and norfloxacin) for the end-product experiments were irradiated in a panoramic type 60 Co-γ irradiation chamber with 8 kGy/hr dose rate. However, in wastewater microbiota, Verde et al. [72] stated that the inactivation response of total coliforms by gamma radiation is not significantly influenced by the dose rate and substrate composition, probably due to the high sensitivity of this type of microorganism to gamma radiation and the lengthy irradiation period needed when low dose rates are used, the repair mechanisms of bacteria can respond more effectively.

Radiation source

UV-C radiation, or ultraviolet C radiation, is typically generated by LP mercury vapor lamps or UV-C LEDs [32] [64] [79] (**Table 3**). This form of UV radiation falls within the wavelength range of 225–300 nm and is widely recognized for its germicidal properties, efficiently inactivating microorganisms [79], including bacteria and viruses [64] by damaging their genetic material, and degrading agriculture pollutant, including pesticides [32] [48] and pharmaceutical residues [28]. Besides, gamma-ray arise from the atomic nucleus and are produced through the decay of radioactive isotopes (Co-60 and Cs-137) [42] [76] that have characterized by its extremely short wavelength and high energy. This radiation serve various purposes, one of them in agriculture wastewater [2]. Additionally, EB radiation is generated by accelerating electrons through an electric field using electron or linear accelerators, and measured in electronvolts (eV) [80] [81]. EB find application in sterilizing medical devices, cross-linking polymers in materials production [43], and degrading contaminants in agricultural wastewater treatment [80]. Each radiation source is selected based on its specific properties and suitability for the intended applications.

Characteristics of wastewater

The properties of the agricultural wastewater that is being treated have a big impact on how effective radiation methods are. The treatment process can be impacted by variables like pH, turbidity, organic load, suspended solids, and the presence of interfering compounds [73] [18]. High turbidity or suspended particulates might hinder radiation's ability to penetrate the water and impact how well it interacts with contaminants. To maximize the effectiveness of the radiation in such circumstances, pre-treatment procedures like filtration or sedimentation may be required. For example, two different types of wastewater samples, such as a municipal wastewater treatment plant (MWTP) and the other from a slaughterhouse treatment plant (SWTP) [72]. With a flow rate of 54,000 m^3 effluent per day from a population of 215,000 inhabitants, the MWTP in Lisbon, Portugal, primarily uses gravity and pumping, screening, grit, oil, fat, and grease removal, primary sedimentation, activated sludge reactor, secondary sedimentation, sand filters, and UV irradiation as tertiary treatment. Before the UV treatment, samples of 1 L volume were taken from the effluent and transported at 4^0C to the lab in sterilized flasks. Whereas, the SWTP produces approximately 143 ton of hog meat daily and generates solid residues and wastewater. It takes 7 days for wastewater to be treated, a continuous process that includes anaerobic and aerobic digestion as well as sedimentation lagoons. After mechanical screening, which included the removal of solids, samples of 5 L were taken from primary-treated wastewater in sterilized flasks and transported at 4^0C to the lab [72].

pH

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In treatment methods based on radiation, the pH of the wastewater is crucial. pH can affect the level of ionization, reactivity, and production of reactive species during radiation of pollutants [77] [78]. At various pH levels, some pollutants may show varying degrees of ionization [18], which may alter how susceptible they are to destruction. The production and reactivity of hydroxyl radicals (•OH), which are essential for pollutant removal, can also be impacted by the pH of the wastewater [78]. UV radiation, for instance, has optimized pH conditions at 7 to degrade three calcium channel blockers [28]. Yet, for other pollutants, like indole and 3-methylindole, have pH conditions at 5 and 3, respectively [39] [68]. The effectiveness of pollutant removal during radiation can be increased by adjusting the pH conditions. To reach the correct pH range for effective treatment, pH modification may involve pre-treatment procedures like pH buffering or the inclusion of suitable chemicals.

Temperature

Temperature may affect the kinetics of the reaction, the solubility of the contaminants, and the production of reactive species during radiation [73] [78]. In general, UV, gamma and EB radiation have room or ambient temperature for various purposes. Higher temperatures encourage quicker reaction times, which can hasten the breakdown of pollutants. Elevated temperatures can also make some pollutants more soluble, making them more accessible to radiation and encouraging more effective clearance. The effect of temperature on radiation-based treatment, however, varies depending on the particular pollutants and process circumstances and is system-specific.

BENEFITS AND LIMITATIONS

The Advantages of Using Radiation Techniques

The employment of radiation techniques in the management of agricultural wastewater has a number of benefits that make it a desirable and adaptable choice for contaminant removal, as shown in **Table 3**. Some major benefits include:

- **Broad spectrum of contaminant removal**. Agricultural wastewater contains a variety of toxins that can be targeted by radiation treatments. The production of reactive species during radiation can effectively destroy organic contaminants, such as pesticide, herbicide, and medicinal residues [27]. Additionally, microbiological pathogens including bacteria, viruses, and parasites can be inactivated or destroyed by radiation [65], which has disinfectant effects [40] [4]. Radiation is a comprehensive method for treating agricultural wastewater since it can remove a wide range of contaminants.

- **Versatility and applicability**. Since they are adaptable, radiation techniques can be used with a variety of agricultural effluent [1]. Depending on the particular needs of the wastewater treatment facility, they can be used in a variety of treatment configurations, including batch or continuous flow systems [27]. Radiation procedures can also be combined with other processes, like biological treatment [13] or filtration [27], to increase the effectiveness of the treatment as a whole. Radiation is ideal for a range of agricultural wastewater treatment scenarios because of its versatility [18].

- **Chemical-free process**. Radiation treatments have the important benefit of not using any chemicals. Balakrishnan et al [65] stated that radiation does not leave chemical residues after the treatment to the wastewater, unlike certain chemical-based treatments. This ensures a cleaner and more ecologically friendly treatment method by removing the possibility of the accumulation of chemical residues [50] [81] or the creation of dangerous disinfection byproducts [7]. Additionally, it eliminates the requirement for chemical agent storage, handling, and disposal, streamlining the entire treatment procedure.

- **Rapid treatment response**. Radiation techniques provide effective pollutant removal within comparatively short contact durations by providing a quick treatment response [77], including seconds, minutes, hours, and days. When contaminants are exposed to radiation, such as hydroxyl radicals (•OH), are produced, which causes pollutants to degrade and become inactive quickly. This quick response from the treatment system enables efficient and speedy wastewater treatment,

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cutting down on overall treatment time and raising operational effectiveness [27].

- **Decreased sludge production**. The generation of sludge is often decreased when using radiation techniques in comparison to some conventional treatment procedures [40] [27]. Lower sludge production is frequently the result of the breakdown of organic contaminants and microbial inactivation under radiation [40] [21]. Additionally, Al-Gheethi et al. [11] stated that bacterial inactivation by UV radiation approximately to 99.99%. This lessens not just the amount of trash produced, but also the expenses and difficulties of managing sludge, such as disposal and the dangers of secondary pollution [78].

- **Compatibility with existing treatment processes**. It is simple to include radiation techniques into the current wastewater treatment systems [34]. They can improve the effectiveness of treatments overall by acting as a supplementary step to traditional ones. The implementation of this technology is made possible by the adaptability and compatibility of radiation techniques, which enable flexible retrofitting or modification of existing treatment plants without causing major infrastructure changes or disruptions [27] [34].

- **Potential for resource recovery**. Radiation techniques have the ability to recover resources from agricultural wastewater in addition to removing contaminants. For instance, the oxidation of organic contaminants during radiation can produce carbon dioxide [37], which can be trapped and possibly used for processes like the growth of algae or the creation of renewable energy [82]. The possibility of resource recovery enhances the treatment procedure and helps keep agricultural wastewater management sustainable [50] [83].

The Limitations and Challenges

- **Energy consumption**. Radiation procedures might demand significant energy inputs when substantial radiation doses are required for efficient pollutant removal. Besides, Chen et al. [33] explained that one challenge to destructing complex groups of synthetic chemicals like perfluoroalkyl is the need for high energy consumption. Additionally, particularly for large-scale applications, the energy consumption of radiation systems can be a constraint. In order to reduce energy consumption and guarantee cost-effectiveness [19], efficient system design and optimization procedures are essential [84].

- **Cost**. Implementing radiation treatments might be expensive (high cost) associated with its installation [1], especially in comparison to traditional method options. Bartolomeu et al. [40] explained that the issue of chemical contaminants in the environment is still a problem since conventional methods employed in wastewater treatment are limited and have significant operational and capital expenses. Further, the initial cost of purchasing, installing, and equipping oneself with radiation sources might be high. In addition, operating expenditures like energy and maintenance must be taken into account. But as technology develops and economies of scale take hold, expenses might eventually go down [27] [75].

