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Radiation-Induced Degradation of Methylene Blue Dye Water using Gamma and Electron Beam Irradiation

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ABSTRACT

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Title of the Study:	Radiation-Induced Degradation of Methylene Blue Dye Water using Gamma and Electron Beam Irradiation
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Access to clean and safe water is a global priority, with Sustainable Development Goal 6 aiming to ensure water and sanitation for all. In the Philippines, where the textile industry is actively striving, concerns with wastewater treatment are faced with more pressing challenges. This study examines the application of irradiation technology, particularly in gamma and Electron Beam Irradiation (EBI) as an advanced treatment option for dye-containing wastewater concerned with feasibility and application under institutional settings. Taking from both global and local literature, this study reviews water sustainability issues, Gamma and EBI's underlying concepts, and its effectiveness in treatment of the dye-containing wastewater. It also examines the supporting case for integration between irradiation and currently existing sanitation frameworks to promote environmental goals that can drive sustainable water use within academic communities. The findings aim to support the implementation of efficient dye-containing wastewater treatment technologies in different institutions to promote safe water reuse, sustainability, and public health.

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ACRONYMS

ACRONYM	DEFINITION
ANOVA	Analysis of Variance
au	Absorbance Unit
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand

DENR	Department of Environment and Natural Resources
DOST	Department of Science and Technology
PNRI	Philippine Nuclear Research Institute
EBI	Electron Beam Irradiation
GSC	Gamma Source Chamber
HSD	Honestly Significant Difference
IAEA	International Atomic Energy Agency
IIA	International Irradiation Association
kGy	Kilogray
L	Liter
MB	Methylene Blue
mg	Milligram
mL	Milliliter
MSc	Master of Science

nm	nanometer
pH	Potential of Hydrogen
PNU	Philippine Normal University
ppm	Parts Per Million
PTRI	Philippine Textile Research Institute
SDG	Sustainable Development Goals
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
UN	United Nations
UV	Ultraviolet
UV-Vis	Ultraviolet-Visible Spectrophotometry

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CHAPTER 1

THE PROBLEM AND THE LITERATURE REVIEW

This chapter includes the background of the study, the literature review, the research problems, the conceptual framework, and the definition of terms used in the study.

Background of the Study

The escalating crisis of global water pollution presents a profound challenge to ensuring safe and sufficient water supplies for all. As highlighted by UN Water (2024), the quantity of wastewater generated and its associated pollution load are increasing throughout the entire water cycle, with the economic industry acting as one of the significant polluters through the discharge of untreated waste, chemical fertilizers, and pesticides into water courses.

The 6th SDG focuses on making clean water and sanitation accessible to everyone through sustainable use and management. However, this goal is critically undermined by the widespread neglect of wastewater management, particularly in urban areas where the direct discharge of untreated effluent continues to contaminate ecosystems and jeopardize public health.

This gap between international initiative and on-the-ground implementation is starkly evident at the national level. In the Philippines, Republic Act No. 9275, also known as the Clean Water Act of 2004, establishes the legal framework for wastewater management; however, its implementation has been uneven. To make meaningful progress, enhanced regulatory monitoring and stricter implementation are required.

Aligned with the Philippine Development Plan 2023–2028, which emphasizes expanding access to safe drinking water, sanitation, and improved public health, institutions face an urgent demand for adopting sustainable and efficient water treatment solutions.

Industrial textile operations generate substantial wastewater streams heavily contaminated with synthetic dyes, presenting a major challenge for water treatment systems. Methylene blue (MB) is one such pollutant, characterized as a stable cationic dye with a heterocyclic composition that makes it resistant to natural breakdown (Oladoye et al., 2022). Due to its toxic and potentially carcinogenic nature, the occurrence of MB in aquatic systems poses serious risks to both the environment and human health, underscoring the need for advanced treatment methods.

The need for such advanced treatment solutions has propelled significant research into irradiation techniques. Among these, gamma rays have been widely reported as an efficient and rapid method for degrading industrial pollutants (Limam et al., 2018; Wang et al., 2019). Additionally, according to the study of Emami-Meibody et al. (2016), electron beam irradiation can also be used to treat sewage and industrial wastewater. Gamma irradiation's and EBI's one key advantage is their superior penetrating power to enable more effective ion formation throughout the effluent volume. Water treatment using irradiation technology, Gamma and Electron beam in particular, may be another way to clean and provide sustainable water accessibility.

Literature Review

The Pollutant: Textile Dyes

In research conducted by **Varjani et al. (2020)**, Dye is defined as a colorful substance used in materials such as textiles, papers, and any colorable material of a distinct color. Some dyes are derived from natural sources, including plants and insects; these dyes are classified as natural dyes **(Saxena & Raja, 2014)**. While artificially created dyes are called synthetic dyes, these dyes are manufactured from chemical compounds, with each type having a different molecular structure, and these dye structures are used to categorize each dye **(Ayadi et al., 2016)**. Synthetic dyes are further categorized based on their use or solubility—soluble types include acid, basic, direct, mordant, and reactive dyes, while insoluble ones comprise disperse, sulfur, and vat dyes.

Compared to natural dyes, synthetic dyes are more extensively used across industries because they offer greater vibrancy, resistance to fading, and affordability for mass production. However, their use poses significant drawbacks, particularly in terms of toxicity and wastewater management **(Liu, 2020)**.

In particular, textile dyes account for the largest share of synthetic dye applications. Textile dyes are generally grouped according to their chemical composition and method of application, factors that influence how they bond with fabrics and how easily they can be treated. Typical categories consist of acid, basic, direct, sulfur, vat, and azo dyes, with azo dyes being the most prevalent, representing roughly 60–70% of synthetic dyes used worldwide **(Tripathi et al., 2023)**. Azo dyes, characterized by their double bonds. nitrogen-to-nitrogen, (-N=N-), are particularly favored for their vibrant color range, cost-effectiveness, and stability, which make them widely applicable in textiles, food, cosmetics, and pharmaceuticals **(Benkhaya et al., 2017)**.