- **System design and engineering**. For radiation techniques to be used effectively, proper system design is essential [84] [34]. To guarantee the best radiation exposure and treatment results, factors like reactor configuration [65], radiation source placement [65], and hydraulic design must be properly taken into account. To achieve the required treatment goals, the design must also take into account elements like flow rate [27], contact time [27], and radiation dose [65]. Subpar performance and decreased treatment efficacy can result from inadequate system design.

- **Waste disposal**. Depending on the radiation source used, radiation processes may produce radioactive waste [23]. Adeola et al. [22] explained that exposure to high concentrations of radioactive elements causes health concerns. In addition, they obtain reports that many rivers and potable water in several parts of Europe and Asia have recorded radionuclide concentrations much higher than the permissible level of 1 Bq/L. Thus, to avoid risks to the environment and public health [22], radioactive waste must be managed, stored and disposed of properly. Even, high-level radioactive wastes must be stored for a longer period (>50 years) than low-level radioactive wastes before being disposed [22] [85]. To guarantee the safe handling and disposal of radioactive materials, compliance with pertinent laws, rules, and regulations is essential [23] [22].

- **Byproduct formation**. Byproducts may develop during radiation as a result of the breakdown of pollutants or interactions with other elements in the effluent [36]. Several organic byproducts of diclofenac such as 2,6-dichlorophenol (2,6 DCP), 4-chlorocatechol (4-Clcat), catechol (Cat), and hydroquinone (HQ) were characterized by high performance liquid chromatography (HPLC). In similar, Chen et al. [63] also found byproducts after using gamma irradiation destroying the cephalosporin C, including byproducts with opened β-lactam ring and dihydrothiazine ring, as well as formic acid, acetic acid and sulfate, were found, proving that gamma irradiation destroyed the CEP-C's active position. Hydroquinone, 2,6-dichlorophenol, 4-chlorcatechol, Cl^-, NH_4^+, and CH_3COO^- are some of the organic and inorganic byproducts founded by Nisar et al [36] using gamma-ray. In other study, UV irradiation for ARGs in wastewater treatment plants (WWTP) effluent can be partially removed and produced disinfection byproducts when doses are higher than those typically reported in WWTPs [86]. Besides, in 2018, Miklos et al [87] analysed the most recent AOPs, the primary reaction mechanisms, and the generation of byproducts in several major groups for the removal of contaminants from water. Additionally, a benefit of UV-C disinfection system for treating aqueous effluent in contact with food or vegetables is that it produces fewer hazardous byproducts than AOPs that use catalysts [32]. Further, UV-C treatment of MAL in the presence of TiO_2 catalysts results in the production of highly hazardous phosphate byproducts [88]. In contrast, Singh et al. [89] stated that there are no toxic byproducts or chemical residues generated after UVC-based food disinfection.

- **Treatment efficiency for some contaminants**. While a variety of organic pollutants can be successfully removed or degraded using radiation techniques, some contaminants could be resistant to degradation or need higher radiation doses for effective elimination [6]. In addition, organic pollutants from wastewater with 70 and 80% degradation efficiency for dye and Bisphenol A, respectively using UV or visible light radiation [77]. Even, in an aqueous solution containing As^{5+} and Cr^{6+} a synthesized 3D-Fe_2O_3 was used to achieve nearly a hundred percent removal rates using solar light radiation and photocatalytic activity [77] [90]. Then, some complex or persistent organic contaminants may be less amenable to radiation, requiring further processing or alternate technologies to completely remove them.

- **Safety and Regulatory considerations**. Regulations and permissions may apply to the use of radiation techniques. It might be necessary to comply with environmental laws, and radiation permits [89]. To protect the safety of workers, the environment, and the general public, it is crucial to make sure that the application of radiation techniques complies with the relevant legislation and norms. Despite these restrictions and difficulties, continuous research and technology improvements keep these problems in mind and work to address and resolve them. These issues can be resolved and radiation techniques can become a more viable and sustainable choice for the treatment of agricultural wastewater with continued innovation in system design [27], energy efficiency [27], cost-effectiveness [21] [89], and waste management [23]. Before choosing to use radiation techniques, it is essential to do feasibility studies, weigh costs and benefits, and analyze the unique site characteristics. In UV utilization, ensuring safe installation, adherence to lamp safety standards, and establishing safety margins for exposures are crucial considerations [91]. On the other hand, in the context of gamma-ray, integrated design innovation, effective radiation shielding [83] [12], and proper management of radioactive waste [92] are of paramount importance.

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Similarly, for EB radiation, integrated design innovation, incorporating features like automatic control, guided vehicles and rails, sealed doors, radiation shielding, and comprehensive safety precautions, is essential [89].

IMPLEMENTATIONS IN DIFFERENT AGRICULTURAL SECTORS

Crop irrigation

One of problems in crop irrigation is accumulation of pharmaceutical residues like antibiotics and micropollutants in the irrigated/agricultural soil [11] [57] and inflowing wastewater [56]. Malchi et al [93] described that pharmaceutical compunds (PCs), including carbamazepine, caffeine, and lamotrigine were detected at significantly higher concenterations than ionic PCs (metoprolol, bezafibrate, clofibric acid, diclofenac, gemfibrozil, ibuprofen, ketoprofen, naproxen, sulfamethoxazole, and sildenafil). PCs were identified in leaves at higher levels than in roots. The concentration of the metabolite 10,11-epoxycarbamazepine was substantially higher than the parent drug in the leaves, where carbamazepine metabolites were primarily observed. The threshold of toxicological concern (TTC) technique was used to calculate the potential health risk associated with eating root vegetables grown utilising wastewater irrigation. Our findings indicate that a child everyday at a daily consumption of half a carrot (or about 60 g) and still attain the TTC value of lamotrigine [93]. In other case, one of research reported that there are many microorganisms in pharmaceutical wastewater in Nigeria, such as *E. coli, Salmonella sp., Klebsiella sp., P. aeruginosa, S. aureus, P. vulgaris, Clostridium sp.* and *E. faecalis* [11] [94] [95].

Arzate et al [1] performed a comparative analysis between the ozonation and the photo-Fenton process (UV light radiation) as tertiary wastewater treatment in Almeria, Spain. These techniques are able to produce reclaimed wastewater for agricultural irrigation. Furthermore, in other research explain compounds that contribute to odor and color problems in agricultural effluent [46]. This condition can lead to negative impact in crop irrigation and surrounding. Thus, by destroying the chemical components, radiation procedures like UV and EB radiation can efficiently diminish these qualities. The complex organic molecules are broken down by the reactive species produced during radiation, which also removes color and reduces odor, enhancing the overall aesthetic quality of the treated effluent. These effective uses show how radiation techniques can remove different impurities and raise the caliber of agricultural wastewater. It is crucial to remember that the precise efficacy of radiation procedures can change based on the kind and quantity of pollutants, water quality indicators [8], and system design factors. To evaluate the applicability and efficacy of radiation techniques in agricultural wastewater management applications, site-specific feasibility studies and pilot-scale tests are essential.

Livestock farming

Agricultural wastewater from livestock areas is known to contain a variety of contaminants, posing potential threats to both the environment and public health. One major category of contaminants includes pathogens, such as bacteria, viruses, and parasites, commonly found in animal waste. When untreated, these microorganisms can lead to waterborne diseases in humans and other animals. Another significant concern is the presence of nutrients, particularly nitrogen and phosphorus, abundant in animal manure. While essential for plant growth, an excess of these nutrients in water bodies can result in nutrient pollution. This can manifest as issues like algal blooms, which have detrimental effects on aquatic ecosystems, causing oxygen depletion and disrupting the balance of the aquatic food chain. Livestock wastewater may also contain various chemicals and pharmaceutical residues. These include veterinary drugs, antibiotics, and hormones used in animal husbandry. Runoff from these substances, combined with chemicals used in agricultural practices, can contaminate water sources, raising ecological and health concerns [54] [75].

Addressing the challenges associated with livestock wastewater requires the implementation of effective wastewater management practices. These practices encompass a range of strategies, including treatment methods, runoff control measures, and the adoption of best management practices within the agricultural sector. One innovative approach involves the use of radiation techniques as part of wastewater treatment, presenting a valuable contribution to reducing the

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concentration of contaminants. This application is particularly relevant in livestock farming, encompassing diverse facilities such as dairy farms, poultry farms, and other agricultural operations [82] [54] [75].

Radiation techniques prove efficient in treating livestock wastewater, known for its high organic content and microbial contamination. The primary objectives include the elimination of organic contaminants, the inactivation of pathogens, and the reduction of potential environmental impacts. Following treatment, the wastewater can be responsibly released or recycled for various purposes, such as nutrient recovery or land irrigation. The successful integration of radiation techniques into livestock farming practices hinges on system optimization [82] [54]. This optimization considers crucial elements like wastewater composition, flow rates, and treatment goals. Recognizing the increasing importance of effluent and water management, especially in pathogen inactivation, becomes pivotal for the livestock farming industry. This perspective is vital not only for public health concerns [75], but also for aspects related to meat structure and tenderness, including considerations for Bos taurus and Bos indicus beef [96], sheep, and buffalo [97] [98]. The comprehensive approach to wastewater management becomes an integral factor in sustaining both environmental and animal health.

Food processing

One of cases is freshly picked spices are typically contaminated by microorganisms from the environment, such as dust and animal excrement. Other potential sources of microbial contamination for spices include native plant microorganisms, unhygienic food processing area dust, contaminated water sources and irrigation systems, improper pre- and post-harvest handling during processing, storage, and distribution, and unclean air. As a result, this may lessen the shelf life of foods that have spices added that are raw or hardly processed but pose a serious health risk [65]. With little impact on essential physical qualities, radiation effectively protects dried chili against dangerous germs. Furthermore, radiation treatment leaves no chemical residues behind, guaranteeing the dried chilli's purity and safety. The initial degree of contamination and the longevity of the dangerous bacterium are the key factors influencing radiation effectiveness. Although a minimum radiation dose of 10 kGy is needed for full sterilization, a modest radiation dose is adequate to reduce the microbial load to an acceptable level and eradicate pathogens in dried chili [65].

The treatment of wastewater produced during food processing processes makes use of radiation techniques [92] [65] [81]. Foodborne pathogens, suspended particles, and organic materials may all be present in the wastewater from food processing operations. To disinfect and destroy organic contaminants in wastewater, radiation techniques like UV, gamma and EB radiation can be used [4] [21]. This guarantees regulatory compliance and reduces possible threats to human health and the environment. The wastewater can then be safely released or put through additional treatment steps for resource recovery or reuse and promote sustainable practices [65].

It is significant to note that the application of radiation techniques in various agricultural sectors necessitates careful consideration of the requirements of the individual sectors, the characteristics of the wastewater, and the regulatory frameworks. In order to evaluate the applicability, cost-effectiveness, and possible effects of radiation techniques in each agricultural sector, site-specific assessments, feasibility studies, and pilot-scale testing are required. For radiation-based wastewater treatment to be implemented and run sustainably in a variety of agricultural applications, good system design, process parameter optimization, and adherence to applicable regulations are essential.

CONCLUSION

In conclusion, radiation techniques have emerged as effective tools for agricultural wastewater management. The destruction of organic pollutants, the eradication of microbiological contaminants, the reduction of pesticides, pharmaceutical residues, and other dangerous compounds are all possible with the help of UV-C, gamma, and EB radiation. These methods have numerous uses in many areas, such as crop irrigation, livestock farming, and food processing. There are three important information related to these techniques:

1. UV-C radiation can effectively use for surface disinfection, pathogen inactivation, certain pesticides and pharmaceutical residues

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degradation, but it is primarily effective on surfaces and in air or water surface, as it has limited penetration capabilities. It may not reach microorganisms hiding in crevices or inside materials.

2. Gamma-ray more effective than UV for microorganism sterilization and inactivation, pesticide and pharmaceutical residues degradation, but this radiation are exvensive tool and facility, also it is generated from a radioactive source (Co-60 and/or Cs-137) which requires careful handling and disposal of the source material.
3. EB has high dose rate and selective penetration, the technique also has speed and precision, feasible for practical application for polymerization, disinfectan, sterilization, crosslinking, degradation and more environmentally friendly, but it has limited penetration depth and high cost.

To guarantee optimal treatment efficiency and reduce potential environmental and health concerns, it is vital to carefully analyze process parameters, system design, and adherence to safety requirements. While challenges such as energy consumption, cost, and proper system design exist, ongoing research and technological advancements continue to enhance the effectiveness and sustainability of radiation-based wastewater treatment processes.

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AUTHOR CONTRIBUTIONS

AK: Conseptualization, writing original draft, investigation; **IKM** and **ADS**: Editing, review and data exploration. **A**: Conceptualization, review and analysis, **MHS**: Review, visualization, and analysis.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

ABBREVIATIONS

AML : Amlodipine
AOPs : Advanced Oxidation Processes
ARGs : Antibiotic Resistance Genes
Bq/L : Becquerel per Liter
DIL : Diltiazem
CCBs : Calcium Channel Lockers
DDVP : 2,2-dichlorovinyl dimethyl phosphate
DNA : Deoxyribonucleic Acid
EB : Electron Beam
HPLC : High Performance Liquid Chromatogr.
IBU : Ibuprofen
LEDs : light-emitting diodes
LP-UV : Low Pressure Ultraviolet
MeV : Million Electron Volt
MP-UV : Medium Pressure Ultraviolet
MP : Methyl Parathion
MWTP : Municipal Wastewater Treatment Plant
OP : Organophosphorus
PA : Parathion
PBS : Phosphate-buffered saline
PCs : Pharmaceutical Compunds
PhACs : Pharmaceutically Active Compounds
PEGDA : Poly (ethylene glycol) diacrylate
RNA : Ribonucleic Acid
ROS : Reactive Oxygen Species
RONS : Reactive Oxygen and Nitrogen species
SWTP : Slaughterhouse Treatment Plant
TOC : Total Organic Carbon
TTC : The threshold of toxicological concern
UV : Ultraviolet
VER : Verapamil
WWTP : Wastewater Treatment Plant

DESIGN SOFTWARE PROGRAMS

The authors used Inkscape 1.2.2 (https://inkscape.org/id/release/0.92.4/windows/64-bit/) and Canva Pro and Free License (https://www.canva.com/id_id/) for illustration.

REFERENCES

[1] S. Arzate, S. Pfister, C. Oberschelp, and J. A. Sánchez-Pérez, “Environmental impacts of an advanced oxidation process as tertiary treatment in a wastewater treatment plant,” *Sci. Total Environ.*, vol. 694, no. 133572, 2019, doi: 10.1016/j.scitotenv.2019.07.378.

[2] T. Khedr, A. A. Hammad, A. M.

Elmarsafy, E. Halawa, and M. Soliman, “Degradation of some organophosphorus pesticides in aqueous solution by gamma irradiation,” *J. Hazard. Mater.*, vol. 373, pp. 23–28, 2019, doi: 10.1016/j.jhazmat.2019.03.011.

[3] K. Hossain, Y. A. Maruthi, N. L. Das, K. P. Rawat, and K. S. S. Sarma, “Irradiation of wastewater with electron beam is a key to sustainable smart/green cities: a review,” *Appl. Water Sci.*, vol. 8, no. 6, pp. 1–11, 2018, doi: 10.1007/s13201-018-0645-6.

[4] S. Shahi, R. Khorvash, M. Goli, S. M. Ranjbaran, A. Najarian, and A. Mohammadi Nafchi, “Review of proposed different irradiation methods to inactivate food-processing viruses and microorganisms,” *Food Sci. Nutr.*, vol. 9, no. 10, pp. 5883–5896, 2021, doi: 10.1002/fsn3.2539.

[5] T. Jäger *et al.*, “Reduction of Antibiotic Resistant Bacteria During Conventional and Advanced Wastewater Treatment, and the Disseminated Loads Released to the Environment,” *Front. Microbiol.*, vol. 9, pp. 1–16, 2018, doi: 10.3389/fmicb.2018.02599.

[6] D. Kanakaraju, B. D. Glass, and M. Oelgemöller, “Advanced oxidation process-mediated removal of pharmaceuticals from water: A review,” *J. Environ. Manage.*, vol. 219, pp. 189–207, 2018, doi: 10.1016/j.jenvman.2018.04.103.

[7] I. A. Saleh, N. Zouari, and M. A. Al-ghouti, “Removal of pesticides from water and wastewater : Chemical , physical and biological treatment approaches,” *Environ. Technol. Innov.*, vol. 19, p. 101026, 2020, doi: 10.1016/j.eti.2020.101026.

[8] M. de Oliveira, B. E. F. Frihling, J. Velasques, F. J. C. M. Filho, P. S. Cavalheri, and L. Migliolo, “Pharmaceuticals residues and xenobiotics contaminants: Occurrence, analytical techniques and sustainable alternatives for wastewater treatment,” *Sci. Total Environ.*, vol. 705, p. 135568, 2020, doi: 10.1016/j.scitotenv.2019.135568.