Within the Philippine textile sector, reactive dyes—particularly Remazol Blue RGB, an azo dye—are commonly utilized because they form durable covalent bonds with natural fibers such as cotton, producing bright colors that withstand washing and heat **(Aljamali, 2015)**. Facilities such as those under the Philippine Textile Research Institute (PTRI) commonly use these dyes for their durability and commercial value **(Philippine Freedom of Information, 2025)**. However, this widespread usage also creates a pressing environmental challenge, as only a fraction of the dye binds to fabrics during processing, with the remainder discharged into wastewater streams **(Arora, 2014)**.

Industries that utilize dyes store their dye effluents as waste, and upon release to environmental waters, these effluents contaminate otherwise clean and colorless water **(Garg & Chopra, 2022)**. This highlights the urgent need for strict regulation and monitoring of dye wastewater to mitigate its environmental impact. Thus, industries that use dyes are required to comply with the unified international Dye Industry Wastewater Discharge Quality Standards issued by **ZDHCP (2015)** and to regulate key indicators, including biological oxygen demand (BOD), chemical oxygen demand (COD), color, pH, total suspended solids (TSS), total dissolved solids (TDS), and effluent temperature. In addition, the toxicity of the effluent must be strictly evaluated before release to ensure wastewater safety and minimal environmental damage **(Azanaw et al., 2022)**.

The persistence of azo and reactive dyes in wastewater is a major environmental concern. Their complex structures make them resistant to biodegradation, contributing to long-term aquatic pollution as presented in the review of **Mishra & Maiti (2018**). If left untreated, wastewater containing dyes limits light penetration in aquatic environments, which interferes with photosynthesis and harms ecosystem balance. Moreover, some azo dyes and their byproducts are associated with health risks, including dermatological issues, respiratory problems, and potential carcinogenicity **(Chung, 2016)**. Recognizing these hazards, regulatory agencies such as the **Department of Environment and Natural Resources (DENR)** in the Philippines, in 2016, established, through its administrative order, effluent standards that specifically regulate "color" as a critical parameter of wastewater quality.

Therefore, while dyes are indispensable for textile quality and market competitiveness, their environmental persistence underscores the importance of targeted, sustainable, and context-specific treatment solutions.

Current Treatment Strategies and Their Limitations

Effective treatment of dye-containing wastewater requires careful parameter consideration such as dye concentration, pH, temperature, biodegradability, and toxicity **(John, 2024)**. For instance, **Montiague et al. (2020)** demonstrated that crude laccase extracted from Pleurotus Florida achieved significant decolorization of Remazol Blue RGB, though efficiency depended on treatment duration and dye concentration. Similarly, global studies highlight that structural resistance and toxicity vary across dye classes, making classification essential for selecting appropriate remediation strategies. Treatments range from conventional biological processes to advanced enzymatic, nanotechnology-based, or irradiation techniques, all of which depend on understanding dye chemistry for optimal results **(Gita et al., 2016)**.

Al-Tohamy et al. (2022) discussed various approaches for treating dye-contaminated water, which they grouped into three main categories: physical, chemical, and biological methods. Physical approaches to dye water treatment consist of adsorption, ion exchange, and membrane filtration. In a review article, Comparison of dye wastewater treatment methods: A review, published in GSC Advanced Research and Reviews, **Adesanmi et al. (2022)** also classified irradiation and coagulation–flocculation as physical methods for dye removal. These approaches are frequently adopted because they are affordable and relatively simple to implement. Another factor to use is its effectiveness; physical methods of dye water treatment yielded roughly 95 to 99% of dye removal **(Samsami et al., 2020).** However, these physical methods can be subjected to membrane degradation and fouling by members, requiring consistent maintenance **(Singh et al., 2023).**

Chemical treatment of the dye water follows the following methods: Coagulation-flocculation, electrochemical, and advanced oxidation processes. These treatments typically require substantial chemical inputs, specialized equipment, and significant electrical energy to operate the machinery and reactors where the process takes place. From an industrial standpoint, these techniques are considered commercially impractical due to the significant expenses required for procuring essential materials and equipment **(Nachiyar et al., 2023)**. Furthermore, different dyes may require different reagents, and the process often produces toxic byproducts, which necessitate an additional round of treatment.

Biological methods of dye water treatment involve bacteria, fungi, yeast, and algae through bacterial degradation. Typically, both anaerobic and aerobic practices are used in the implementation of the dye water treatment **(Holkar et al., 2016).** Furthermore, these methods are eco-friendly, non-hazardous, and have low water consumption; however, despite these benefits, their efficiency is not enough to completely treat the wastewater, and does not completely remove hazardous particles from the water **(Katheresan et al., 2018).**

While physical, chemical, and biological methods each demonstrate important strengths in dye wastewater treatment, their limitations in cost, efficiency, or completeness of removal highlight the need for complementary approaches. Irradiation has emerged as one such method **(Nachiyar et al., 2023),** offering an additional pathway to address the challenges posed by persistent dye pollutants.

A Promising Alternative: Irradiation Technology

Irradiation is listed among the methods that could be used in order to treat dye-containing water. Among these, gamma irradiation can be utilized in order to degrade the contaminants within the dye effluent **(Bhuiyan et al., 2015)**. Gamma rays, commonly sourced from cobalt-60 **(Van Dyk et al., 2020)**, initiate the radiolysis of water molecules

(Imanova, 2022). The process generates reactive agents such as hydroxyl radicals (•OH), hydrated electrons (e^-_{aq}), and hydrogen atoms (H•), which then attack and degrade the complex aromatic structures of dye compounds **(Arshad et al., 2020)**. This process not only targets color removal but also reduces harmful physicochemical parameters. For example, **Bhuiyan et al. (2016)** reported that applying a 10 kGy gamma dose to knit dye effluent with H_2O_2 significantly reduced BOD, TSS, and potential of Hydrogen (pH) levels, while **Zaouak et al. (2018)** observed that indigo carmine dye effluents became nearly colorless after irradiation, with notable decreases in COD and BOD.