[9] A. Tawfik *et al.*, “Solar photo-oxidation of recalcitrant industrial wastewater: a review,” *Environ. Chem. Lett.*, vol. 20, no. 3, pp. 1839–1862, 2022, doi: 10.1007/s10311-022-01390-4.

[10] J. Ravanat and T. Douki, “UV and ionizing radiations induced DNA damage , differences and similarities,” *Radiat. Phys. Chem.*, vol. 128, pp. 92–102, 2016, doi: 10.1016/j.radphyschem.2016.07.007.

[11] A. A. Al-Gheethi, A. N. Efaq, J. D. Bala, I. Norli, M. O. Abdel-Monem, and M. O. Ab Kadir, “Removal of pathogenic bacteria from sewage - treated effluent and biosolids for agricultural purposes,” *Appl. Water Sci.*, vol. 8, pp. 1–25, 2018, doi: 10.1007/s13201-018-0698-6.

[12] S. Dezhampanah, I. M. Nikbin, S. Mehdipour, and R. Mohebbi, “Fiber-reinforced concrete containing nano - TiO2 as a new gamma-ray radiation shielding materials,” *J. Build. Eng.*, vol. 44, p. 102542, 2021, doi: 10.1016/j.jobe.2021.102542.

[13] J. Wang, R. Zhuan, and L. Chu, “The occurrence, distribution and degradation of antibiotics by ionizing radiation: An overview,” *Sci. Total Environ.*, vol. 646, pp. 1385–1397, 2019, doi: 10.1016/j.scitotenv.2018.07.415.

[14] J. Wang and X. Chen, “Removal of antibiotic resistance genes (ARGs) in various wastewater treatment processes: An overview,” *Crit. Rev. Environ. Sci. Technol.*, vol. 52, no. 4, pp. 571–630, 2022, doi: 10.1080/10643389.2020.1835124.

[15] M. Arab, M. Jallab, M. Ghaffari, E. Moghbelli, and M. Reza, “Synthesis, rheological characterization, and antibacterial activity of polyvinyl alcohol (PVA)/ zinc oxide nanoparticles wound dressing, achieved under electron beam irradiation,” *Iran. Polym. J.*, vol. 30, no. 10, pp. 1019–1028, 2021, doi: 10.1007/s13726-021-00952-7.

[16] R. O. Abdel Rahman and Y.-T. Hung, “Application of ionizing radiation in wastewater treatment: An overview,” *Water (Switzerland)*, vol. 12, no. 19, pp. 1–

p ISSN 1907-0322
e ISSN 2527-6433

16, 2020, doi: 10.3390/w12010019.

[17] O. Desouky, N. Ding, and G. Zhou, "Targeted and non-targeted effects of ionizing radiation," *J. Radiat. Res. Appl. Sci.*, vol. 8, no. 2, pp. 247–254, 2015, doi: 10.1016/j.jrras.2015.03.003.

[18] A. Ashfaq *et al.*, "Polymerization Reactions and Modifications of Polymers by Ionizing Radiation," *Polymers (Basel).*, vol. 12, no. 12, p. 2877, 2020, doi: https://doi.org/10.3390/polym12122877.

[19] L. Chu, R. Zhuan, D. Chen, J. Wang, and Y. Shen, "Degradation of macrolide antibiotic erythromycin and reduction of antimicrobial activity using persulfate activated by gamma radiation in different water matrices," *Chem. Eng. J.*, vol. 361, pp. 156–166, 2019, doi: 10.1016/j.cej.2018.12.072.

[20] F. Palma, G. Baldelli, G. F. Schiavano, G. Amagliani, M. P. Aliano, and G. Brandi, "Use of Eco-Friendly UV-C LEDs for Indoor Environment Sanitization: A Narrative Review," *Atmosphere (Basel).*, vol. 13, no. 9, p. 1411, 2022, doi: 10.3390/atmos13091411.

[21] C. Hertwig, N. Meneses, and A. Mathys, "Cold atmospheric pressure plasma and low energy electron beam as alternative nonthermal decontamination technologies for dry food surfaces: A review," *Trends Food Sci. Technol.*, vol. 77, pp. 131–142, 2018, doi: 10.1016/j.tifs.2018.05.011.

[22] A. O. Adeola *et al.*, "Advances in the management of radioactive wastes and radionuclide contamination in environmental compartments: a review," *Environ. Geochem. Health*, vol. 45, pp. 2663–2689, 2023, doi: 10.1007/s10653-022-01378-7.

[23] D. Deng, L. Zhang, M. Dong, R. E. Samuel, A. Ofori-Boadu, and M. Lamssali, "Radioactive waste: A review," *Water Environ. Res.*, vol. 92, no. 10, pp. 1818–1825, 2020, doi: 10.1002/wer.1442.

[24] A. Tegze, G. Sági, K. Kovács, T. Tóth, E. Takács, and L. Wojnárovits, "Radiation induced degradation of ciprofloxacin and norfloxacin: Kinetics and product analysis," *Radiat. Phys. Chem.*, vol. 158, pp. 68–75, 2019, doi: 10.1016/j.radphyschem.2019.01.025.

[25] Y. S. Pavlov, V. V. Petrenko, P. A. Alekseev, P. A. Bystrov, and O. V. Souvorova, "Trends and opportunities for the development of electron-beam energy-intensive technologies," *Radiat. Phys. Chem.*, vol. 198, no. 110199, 2022, doi: 10.1016/j.radphyschem.2022.110199.

[26] M. Syafrudin *et al.*, "Pesticides in Drinking Water — A Review," *Int. J. Environ. Res. Public Health*, vol. 18, no. 2, p. 468, 2021.

[27] A. Barjasteh, Z. Dehghani, P. Lamichhane, N. Kaushik, E. H. Choi, and N. K. Kaushik, "Recent Progress in Applications of Non-Thermal Plasma for Water Purification, Bio-Sterilization, and Decontamination," *Appl. Sci.*, vol. 11, no. 8, p. 3372, 2021.

[28] B. Zhu *et al.*, "Degradation kinetics and pathways of three calcium channel blockers under UV irradiation," *Water Res.*, vol. 86, pp. 9–16, 2015, doi: 10.1016/j.watres.2015.05.028.

[29] Y. Deng and R. Zhao, "Advanced Oxidation Processes (AOPs) in Wastewater Treatment," *Curr. Pollut. Reports*, vol. 1, pp. 167–176, 2015, doi: 10.1007/s40726-015-0015-z.

[30] A. R. Ribeiro, O. C. Nunes, M. F. R. Pereira, and A. M. T. Silva, "An overview on the advanced oxidation processes applied for the treatment of water pollutants defined in the recently launched Directive 2013/39/EU," *Environ. Int.*, vol. 75, pp. 33–51, 2015, doi: 10.1016/j.envint.2014.10.027.

[31] J. L. Wang and L. J. Xu, "Advanced Oxidation Processes for Wastewater Treatment: Formation of Hydroxyl Radical and Application," *Crit. Rev. Environ. Sci. Technol.*, vol. 42, no. 3, pp. 251–325, Feb. 2012, doi: 10.1080/10643389.2010.507698.

[32] N. Bustos, A. Cruz-Alcalde, A. Iriel, A. Fernández Cirelli, and C. Sans, "Sunlight and UVC-254 irradiation induced photodegradation of organophosphorus

pesticide dichlorvos in aqueous matrices," *Sci. Total Environ.*, vol. 649, pp. 592–600, 2019, doi: 10.1016/j.scitotenv.2018.08.254.

[33] M. A. M. L. Jesus, A. M. Ferreira, L. F. S. Lima, G. F. Batista, R. V. Mambrini, and N. D. S. Mohallem, "Micro-mesoporous TiO2/SiO2 nanocomposites: Sol-gel synthesis, characterization, and enhanced photodegradation of quinoline," *Ceram. Int.*, vol. 47, no. 17, pp. 23844–23850, 2021, doi: 10.1016/j.ceramint.2021.05.092.

[34] K. Nakata and A. Fujishima, "TiO2 photocatalysis: Design and applications," *J. Photochem. Photobiol. C Photochem. Rev.*, vol. 13, no. 3, pp. 169–189, 2012, doi: https://doi.org/10.1016/j.jphotochemrev.2012.06.001.

[35] J. Wang and S. Wang, "Reactive species in advanced oxidation processes: Formation, identification and reaction A," *Chem. Eng. J.*, vol. 401, p. 126158, 2020, doi: 10.1016/j.cej.2020.126158.

[36] J. Nisar *et al.*, "Gamma - Irradiation induced degradation of diclofenac in aqueous solution: Kinetics, role of reactive species and influence of natural water parameters," *J. Environ. Chem. Eng.*, vol. 4, no. 2, pp. 2573–2584, 2016, doi: 10.1016/j.jece.2016.04.034.

[37] T. Liu, L. Wang, C. Sun, X. Liu, R. Miao, and Y. Lv, "A comparison of the photolytic and photocatalytic degradation of fluvastatin," *Chem. Eng. J.*, vol. 358, pp. 1296–1304, 2018, doi: 10.1016/j.cej.2018.10.107.

[38] S. Bhattacharjee, *Reactive Oxygen Species in Plant Biology*, 1st ed. New Delhi, India: Springer, 2019.

[39] H. He, S. Wang, and J. Wang, "The performance and pathway of indole degradation by ionizing radiation," *Chemosphere*, vol. 287, p. 131983, 2022, doi: 10.1016/j.chemosphere.2021.131983.

[40] M. Bartolomeu, M. G. P. M. S. Neves, M. A. F. Faustino, and A. Almeida, "Wastewater chemical contaminants: remediation by Advanced Oxidation Processes," *Photochem. Photobiol. Sci.*, vol. 17, no. 11, pp. 1573–1598, 2018, doi: 10.1039/C8PP00249E.

[41] L. Chu, D. Chen, J. Wang, Z. Yang, Q. Yang, and Y. Shen, "Degradation of antibiotics and inactivation of antibiotic resistance genes (ARGs) in Cephalosporin C fermentation residues using ionizing radiation, ozonation and thermal treatment," *J. Hazard. Mater.*, vol. 382, p. 121058, 2020, doi: 10.1016/j.jhazmat.2019.121058.

[42] G. Martínez-Barrera, A. Martínez-López, E. Vigueras-Santiago, and M. Martínez-López, "Effects of Gamma Radiation on the Physicochemical Properties of Polyester Resin and Its Use in Composite Materials," in *Recycled Polyester. Textile Science and Clothing Technology*, S. (eds) Muthu, Ed. Singapore: Springer, 2020, pp. 15–28.

[43] S. Glass, M. Kühnert, B. Abel, and A. Schulze, "Controlled electron-beam synthesis of transparent hydrogels for drug delivery applications," *Polymers (Basel).*, vol. 11, no. 3, p. 501, 2019, doi: 10.3390/polym11030501.

[44] B. Ranković *et al.*, "Utilization of gamma and e-beam irradiation in the treatment of waste sludge from a drinking water treatment plant," *Radiat. Phys. Chem.*, vol. 177, p. 109174, 2020, doi: 10.1016/j.radphyschem.2020.109174.

[45] L. Xie *et al.*, "Modes of action and adverse effects of gamma radiation in an aquatic macrophyte Lemna minor," *Sci. Total Environ.*, vol. 680, pp. 23–34, 2019, doi: 10.1016/j.scitotenv.2019.05.016.

[46] M. T. Munir and M. Federighi, "Control of foodborne biological hazards by ionizing radiations," *Foods*, vol. 9, no. 7, pp. 1–23, 2020, doi: 10.3390/foods9070878.

[47] G. Chen *et al.*, "Hydrogen-polarized vacuum ultraviolet photolysis system for enhanced destruction of perfluoroalkyl substances," *J. Hazard. Mater. Lett.*, vol. 3, p. 100072, 2022, doi: 10.1016/j.hazl.2022.100072.

[48] S. Ferhi *et al.*, "Pilot-scale direct UV-C

p ISSN 1907-0322
e ISSN 2527-6433

photodegradation of pesticides in groundwater and recycled wastewater for agricultural use," *J. Environ. Chem. Eng.*, vol. 9, no. 5, p. 106120, 2021, doi: 10.1016/j.jece.2021.106120.

[49] A. Kushniarou *et al.*, "Solar photocatalytic reclamation of agro-waste water polluted with twelve pesticides for agricultural reuse," *Chemosphere*, vol. 214, pp. 839–845, 2019, doi: 10.1016/j.chemosphere.2018.09.180.

[50] J. A. Garrido-Cardenas, B. Esteban-García, A. Agüera, J. A. Sánchez-Pérez, and F. Manzano-Agugliaro, "Wastewater treatment by advanced oxidation process and their worldwide research trends," *Int. J. Environ. Res. Public Health*, vol. 17, no. 1, p. 170, 2020, doi: 10.3390/ijerph17010170.

[51] I. Garrido, P. Flores, P. Hellín, N. Vela, S. Navarro, and J. Fenoll, "Solar reclamation of agro-wastewater polluted with eight pesticides by heterogeneous photocatalysis using a modular facility. A case study," *Chemosphere*, vol. 249, p. 126156, 2020, doi: 10.1016/j.chemosphere.2020.126156.

[52] A. K. Sharma, R. K. Tiwari, and M. S. Gaur, "Nanophotocatalytic UV degradation system for organophosphorus pesticides in water samples and analysis by Kubista model," *Arab. J. Chem.*, vol. 9, pp. S1755–S1764, 2016, doi: 10.1016/j.arabjc.2012.04.044.

[53] H. Unger, R. T. Kangethe, F. Liaqat, and G. J. Viljoen, "Advances in Irradiated Livestock Vaccine Research and Production Addressing the Unmet Needs for Farmers and Veterinary Services in FAO/IAEA Member States," *Front. Immunol.*, vol. 13, pp. 1–8, 2022, doi: 10.3389/fimmu.2022.853874.

[54] A. R. Pereira, A. G. de O. Paranhos, S. F. de Aquino, and S. de Q. Silva, "Distribution of genetic elements associated with antibiotic resistance in treated and untreated animal husbandry waste and wastewater," *Environ. Sci. Pollut. Res.*, vol. 28, pp. 26380–26403, 2021, doi: 10.1007/s11356-021-13784-y.

[55] F. F. Al-Qaim, M. P. Abdullah, M. R. Othman, J. Latip, and Z. Zakaria, "Multi-residue analytical methodology-based liquid chromatography-time-of-flight-mass spectrometry for the analysis of pharmaceutical residues in surface water and effluents from sewage treatment plants and hospitals," *J. Chromatogr. A*, vol. 1345, pp. 139–153, 2014, doi: 10.1016/j.chroma.2014.04.025.

[56] J. Vymazal, T. Dvořáková Březinová, M. Koželuh, and L. Kule, "Occurrence and removal of pharmaceuticals in four full-scale constructed wetlands in the Czech Republic – the first year of monitoring," *Ecol. Eng.*, vol. 98, pp. 354–364, 2017, doi: https://doi.org/10.1016/j.ecoleng.2016.08.010.

[57] E. Estevez, J. M. Hernandez-Moreno, J. R. Fernandez-Vera, and M. P. Palacios-Diaz, "Ibuprofen adsorption in four agricultural volcanic soils," *Sci. Total Environ.*, vol. 468–469, no. January 2012, pp. 406–414, 2014, doi: 10.1016/j.scitotenv.2013.07.068.

[58] N. Jallouli *et al.*, "Heterogeneous photocatalytic degradation of ibuprofen in ultrapure water, municipal and pharmaceutical industry wastewaters using a TiO2/UV-LED system," *Chem. Eng. J.*, vol. 334, pp. 976–984, 2018, doi: https://doi.org/10.1016/j.cej.2017.10.045.

[59] A. Kumar and D. Pal, "Antibiotic resistance and wastewater: Correlation , impact and critical human health challenges," *J. Environ. Chem. Eng.*, vol. 6, no. 1, pp. 52–58, 2018, doi: 10.1016/j.jece.2017.11.059.

[60] M. Zhu *et al.*, "K2Ti6O13 hybridized graphene oxide: Effective enhancement in photodegradation of RhB and photoreduction of U(VI)," *Environ. Pollut.*, vol. 248, pp. 448–455, 2019, doi: 10.1016/j.envpol.2019.02.025.

[61] V. J. Pereira, K. G. Linden, and H. S. Weinberg, "Evaluation of UV irradiation for photolytic and oxidative degradation of pharmaceutical compounds in water," *Water Res.*, vol. 41, no. 19, pp. 4413–4423,

p ISSN 1907-0322
e ISSN 2527-6433

2007, doi: 10.1016/j.watres.2007.05.056.