Beyond decolorization, gamma irradiation also enhances the biodegradability and reusability of treated effluents. **Parvin et al. (2015)** showed that textile wastewater exposed to 10–15 kGy gamma irradiation doses experienced substantial reductions in COD, BOD, turbidity, and TSS. Moreover, the treatment broke down recalcitrant azo dye structures into simpler compounds such as amides and ammonium, improving dissolved oxygen levels and nutrient availability. Such processes lessen toxicity and allow for safe agricultural reuse, consistent with circular economy practices and sustainable water management **(Pricaz & Uta, 2015)**.

Electron beam irradiation (EBI) has also become an important tool across various industries, from sterilizing medical equipment to improving materials and reducing contaminants in food. Compared to cobalt-60 gamma radiation, which has a higher penetration but a much slower dose rate (around 10 kiloGray per hour), electron beams offer a much faster dose rate—about 500 kiloGray per second—though they have limited penetration (NHV Corporation, 2023). This makes EBI especially effective for surface treatments and sterilization of thin materials. The energy of the electron beam can be carefully controlled, ranging from 80 kiloelectron volt to 10 mega electron volt, allowing precise delivery of high doses to materials in a very short time (IAEA, 2015).

The primary reason for employing irradiation is its ability to degrade recalcitrant organic pollutants that resist conventional treatment methods. Unlike chemical or biological techniques, gamma and electron beam irradiation does not transfer pollutants to another phase (like sludge) but completely mineralizes them, ensuring a zero-waste process. Different irradiation types, such as gamma rays, electron beams, and X-rays, differ in their penetration power, dose delivery rate, and cost-efficiency. Gamma rays have high penetration and are effective for bulk liquid treatment, as presented by the study of **Parvin et al. (2015)**. In contrast, electron beam irradiation, as discussed by **Abou Elmaaty et al. (2022)**, has a higher dose rate and is more energy-efficient, although it may be limited by penetration depth and equipment cost.

In the Philippine context, the use of both gamma and electron beam irradiation holds a practical advantage due to the existing Philippine Nuclear Research Institute's Multipurpose Cobalt-60 Gamma Irradiation Facility and the Semi-Commercialized

Electron beam Irradiation , which supports research and industrial applications **(DOST-PNRI, 2015)**. Its local availability makes it an accessible and feasible option for wastewater treatment strategies in the country.

Focus on Gamma Irradiation

In a book published by the **IAEA (2005)**, Gamma processing or Gamma Irradiation utilizes the ionizing capabilities of the high-energy gamma rays. The process of irradiation starts from a Gamma ray emitter, from an unstable isotope source such as Cobalt-60. This isotope species undergoes gamma decay, which produces a gamma ray **(Mansor et al., 2023)**. An object is placed within the vicinity of the species for a fixed time interval; the effect of this placement is dependent on the amount of radiation energy.

The Cobalt-60 radionuclide is produced from the Cobalt-59 isotope via bombardment and absorption of neutrons, creating the unstable Cobalt-60 **(Greenwood, 2017)**. Upon continuous gamma decay, the radionuclide is then converted into the stable nickel-59 in roughly 50 years.

Due to the high penetrating power and ionizing capability of the gamma radiation, facilities utilizing gamma irradiation must strictly adhere to the safety standards as proposed by the International Atomic Energy Agency (IAEA). The **IAEA Safety Standard Series No. 22G-8 (2010)** details the necessary precautions to be considered in an Irradiation Facility. It divided the Types of Facility into two: Gamma Irradiators and

Irradiation Facilities with Radiation Generators, an example of the latter includes electron beams and X-ray generators. Gamma irradiators are classified into four categories, excluding Category I, which refers to self-shielded facilities. Category II consists of panoramic dry-source storage irradiators, where the radiation source is kept inside a fully shielded, solid dry container when not in use. Category III includes underwater irradiators, in which the source remains completely submerged in a water pool. Lastly, Category IV includes panoramic wet source storage irradiators, similar to Category II, which are enclosed in a fully shielded material and contain a source in a pool of water.

Regardless of the category, the safety standard ensures that all personnel working within the facility have adequate training and are informed regarding the risks associated with facilities, as well as the safety protocol devised by the facility in case of an emergency. Furthermore, these facilities should be shielded as well as personnel working in the facility, with utmost consideration to those who work closely with the radiation source.

In practice, Gamma irradiation has been used in various sectors and fields of study. In medicine, gamma irradiation is used for treatment or radiotherapy, using the ionizing radiation in order to treat cancers and tumors, as well as sterilization of medical products, equipment, and pharmaceuticals **(Pricaz & Uta, 2015)**. For the case of the food industry and agriculture, the technology can be used in order to prolong the shelf life of produce such as bananas, apples, and even fruit juices **(Pillai & Shayanfar, 2016)**. Sterilization of food products can also be achieved, minimizing the risk of food-borne pathogens from untreated produce **(Kobayashi, 2018)**. Additionally, irradiation may induce changes in the physiological characteristics of crops, such as mutations that result in specialized traits including altered flower buds, plant size, ripening time, pathogen resistance, and seed germination **(Zanzibar & Sudrajat, 2016)**.

Focus on Electron Beam Irradiation

Electron beam (EB) irradiation is a type of radiation processing technology that utilizes high-energy electrons generated by electron accelerators to modify the physical, chemical, or biological properties of materials. This technique has proven effective in sterilization, polymer crosslinking, curing, and pollution control. Unlike gamma radiation, which relies on radioactive isotopes such as cobalt-60, EB systems use electricity to generate radiation, allowing for instant on/off operation and eliminating the risk of residual radioactivity **(International Atomic Energy Agency [IAEA] & International Irradiation Association [IIA], 2011).**

The process works by accelerating electrons to high velocities and directing them toward the target material. When these electrons collide with the material, they cause ionization and excitation of atoms and molecules, which can lead to chain scission or crosslinking in polymers. For example, electron beams are used to enhance the durability and heat resistance of plastic cables, improve the shelf life of food through microbial inactivation, and support the production of advanced materials like semiconductors and nanocomposites. EB systems can be configured in low, medium, or high-energy setups depending on the desired penetration depth and industrial application.