[62] I. Z. Zafira and J. Nandong, "Optimal feeding strategy of Cephalosporin C fermentation," in *IOP Conference Series: Materials Science and Engineering*, 2019, vol. 495, no. 1, p. 012107, doi: 10.1088/1757-899X/495/1/012107.

[63] D. Chen, L. Chu, J. Wang, Z. Yang, Q. Yang, and Y. Shen, "Degradation of antibiotic cephalosporin C in aqueous solution and elimination of antimicrobial activity by gamma irradiation," *Chem. Eng. J.*, vol. 374, pp. 1102–1108, 2019, doi: 10.1016/j.cej.2019.06.021.

[64] K. A. Sholtes, K. Lowe, G. W. Walters, M. D. Sobsey, K. G. Linden, and L. M. Casanova, "Comparison of ultraviolet light-emitting diodes and low-pressure mercury-arc lamps for disinfection of water," *Environ. Technol. (United Kingdom)*, vol. 37, no. 17, pp. 2183–2188, 2016, doi: 10.1080/09593330.2016.1144798.

[65] N. Balakrishnan, S. M. Yusop, I. A. Rahman, E. Dauqan, and A. Abdullah, "Efficacy of Gamma Irradiation in Improving the Microbial and Physical Quality Properties of Dried Chillies (Capsicum annuum L.): A Review," *Foods*, vol. 30, no. 11, p. 91, 2021, doi: 10.3390/foods11010091.

[66] S. Fetzner, "Bacterial degradation of pyridine, indole, quinoline, and their derivatives under different redox conditions," *Appl. Microbiol. Biotechnol.*, vol. 49, no. 3, pp. 237–250, 1998, doi: 10.1007/s002530051164.

[67] X. Zhang *et al.*, "Performance and microbial community analysis of bioaugmented activated sludge for nitrogen-containing organic pollutants removal," *J. Environ. Sci.*, vol. 101, pp. 373–381, 2021, doi: https://doi.org/10.1016/j.jes.2020.09.002.

[68] H. He, S. Wang, and J. Wang, "Degradation of 3-methylindole by ionizing radiation: Performance and pathway," *Sep. Purif. Technol.*, vol. 278, p. 119515, 2022, doi: 10.1016/j.seppur.2021.119515.

[69] J. Jing, W. Li, A. Boyd, Y. Zhang, V. L. Colvin, and W. W. Yu, "Photocatalytic degradation of quinoline in aqueous TiO2 suspension," *J. Hazard. Mater.*, vol. 237–238, pp. 247–255, 2012, doi: https://doi.org/10.1016/j.jhazmat.2012.08.037.

[70] S. C. Deogaonkar, P. Wakode, and K. P. Rawat, "Electron beam irradiation post treatment for degradation of non biodegradable contaminants in textile wastewater," *Radiat. Phys. Chem.*, vol. 165, p. 108377, 2019, doi: 10.1016/j.radphyschem.2019.108377.

[71] L. Chu, S. Yu, and J. Wang, "Degradation of pyridine and quinoline in aqueous solution by gamma radiation," *Radiat. Phys. Chem.*, vol. 144, pp. 322–328, 2018, doi: 10.1016/j.radphyschem.2017.09.016.

[72] S. C. Verde, T. Silva, and P. Matos, "Effects of gamma radiation on wastewater microbiota," *Radiat. Environ. Biophys.*, vol. 55, no. 1, pp. 125–131, 2016, doi: 10.1007/s00411-015-0617-2.

[73] A. V. Ponomarev and B. G. Ershov, "The Green Method in Water Management: Electron Beam Treatment," *Environ. Sci. Technol.*, vol. 54, no. 9, pp. 5331–5344, 2020, doi: 10.1021/acs.est.0c00545.

[74] A. Kahraman, S. C. Deevi, and E. Yilmaz, "Influence of frequency and gamma irradiation on the electrical characteristics of Er2O3, Gd2O3, Yb2O3, and HfO2 MOS-based devices," *J. Mater. Sci.*, vol. 55, no. 19, pp. 7999–8040, 2020, doi: 10.1007/s10853-020-04531-8.

[75] A. Garrido Sanchis and L. Jin, "Evaluation of the new energy-efficient hot bubble pilot plant (HBPP) for water sterilization from the livestock farming industry," *Water Resour. Ind.*, vol. 24, p. 100135, 2020, doi: 10.1016/j.wri.2020.100135.

[76] A. G. Chmielewski, "Practical applications of radiation chemistry," *Russ. J. Phys. Chem. A*, vol. 81, no. 9, pp. 1488–1492, 2007, doi: 10.1134/S0036024407090270.

[77] N. A. A. Qasem, R. H. Mohammed, and D.

p ISSN 1907-0322
e ISSN 2527-6433

U. Lawal, "Removal of heavy metal ions from wastewater : a comprehensive and critical review," *Npj Clean Water*, vol. 4, no. 1, p. 36, 2021, doi: 10.1038/s41545-021-00127-0.

[78] M. Coha, G. Farinelli, A. Tiraferri, M. Minella, and D. Vione, "Advanced oxidation processes in the removal of organic substances from produced water : Potential, configurations , and research needs," *Chem. Eng. J.*, vol. 414, p. 128668, 2021, doi: 10.1016/j.cej.2021.128668.

[79] J. R. Bolton, K. G. Linden, and M. ASCE, "Standardization of Methods for Fluence (UV Dose) Determination in Bench-Scale UV Experiments," *J. Environ. Eng.*, vol. 129, no. 3, pp. 209–215, 2003, doi: https://doi.org/10.1061/(ASCE)0733-9372(2003)129:3(209).

[80] J. Engohang-ndong, R. M. Uribe, R. Gregory, M. Gangoda, M. G. Nickelsen, and P. Loar, "Effect of electron beam irradiation on bacterial and Ascaris ova loads and volatile organic compounds in municipal sewage sludge," *Radiat. Phys. Chem.*, vol. 112, pp. 6–12, 2015, doi: 10.1016/j.radphyschem.2015.02.013.

[81] M. I. Elias, J. Madureira, P. M. P. Santos, M. M. Carolino, F. M. A. Margaça, and S. C. Verde, "Preservation treatment of fresh raspberries by e-beam irradiation," *Innov. Food Sci. Emerg. Technol.*, vol. 66, p. 102487, 2020, doi: 10.1016/j.ifset.2020.102487.

[82] A. López-Sánchez *et al.*, "Microalgae-based livestock wastewater treatment (MbWT) as a circular bioeconomy approach: Enhancement of biomass productivity, pollutant removal and high-value compound production," *J. Environ. Manage.*, vol. 308, p. 114612, 2022, doi: 10.1016/j.jenvman.2022.114612.

[83] C. Regmi, B. Joshi, S. K. Ray, G. Gyawali, and R. P. Pandey, "Understanding Mechanism of Photocatalytic Microbial Decontamination of Environmental Wastewater," *Front. Chem.*, vol. 6, pp. 1–6, 2018, doi: 10.3389/fchem.2018.00033.

[84] H. Wan, W. Zhao, W. Li, L. Chen, and X. Guo, "An innovative device to transport electron gun automatically in nuclear power plant," *J. Nucl. Sci. Technol.*, vol. 57, no. 1, pp. 40–48, 2020, doi: 10.1080/00223131.2019.1651228.

[85] G. Tochaikul, A. Phattanasub, P. Khemkham, K. Saengthamthawee, N. Danthanavat, and N. Moonkum, "Radioactive waste treatment technology: A review," *Kerntechnik*, vol. 87, no. 2, pp. 208–225, 2022.

[86] Y. Zhuang *et al.*, "Inactivation of antibiotic resistance genes in municipal wastewater by chlorination, ultraviolet, and ozonation disinfection," *Environ. Sci. Pollut. Res.*, vol. 22, pp. 7037–7044, 2015, doi: 10.1007/s11356-014-3919-z.

[87] D. B. Miklos, C. Remy, M. Jekel, K. G. Linden, J. E. Drewes, and U. Hübner, "Evaluation of advanced oxidation processes for water and wastewater treatment – A critical review," *Water Res.*, vol. 139, pp. 118–131, 2018, doi: 10.1016/j.watres.2018.03.042.

[88] M. Bavcon Kralj, U. Černigoj, M. Franko, and P. Trebše, "Comparison of photocatalysis and photolysis of malathion, isomalathion, malaoxon, and commercial malathion-Products and toxicity studies," *Water Res.*, vol. 41, no. 19, pp. 4504–4514, 2007, doi: 10.1016/j.watres.2007.06.016.

[89] H. Singh, S. K. Bhardwaj, M. Khatri, K. H. Kim, and N. Bhardwaj, "UVC radiation for food safety: An emerging technology for the microbial disinfection of food products," *Chem. Eng. J.*, vol. 417, p. 128084, 2021, doi: 10.1016/j.cej.2020.128084.

[90] S. C. Lee *et al.*, "Hierarchically three-dimensional (3D) nanotubular sea urchin-shaped iron oxide and its application in heavy metal removal and solar-induced photocatalytic degradation," *J. Hazard. Mater.*, vol. 354, pp. 283–292, 2018, doi: 10.1016/j.jhazmat.2018.04.048.

[91] D. H. Sliney and B. E. Stuck, "Special Issue Invited Review A Need to Revise Human Exposure Limits for Ultraviolet UV-C Radiation †," vol. 1972, no. 2, pp.

p ISSN 1907-0322
e ISSN 2527-6433

485–492, 2021, doi: 10.1111/php.13402.

[92] R. Ravindran and A. K. Jaiswal, “Wholesomeness and safety aspects of irradiated foods,” *Food Chem.*, vol. 285, pp. 363–368, 2019, doi: 10.1016/j.foodchem.2019.02.002.

[93] T. Malchi, Y. Maor, G. Tadmor, M. Shenker, and B. Chefetz, “Irrigation of Root Vegetables with Treated Wastewater: Evaluating Uptake of Pharmaceuticals and the Associated Human Health Risks,” *Environ. Sci. Technol.*, vol. 48, no. 16, pp. 9325–9333, Aug. 2014, doi: 10.1021/es5017894.

[94] A. Obayiuwana and A. M. Ibekwe, “Antibiotic Resistance Genes Occurrence in Wastewaters from Selected Pharmaceutical Facilities in Nigeria,” *Water*, vol. 12, no. 7. 2020, doi: 10.3390/w12071897.

[95] I. A. Aneyo, F. V Doherty, O. A. Adebesin, and M. O. Hammed, “Biodegradation of pollutants in waste water from pharmaceutical, textile and local dye effluent in Lagos, Nigeria,” *J. Heal. Pollut.*, vol. 6, no. 12, pp. 34–42, 2016.

[96] C. N. Aroeira *et al.*, “Freezing, thawing and aging effects on beef tenderness from Bos indicus and Bos taurus cattle,” *Meat Sci.*, vol. 116, pp. 118–125, 2016, doi: https://doi.org/10.1016/j.meatsci.2016.02.006.

[97] H.-S. Yook, J.-W. Lee, K.-H. Lee, M.-K. Kim, C. -wo. Song, and M.-W. Byun, “Effect of gamma irradiation on the microstructure and post-mortem anaerobic metabolism of bovine muscle,” *Radiat. Phys. Chem.*, vol. 61, no. 2, pp. 163–169, 2001, doi: https://doi.org/10.1016/S0969-806X(00)00392-3.

[98] S. R. Kanatt, S. P. Chawla, and A. Sharma, “Effect of radiation processing on meat tenderisation,” *Radiat. Phys. Chem.*, vol. 111, pp. 1–8, 2015, doi: https://doi.org/10.1016/j.radphyschem.2015.02.004.

[99] M. Emami-meibodi *et al.*, “An experimental investigation of wastewater treatment using electron beam irradiation,” *Radiat. Phys. Chem.*, vol. 125, pp. 82–87, 2016, doi: 10.1016/j.radphyschem.2016.03.011.

[100] Y. Zhang, Y. Zhuang, J. Geng, H. Ren, K. Xu, and L. Ding, “Reduction of antibiotic resistance genes in municipal wastewater effluent by advanced oxidation processes,” *Sci. Total Environ.*, vol. 550, pp. 184–191, 2016, doi: 10.1016/j.scitotenv.2016.01.078.

[101] V. H. O. Silva, A. P. dos Santos Batista, A. C. Silva Costa Teixeira, and S. I. Borrely, “Degradation and acute toxicity removal of the antidepressant Fluoxetine (Prozac®) in aqueous systems by electron beam irradiation,” *Environ. Sci. Pollut. Res.*, vol. 23, no. 12, pp. 11927–11936, 2016, doi: 10.1007/s11356-016-6410-1.

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Table 1. Comparison of radiation techniques for microorganism species removal in wastewater

Radiation techniques	Degradation type	Additional treatment	Species	Group	Radiation Dose	Scale	Refs.
Gamma-ray	Radiolysis	Lime	Pathogens	Microorganisms	10 kGy	Institution	[44]
	Radiolysis	Persulfate; erythromycin	*E. coli* and *S. aureus*	Microorganisms	1 and 10 kGy	Institution	[19]
	Radiolysis	-	*Methylobacterium* spp., coliforms and mesophilic microbiota	Microorganisms	0.32 and 0.30 kGy	Semi-industrial	[72]
Electron Beam	Radiolysis	-	Fecal and total coliform, and heterotrophic bacterial	Microorganisms	4.5 kGy	Pilot and Industry	[80]
	Radiolysis	Coagulation	Coliforms bacteria	Microorganisms	2 to 3 kGy	Pilot and Industry	[99]
	Radiolysis	Lime	Pathogens	Microorganisms	10 kGy	Institution	[44]
	Radiolysis	-	Mesophilic bacteria, and pathogens	Microorganisms	3 kGy	Industry	[81]
UV-C	Photolysis - Oxidation	H_2O_2 (30% w/w)	ARGs (sul1, tetX, tetG, intI1, and 16S rRNA genes)	Microorganisms	500 mJ/cm^2	Urban (Pilot)	[100]
	Photolysis	Light-emitting diodes (LEDs)	*E. coli (E),* a non-enveloped virus *(V)* and *B. atrophaeus (B)*	Microorganisms, viruses, and spores	6.5 mJ/cm^2 (E), 59.3 mJ/cm^2 (V), 30.0 mJ/cm^2 (B)	Institution	[64]

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Table 2. Comparison of radiation techniques for the removal of pesticides, pharmaceutical residues, and organic compounds in wastewater

Radiation techniques	Degradation types	Additional treatment	Compounds	Group	Radiation Dose	Scale	Refs.
Gamma-ray	Radiolysis	-	Chlorfenvinphos (CHV), diazinon (D), dimethoate (DM), profenofos (PR), and others (carbaryl, diazinon, & carbosulfan	Pesticides	6.4 kGy (CHV), 8.7 kGy (D), 11 kGy (DM), and 17.7 kGy (PR), and 6 kGy (others)	Institution	[2]
	Radiolysis	-	Anti-inflammatory drug (diclofenac)	PRs	1015 Gy or 1 kGy	Pilot	[36]
	Radiolysis	-	Antibiotics (Cephalosporin C)	PRs	0.4–2.0 kGy	Institution	[63]
	Radiolysis	Ethanol/ chloro-benzene	Ciprofloxacin and norfloxacin	PRs	4–6 kGy	Institution	[24]
	Radiolysis	Persulfate (PS)	Antibiotics (erythromycin)	PRs	6 kGy	Institution	[19]
	Radiolysis	-	3-methylindole	Organic compounds	3 kGy	Institution	[68]
	Radiolysis	TiO_2 nanoparticle	Pyridine (P) and Quinolone (Q)	Organic compounds	14 kGy (P), 7.0 kGy (Q)	Institution	[71]
	Radiolysis	-	Indole	Organic compounds	5 kGy	Institution	[39]
	Radiolysis	-	Acrylamide	Organic compounds	1 to 25 kGy	Institution	[44]
Electron Beam	Radiolysis	-	Acrylamide	Organic compound	1 to 25 kGy	Institution	[44]
	Radiolysis	-	Dimethyl sulfide, dimethyl disulfide and carbon disulfide	Organic compound	25.7 and 30.7 kGy	Industry	[80]
	Poly-merization	PEGDA, methylene blue, & PBS	Hydrogels	Organic/ inorganic compound	12–18 kGy	Institution	[43]
UV-C	Photolysis/ Photo-degradation	-	Atrazine (A), Malathion (M), Glyphosate (G)	Pesticides	9244 kJ/m^3 (A), 9244 kJ/m^3 (M) 3698 kJ/m^3 (G)	Pilot	[48]
	Photocatalytic	UV-A, TiO_2 and $Na_2S_2O_8$	Acetamiprid, cyproconazole, cyprodinil, difenoconazole, fenhexamid, myclobutanil hexythiazox, and thiamethoxam	Pesticides	7000 kJ/m	Institution and pilot	[75]
	Photo-degradation	-	Organophosphorus (dichlorvos)	Pesticides	0.1 Einstein/L	Pilot	[32]
	Nano-photocatalytic	Synthesized Zinc oxide (ZnO)	Organophosphorus (methyl parathion, parathion)	Pesticides	1.0 mW/cm^2	Pilot and industry	[52]
	Photolysis	LP mercury lamp	CCBs (Amlodipine, diltiazem, & verapamil)	PRs	40e100 mJ/cm^2	Pilot	[28]
	Photolysis and oxidative degradation	UV/H_2O_2, LP and MP UV	Ciprofloxacin, carbamazepine iohexol, clofibric acid, ketoprofen, and naproxen	PRs	40 and 100 mJ/cm^2	Institution	[61]