One major advantage of electron beam irradiation is its high dose rate, which allows for faster processing times compared to gamma radiation. Additionally, EB irradiation can be combined with X-ray generation (via bremsstrahlung) to expand its utility to bulkier or denser materials that require deeper penetration. Globally, over 1,200 EB accelerators are in commercial use, yet countries like the Philippines are only beginning to scale up such technologies. The International Atomic Energy Agency encourages the adoption of EB processing as a safer, environmentally-friendly alternative that can support sustainable development in sectors ranging from healthcare to manufacturing.

Recent studies have further demonstrated the potential of EBI in water treatment applications. **Ye et al. (2022)** reported that electron beam irradiation combined with graphite carbon nitride and carbon nanodots (EBI & g-C_3N_4/CDs) achieved higher removal efficiency of methylene blue compared to EBI alone, particularly at high dye concentrations. Their findings also revealed the synergistic effects of reactive radicals, notably ·OH, and highlighted the stability and reusability of the catalytic material, reinforcing the role of EBI as a promising approach for dye degradation and wastewater remediation.

The Model Pollutant: Methylene Blue

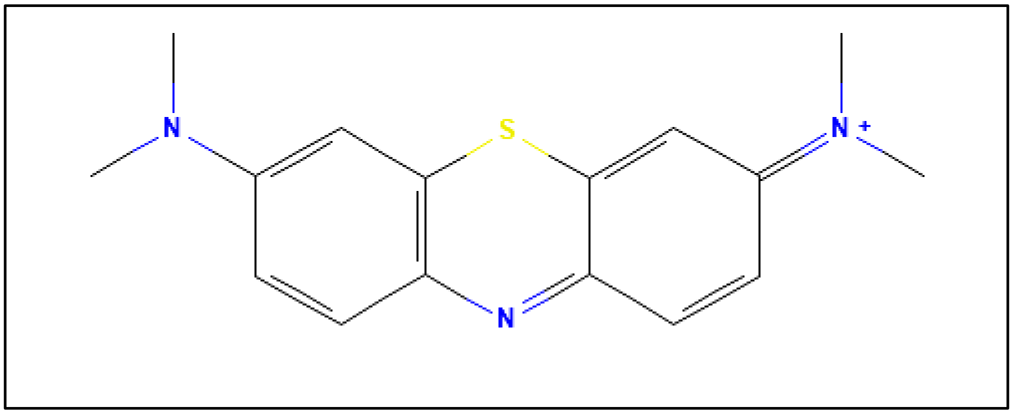

Figure 1.1 *Chemical Structure of Methylene Blue*

Methylene blue (MB) is a cationic dye characterized by an aromatic heterocyclic ring containing sulfur and nitrogen atoms **(Suresh & Sundaramoorthy, 2014)**. This structure makes it a persistent water contaminant with toxic, carcinogenic, and non-biodegradable properties. It poses severe risks to both human health and the environment due to its destructive effects when released untreated into aquatic systems **(Neethu & Choudhury, 2018)**. Despite these hazards, MB is widely applied in industries such as wool dyeing, paint production, pharmaceuticals, medicine, microbiology, diagnostics, aquaculture, and as a sensitizer in pollutant photo-oxidation **(Oladoye et al., 2022)**. The growing demand from the pharmaceutical and chemical industries further escalates its market use **(Khan et al., 2022)**. Given these challenges, wastewater treatment and the removal of MB remain urgent global priorities for ensuring both environmental protection and water security.

Various strategies have been explored for MB treatment, such as biological and chemical treatments, membrane filtration, reverse osmosis, ultrafiltration, and coagulation/flocculation. However, the said conventional ones have been presented to be less effective, often failing to achieve complete removal or requiring high operational costs and complex infrastructure **(Oladoye et al., 2022)**.

In contrast, adsorption demonstrates higher adaptability and efficiency. For example, kaolin and zeolite-X synthesized from Ethiopian kaolin achieved maximum removal efficiencies of 86.86% and 97.77% respectively, under optimized pH, contact time, and dosage conditions, with adsorption kinetics fitting the pseudo-second-order model **(Mulushewa et al., 2021)**. Similarly, activated carbon derived from Rumex abyssinicus showed remarkable efficiency, removing up to 99.9% of MB under optimized conditions using the Box–Behnken design, with the Freundlich isotherm fitting best, suggesting heterogeneous multilayer adsorption **(Fito et al., 2023).**

Beyond adsorption, photodegradation techniques are also extensively studied for MB removal. **Khan et al. (2022)** describe a multistep photodegradation process involving demethylation, ring cleavage, and conversion of intermediates into harmless end products such as CO_2, H_2O, NH_4^+, and SO_4^{2-}. Recent advances in nanotechnology further enhance this approach, as demonstrated by hematite (α-Fe_2O_3) nanoparticles biosynthesized using Mentha pulegium extract, which achieved 78% MB degradation within 120 minutes through an irradiation method under UV light **(Goudjil et al., 2024).**

Synthesis & Research Gap

The widespread post-mismanagement of synthetic dyes is a major source of aquatic pollution due to their complex structures and resistance to biodegradation. The containment of dyes in textile wastewater poses a significant environmental threat, which necessitates stronger regulatory standards and effective treatment methods that can address its complex physicochemical parameters. While conventional biological, physical, and chemical treatments are often limited– by efficiency or the production of secondary waste— irradiation technology, specifically, gamma and electron beam, presents a robust alternative by utilizing ionizing radiation to generate reactive species that completely mineralize dye molecules. The principles of gamma and electron beam irradiation technology are well-established for wastewater sterilization, in which ionizing radiation is used to eliminate pathogens and degrade organic pollutants. Its safe implementation is governed by stringent international protocols, making it a viable and accessible treatment option, particularly in contexts like the Philippines with existing facilities. The cationic dye methylene blue (MB) serves as an ideal model pollutant, exemplifying the challenge due to its toxic, carcinogenic nature and widespread industrial use. Its complex structure makes it an effective benchmark for demonstrating the efficacy of advanced treatment methods, such as gamma irradiation, in achieving high degradation rates and successful environmental remediation.

While gamma irradiation is a well-established technology for wastewater sterilization and has demonstrated efficacy in degrading various complex dyes, recent work by **Ye et al. (2022)** has shown that electron beam irradiation (EBI) can also degrade methylene blue effectively when combined with graphite carbon nitride and carbon nanodots (g-C_3N_4/CDs). However, no study has yet focused on the application of EBI alone—without catalytic enhancement—to evaluate its independent efficiency and degradation kinetics for methylene blue under varying concentrations, pH levels, and irradiation doses. Similarly, there remains a lack of studies that directly evaluate the performance of EBI and gamma irradiation under experimental conditions and objectives. Addressing this gap will provide a clearer understanding of the standalone potential of EBI and Gamma radiation and help establish optimized parameters for the radiation-induced degradation of methylene blue in textile wastewater.

Rationale of the Study

As access to clean and safe domestic water remains a global concern, the need to manage accessible forms of water within households and the environment they are drawn from is critical. In the Philippines, dye substances are a significant contributor to water waste, primarily from the pharmaceutical, plastic, and general textile industries. While not intended for drinking, untreated water effluents still pose sanitation concerns and environmental risks if left unmanaged.

One of the treatment methods that can be utilized in order to address this issue is gamma irradiation. In general, it is used for radiotherapy and sterilization in the field of medicine. But it may also be used in textile effluents by initiating the radiolysis of water molecules. This will produce reactive species that can degrade dye molecules by disintegrating their aromatic structure.

This study will determine the effectiveness of gamma and electron beam irradiation in eliminating contaminants in water effluents, specifically the methylene blue, and improving the general water quality. By ensuring that this treated water effluent meets safety standards, it may be employed as a primary stage of overall water treatment — eventually for purposes such as cleaning, flushing, or irrigation — supporting sustainability and reducing wastewater. It is important to ensure access to clean water as it is an essential part of living. If the quality of water does not meet the expected values of water quality standards, it may cause detrimental health conditions to people and pose a threat to our environment.

Research Problems and Hypotheses

Research Problem

This research aims to assess the effectiveness of Gamma and Electron Beam Irradiation in treating dye-containing wastewater of textile industries by answering the following questions:

1. How does dye concentration influence the effectiveness of radiation-induced methylene blue degradation? Particularly in:
    a. 1 ppm
    b. 5 ppm
    c. 10 ppm
2. How does the initial pH level influence the radiation-induced methylene blue degradation? Particularly in:
    a. 4
    b. 6
    c. 8
    d. 10

3. How does varying absorbed irradiation dosage influence the effectiveness of radiation-induced methylene blue degradation? Particularly in:

    a. 2 kGy

    b. 5 kGy

    c. 7 kGy

    d. 10kGy

4. What is the statistical significance of the changes in methylene blue effluent after gamma and electron beam irradiation, and how do these findings compare to existing water safety standards?

Hypothesis

H_0: The irradiation will not degrade the methylene blue within dye-containing effluents from the textile industries.

H_1: The irradiation will be able to degrade the methylene blue within dye-containing effluents from the textile industries.

Conceptual framework

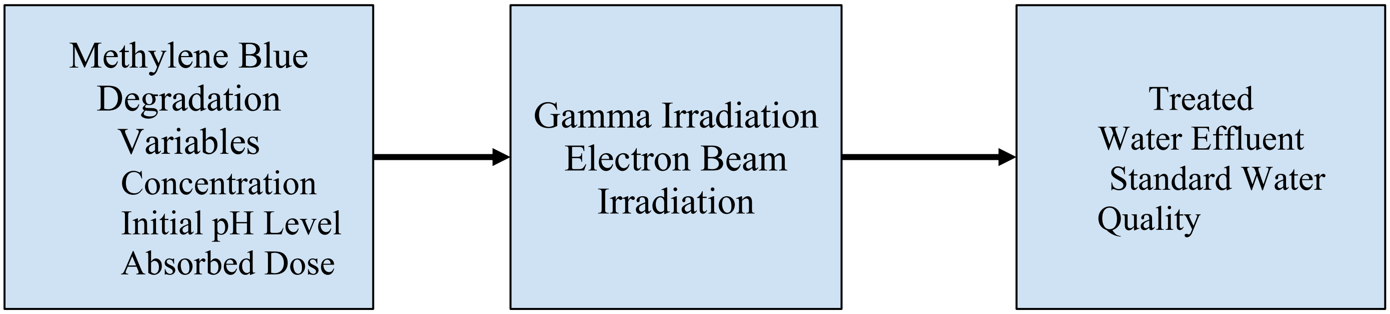

Figure 2.1 *Conceptual Framework of Treatment of Water Effluents from Textile Industries using Gamma and Electron Beam Irradiation*

The figure above shows the conceptual framework of the study. It focuses on how the different variables, like the concentration of methylene blue in the water effluent, the initial pH level, and the absorbed dose, influence the degradation of methylene blue under gamma and electron beam irradiation. The independent variables are expected to affect the state of the wastewater, which can affect the result of the overall treatment. The treated water will then be assessed to determine if it can meet the standard quality of water with particular parameters.

Definition of Terms

1. **Contaminants** – These are unwanted substances that render something dirty, unsafe, or impure.
2. **Dosage -** This refers to the amount of gamma radiation absorbed by the samples, measured in kiloGray.

3. **Dye Concentration** - This pertains to the amount of dye in a given amount of solution; measured in mg/L.
4. **Electron Beam Irradiation** – This is a method of using fast-moving electrons to treat or sterilize materials, often used in food and medical equipment.
5. **Gamma Radiation** – This points out a high-energy type of radiation that can pass through most materials and is often used to kill bacteria or treat cancer.
6. **Industrial** – This pertains to something produced, used, or done on a very large scale, often related to factories or businesses.
7. **Ionizing Radiation** – Ionizing radiation refers to energy powerful enough to remove electrons from atoms, potentially altering or damaging materials or the cells of living organisms.
8. **Irradiation** – This is the process of exposing something to radiation.
9. **Methylene Blue** - This is a chemically stable and persistent heterocyclic cationic dye commonly used in the textile industry. Its high resistance to degradation makes it difficult to remove through traditional treatment methods.
10. **Radiation** – This pertains to the energy that travels through space or materials in the form of waves or particles.
11. **Sterilize** – The process that refers to killing all germs, bacteria, and other harmful organisms, making something completely clean and safe.