Note: PRs: Pharmaceutical residues; UV-A: Ultraviolet A; UV-C: Ultraviolet C; LP-UV: Low Pressure Ultraviolet; MP-UV: Medium Pressure Ultraviolet; PEGDA: Poly (ethylene glycol) diacrylate; PBS: Phosphate-buffered saline; CCBs: Calcium Channel Blockers

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Table 3. Advantages and disadvantages of gamma-ray, electron beam, and UV-C

Radiation techniques	Sources	Advantages	Disadvantages	Refs.
Gamma-ray	Radioactive isotopes (Co-60, Cs-137) [76] [12]	- Microorganisms sterilization and inactivation - Pesticides, pharmaceutical residues, and organic compounds degradation	- Expensive tool and facility - Careful handling - Careful disposal (radioactive waste, e.g. Co-60, Cs-137)	[44]; [19] [68];
Electron Beam	Electron-beam accelerators [80] [81]	- Practical application for polymerization, disinfectan, sterilization, crosslinking, degradation	- Limited penetration depth - High cost (expensive)	[43]; [99]; [44]; [43]; [101];
UV-C	UV lamps, UV LEDs [32] [64] [79]	- Surface disinfection - Pathogen inactivation - Certain pesticides and pharmaceutical residues degradation	- Limited penetration capabilities, - Not reach microorganisms hiding in crevices or inside materials.	[50]; [75]; [48]; [90]; [61]; [28]; [75]

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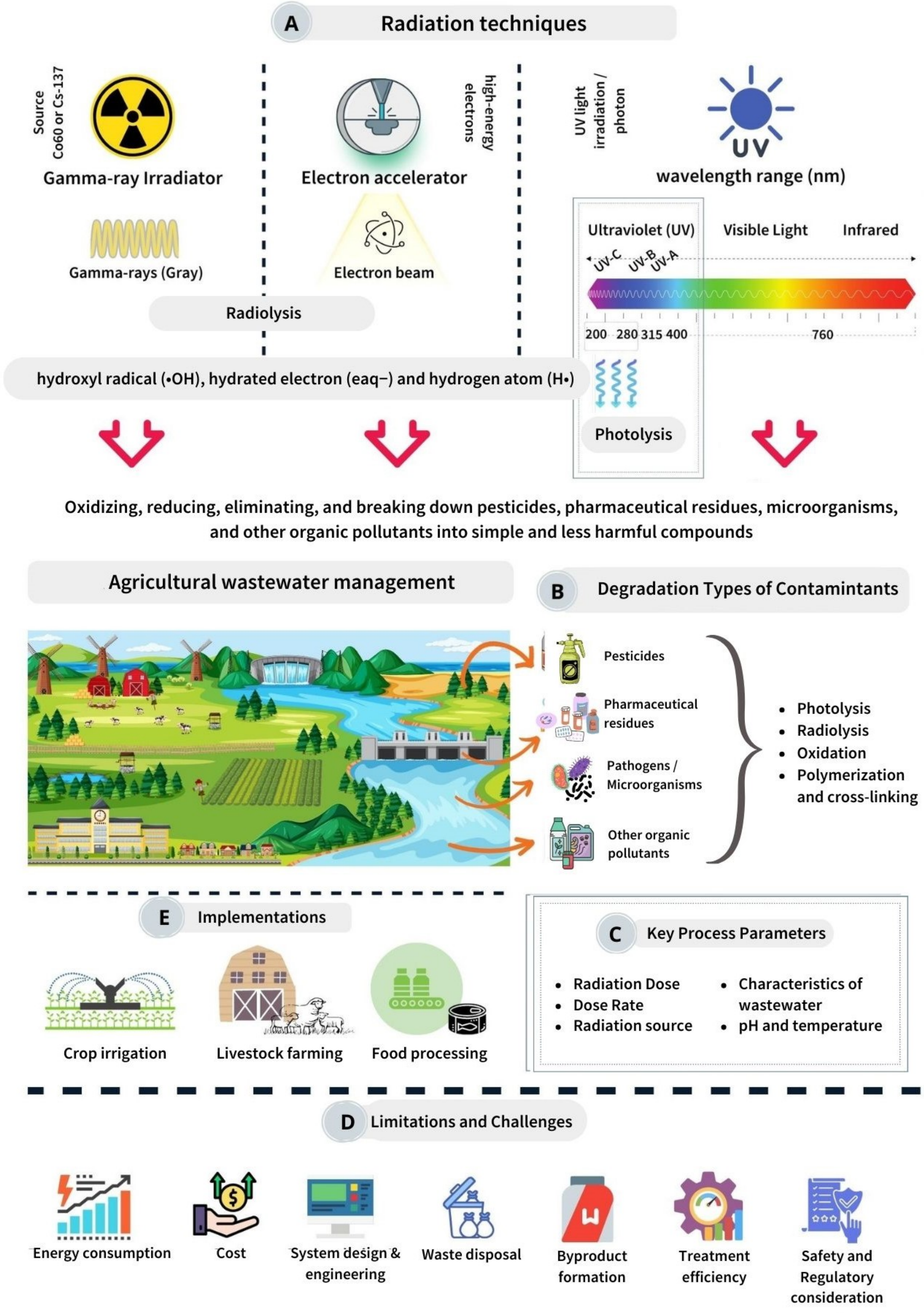

Figure 1. The Radiation techniques widely use in agricultural waswater management. **A)** different types of radiation techniques (UV, gamma-ray, and electron beam radiation); **B)** The degradation of pollutants; **C)** Key process parameters; **D)** Limitations and challenges; **E)** Implementations in three agricultural sectors.

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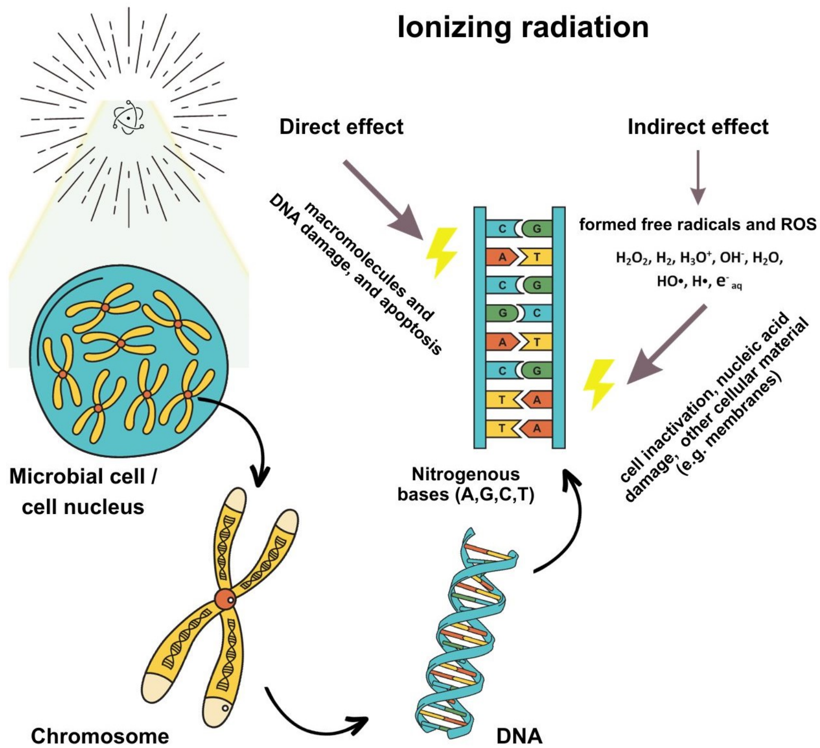

Figure 2. Schematic presentation of the effect of ionizing radiations on the nucleic acid or DNA. The reproductive death of cells is caused by the direct effect of irradiation, which breaks the bonding between base pairs in genetic material. In the indirect effect, damage to DNA or other cellular components is caused by the free radicals and reactive oxygen species (ROS) generated by the breakage of water molecules. A: Adenine; G: Guanine; C: Cytosine; T: Thymine. **Source**: Munir and M. Federighi [45]