12. **Wastewater** – This refers to used water that contains waste from homes, businesses, or factories, which often needs to be cleaned before being released into the environment.

13. **Water Effluent -** This is a liquid waste of water that is being discharged across bodies of water in the environment from industries, sewage systems, and agricultural runoff

CHAPTER 2

METHODOLOGY

This chapter presents the research design and methodology, research site, data collection, role of the researcher, and ethical considerations as used in the study.

Research Design

A full factorial design will be used in this study to determine the effects of initial pH, absorbed irradiation dose, and sample concentration on dye degradation. A complete factorial design allows the evaluation of both the main effects of each factor and the interaction effects arising from changing factors simultaneously (Oimoen, 2019).

For this study, the factor will be the parameters, and the factors will be systematically combined to produce the unique experimental runs. The design will consist of two 3×4 full factorial setups — **one for Gamma Irradiation and one for Electron Beam Irradiation (EBI)** — with three levels of concentration combined with four levels of both absorbed irradiation dose and initial pH level which is irradiated at a fixed rate of 2kGy. Each combined experiment will be replicated three times. This type of experimental design typically follows factorial design applications in agriculture and environmental research, where different levels of parent material and application rates of potassium are combined to evaluate main effects and interactions (Ijah, Ekpo, & Ekwere, 2025).

Factorial experimental designs are widely used to evaluate the statistical significance of multiple factors simultaneously, providing insight into how each factor affects the response variable and how potential interactions modify these effects (Alkhatib et al., 2017). An interaction is present when the influence of one factor varies depending on the levels of another factor. In accordance with this approach, the evaluation of our experimental results was conducted using Analysis of Variance (ANOVA) and multiple regression analysis. ANOVA is particularly valuable because it distinguishes true factor effects from variations caused by random error by partitioning the total sum of squares into components associated with each source of variability. In the context of the study, variability arises from multiple factors—such as dye concentration, pH, irradiation type, and absorbed dose—each with several levels, and interactions may occur between any combination of these factors. The ANOVA procedure yields F-statistics and corresponding p-values that test the significance of each main factor and interaction term, allowing the identification of which variables meaningfully influence methylene blue degradation.

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Table 1.1 3x4 Full Factorial Design Matrix of Sample Concentration with Absorbed Irradiation Dose and Dye Concentration in Methylene Blue Degradation

Concentration (ppm) [1, 5, 10]	**Absorbance Dose (kGy) (2, 5, 7, 10)**			
1 ppm	(1ppm) (2kGy) (3 replications)	(1ppm) (5kGy) (3 replications)	(1ppm) (7kGy) (3 replications)	(1ppm)(10kGy) (3 replications)
5ppm	(5ppm) (2kGy) (3 replications)	(5ppm) (5kGy) (3 replications)	(5ppm) (7kGy) (3 replications)	(5ppm)(10kGy) (3 replications)
10ppm	(10ppm) (2kGy) (3 replications)	(10ppm) (5kGy) (3 replications)	(10ppm) (7kGy) (3 replications)	(10ppm)(10kGy) (3 replications)

Table 2.1 3x4 Full Factorial Design Matrix of Sample Concentration with Initial pH Level and Dye Concentration in Methylene Blue Degradation

Concentration (ppm) [1, 5, 10]	**Initial pH Level (4, 6, 8, 10)**			
1 ppm	(1ppm) (pH 4) (3 replications)	(1ppm) (pH 6) (3 replications)	(1ppm) (pH 8) (3 replications)	(1ppm)(pH 10) (3 replications)
5ppm	(5ppm) (pH 4) (3 replications)	(5ppm) (pH 6) (3 replications)	(5ppm) (pH 8) (3 replications)	(5ppm)(pH 10) (3 replications)
10ppm	(10ppm) (pH 4) (3 replications)	(10ppm) (pH 6) (3 replications)	(10ppm) (pH 8) (3 replications)	(10ppm)(pH 10) (3 replications)

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Research site

This research will take place at two main venues within Metro Manila, Philippines. The experimental protocols occurred at the Chemistry Research Section and Irradiation Services Section of the Philippine Nuclear Research Institute (PNRI) along Commonwealth Avenue, Diliman, Quezon City.

Data synthesis, analysis, and manuscript writing will take place at the Philippine Normal University (PNU) Manila Campus, located at 104 Taft Avenue, Ermita, Manila. Meetings and discussions related to the study will take place in both areas.

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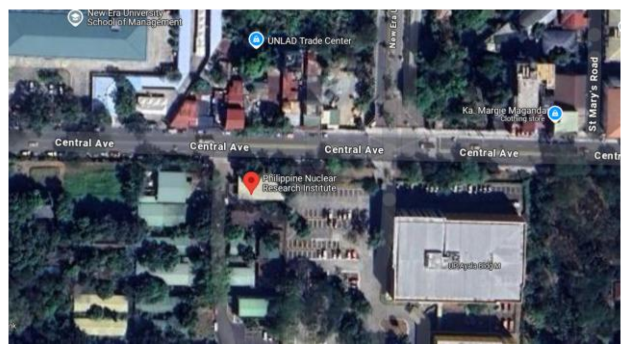
<td>
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Full Resolution: Philippine Nuclear Research Institute</td>
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Center of Transformative Education Faculty of Behavioral and Social Sciences Full Resolution: PNU Manila Campus Map (v2).png	

Table 3.1 Primary Research Sites

Sampling Procedure

Sample preparation will be carried out at the Chemistry Research Section's Radiation Grafting Laboratory, starting with a methylene blue stock solution formulated from analytical-grade dye powder dissolved in deionized water, both supplied by the facility. This stock will then be diluted to achieve target concentrations of 1 ppm, five ppm, and 10 ppm. Each stock solution will then be irradiated at different doses and adjusted to a specific pH with NaOH or HCl. Pre- and post-measurements will be taken with calibrated instruments. All methods will be performed according to accepted standardization methods with respect to sanitary protocols. Each procedure will be completed following standardization through detailed protocols to provide accuracy and reliability.

Role of the researcher

The researchers of this study will undertake the responsibility of executing the experimental protocols along with analyzing the subsequent data. They will also evaluate and mitigate any potential risks associated with the study. They will consult with professionals as needed to assure the accuracy, ethical validity, and safety of the study.

Research instrumentation and methods of validation

The research instruments to be used in this study to collect data are laboratory equipment from the Philippine Nuclear Research Institute Center Lab. These instruments will be used to quantify water parameters in the dye water samples, specifically pH and the effluent absorbance spectrum.

For the dye concentration, a 100 mL stock solution of 1000 ppm methylene blue is prepared. To achieve the necessary concentration, the stock solution was serially diluted to 1 ppm, 5 ppm, and 10 ppm. Each concentration was tested for its initial pH and absorbance spectrum, with Lambda_max set at 664nm, and a calibration curve of Absorbance vs Concentration was generated, showing a direct linear relationship. The pH adjustment for pH-dependent degradation was performed directly in the vial using NaOH or HCl to set each concentration to the desired pH (4, 6, 8, 10). Similarly, these are tested for pH and absorbance spectra. The validation of the absorbance dose from gamma and electron beam irradiation was performed by the irradiation facility technician at PNRI to specify the required absorbance dose. Each sample was labelled with a respective kGy, and the facility also provided a report sheet of the sample's exposure time.

Before creating the necessary solutions, calculations will be performed and validated by the associates and research supervisors within the PNRI Chemistry Research Section.

To ensure the accuracy of the equipment, the pH sensor was calibrated beforehand, and a blank sample of deionized water was used as a calibration standard for the UV-Vis spectrophotometer. After each test, the equipment will be sanitized and undergo an acid wash to ensure that no methylene blue residue or staining can be found on the equipment.

Intervention

This study focuses on the ionizing capability of gamma and electron beam irradiation, aiming to investigate the degradation of methylene blue dye through the said types of irradiation. The researchers will utilize irradiation technology of the Ob-Servo Sanguinis Gamma Irradiator and the Electron Beam Irradiation facility at the Philippine Nuclear Research Institute, which serves as the intervention employed by the researchers.

Data Collection

The study will revolve around analyzing the effect of gamma and electron beam irradiation on the degradation of the methylene blue dye within the dye-containing effluent. The methylene blue solution prepared in the laboratory will be measured for pH and absorbance spectrum using a pH sensor and a UV-Vis spectrophotometer. The sample will undergo irradiation. After the irradiation process, the same parameters are measured for the samples, and the interpretation data from the initial and irradiated samples.

The sample will be conducted with three independent variables: Dye Concentration, pH level, and Absorbed dose. For the concentration, the samples will be done in three different concentration values (1ppm, 5ppm, 10ppm), the pH level will be varied to 4 levels (pH 4, 6, 7, and 8), and lastly, each sample will be irradiated under four different absorbance doses (2kGy, 5kGy, 7kGy, 10kGy)

Each sample follows a unique treatment combination with varying concentration, pH level, and absorbance dose (e.g., 1 ppm, pH 4, 2 kGy dose), and each is triplicated to ensure statistical accuracy for each test. To ensure the control group of the study, each concentration has been tested for pH and absorbance at zero kGy, with each sample having its initial pH and the pH level tested at zero kGy.

Data Analysis

This study will employ quantitative analysis, specifically inferential statistics, to assess the effectiveness of gamma and electron beam irradiation in degrading methylene blue, while controlling for the following independent variables: pH level, concentration, and absorbed dosage. The analysis aims to determine whether the independent variables affect water quality, specifically in the treatment of wastewater. Analyzing the data using this method will enable researchers to examine the combination of samples from controlled and experimental groups based on the collected data. This approach will be used to test the hypotheses—whether the differences observed between the groups are statistically significant.

To achieve this, the study will follow a **true experimental approach**, with the following in consideration:

1. **Non-Random**: Samples are drawn non-randomly from the laboratory-made methylene blue solution.
2. **Control over Treatment**: Treatment is pre-adjusted by the laboratory personnel
3. **Control Group**: Control groups isolate the effect of independent variables (pH level, concentration, and dosage absorbance)

Statistical Methods

The following statistical techniques will be applied:

- **Measures of Central Tendency for Descriptive Statistics**: The Mean, Median, Variance and Standard Deviation will be used to summarize water quality data.
- **Analysis of Variance (ANOVA)**: The ANOVA is a statistical test used to assess the significance of groups with more than two samples. An N-way ANOVA was

used because the study had more than two factors (Statistics Solution, 2025). Aside from the direct influence of the independent variables on the dependent variable, it may also uncover underlying relationships between the independent variables themselves.

a. Dependent Variables: In this study, the percentage of dye degradation from the UV-VIS spectra
b. Factors: The independent variables are the concentration of dye (1ppm, 5ppm, 10ppm), absorbed dosage (2kGy, 5kGy, 7kGy, 10kGy) and pH level (pH 4, 6, 8, and 10)
c. Test: The factorial ANOVA tests the interrelationships among the factors (independent variables). This will reveal interactions among the factors that determine the dependent variables. The factorial design will test the following:

   I. Gamma Irradiation

      1. Main Effect of Concentration
      2. Main Effect of Absorbed Dose
      3. Main Effect of pH
      4. Two-Way Interactions

         4.1. Concentration and Absorbed Dose
         4.2. Concentration and pH

4.3. Dose and pH

5. Three-Way Interaction: Concentration, Absorbed Dose and pH

II. Electron Beam Irradiation

1. Main Effect of Concentration

2. Main Effect of Absorbed Dose

3. Main Effect of pH

4. Two-Way Interactions

4.1. Concentration and Absorbed Dose

4.2. Concentration and pH

4.3. Dose and pH

5. Three-Way Interaction: Concentration, Absorbed Dose and pH

d. Post-Hoc Testing: This is a statistical test conducted after collecting results from a primary statistical method, such as the factorial ANOVA in this research. It will show the significant main effect of the factors on more than two levels. It is necessary to determine whether the levels are significantly different from one another. This study will utilize Tukey's Honestly Significant Difference (HSD) for comparing the factors in finding significant effects within interactions.

Ethical Considerations

In conducting this study, the researchers will consider potential ethical concerns that may arise throughout the research process. The following ethical considerations will be observed:

Non-maleficence

To minimize risks and potential harm, the researchers will follow a systematic plan for utilizing the benefits from the study. All procedures will be reviewed in consultation with the research adviser, faculty members, expert consultants, and collaborators.

The study will be conducted with consideration of the risks present. Gamma and electron beam irradiation are utilized for the ionizing capabilities. This capability of irradiation technology is used to induce radiolysis on the water samples, thereby altering the chemistry of the water. It can be mitigated by using a radiation dose when treating the water samples.

This research aims to contribute to the country's environmental and sanitation efforts. Data collection procedures, results, and interpretations can be shared with relevant institutions to support future initiatives related to wastewater management and water safety.

Accuracy in Analysis and Presentation

To uphold the validity of the study, the researchers will conduct rigorous consultations to analyze and interpret the findings, ensuring the accuracy of the study. The researchers will maintain ethical integrity by preventing biases from influencing the data and results. All findings will be presented objectively, in compliance with the highest standards of scientific rigor and academic integrity.

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Risk Analysis

Research Duration (number of months): 3 months **Start Date:** **August**

End Date: **November**

OBJECTIVES	RISKS AND ASSUMPTIONS	ACTION PLAN
Objective 1: Effects of Varying Concentration on Methylene Blue Degradation **Objective 2: pH-Dependent Irradiation** **Objective 3: Variation of Absorbed dose**	**Risks:** — faulty instrument — closure of laboratory facilities because of renovation — measurement error — MB Contamination of Surrounding Environment **Assumptions:** — MB samples are properly collected and represented	**Risks:** **Faulty Instrument** — Ensure routine maintenance and pre-experiment calibration of all instruments. — Request for back-up instruments that may be available in case of failure.

	— Consistency in sample collection — facility regulatory compliance — calibration of equipment	**Closure of Laboratory Facilities because of Renovation** — Schedule the experiments beforehand or afterward the impending renovation — Asking for the instruments to be borrowed from the laboratory if it is a negotiable case **MB Contamination of Surrounding Environment** — Ensure the sanitation of materials and equipments used before and after the experiment **Measurement Error** — Ensuring that the equipment and instruments that will be using are calibrated and in good condition to be utilized in the study

		— Collect data with multiple trials to know if they are consistent **Assumptions:** **MB Samples Are Properly Collected and Represented** — Document the exact conditions of the MB sample collection. **Consistency in Sample Collection** — Collect all samples following the same procedure and within the same time frame for consistency. —Ensure that each sample is labeled properly to maintain accurate tracking and prevent mix-ups.

		Regulatory Compliance — Review and follow government guidelines on water quality testing and irradiation processes — Obtain necessary permits for the experiment if required **Calibration of Equipment** — Equipment and instruments must be calibrated before and after the experiments to retain to ensure that the collection of data is accurate
Objective 4: Changes in Parameters of Methylene Blue Effluent after Gamma and Electron Beam Treatment Compared to Existing Water Standards	**Risks:** — inaccurate statistical readings — inconsistency in absorbed radiation dose — logistical incapability to consider the rise of degradation by-products	**Risks:** **Inaccurate Statistical Readings** — Ensure routine calibration of expert-suggested statistical software — Verify readings with reference studies of the same statistical methods

	— insignificant statistical effect that'll mismatch the existing water standard **Assumptions:** — basis of water quality standards are timely and appropriate — post-irradiation samples reflect true treatment effects without contamination	**Inconsistency in Absorbed Radiation Dose** — Standardize exposure time, sample placement, and dose rate monitoring for both systems. **Logistical Incapability to Consider the Rise of Degradation By-products** — Refer to relevant studies that will provide deliberate analysis to the said byproducts **Insignificant Statistical Effect/s That'll Mismatch The Existing Water Standard** — Accept the outcome as a valid objective result and conduct further analysis to determine the underlying factors that caused this effect

		— Assign 2 or more group members to conduct the statistical analysis for cross-checking to ensure consistency **Assumptions:** **Basis of Water Quality Standards are Timely and Appropriate** — Refer to the most current DENR (national environmental agency) wastewater regulatory guidelines **Post-irradiation Samples Reflect True Treatment Effects Without Contamination** — No external substances alter the results; closed containers and clean equipment maintain purity.

CHAPTER 3

RESULTS AND DISCUSSION

Preparation of Methylene Blue solutions

Figure 3.1

Dilution of Stock Solution to Different Methylene Blue Concentration

The initial stock solution is diluted into three volumetric flasks with concentration of 1ppm (A), 5ppm (B), and 10 ppm (C), The varying color intensity visually confirms the intended gradient of concentrations, with the 1 ppm solution being the lightest (A) and the 10 ppm solution being the deepest blue (C). This visual verification ensures that the experimental solutions were prepared correctly, which is crucial for subsequent analysis of absorbance and degradation.

Table 4.1

Preparation of Stock and Diluted Methylene Blue Solutions

Concentration (ppm)		Volume (ml)	Gamma and EBI	Total Samples	Volume (mL)
A	**1 ppm**	10	4	12	120
B	**5 ppm**	10	4	12	120
C	**10 ppm**	10	4	12	120

The table outlines the dilution scheme used to prepare the working Methylene Blue solutions at different concentrations for the degradation experiment. The concentrations were specifically chosen to cover the range necessary for studying the concentration-dependent effects of both Gamma and Electron Beam Irradiation (EBI) treatments.

Table 5.1

Stock Preparation and Dilution Scheme of Methylene Blue Solutions

Concentration (ppm)		*Flask Volume (mL)*	*Stock Concentration (ppm)*	*Volume (mL)*
A	**1 ppm**	250	1000	0.25
B	**5 ppm**	250	1000	1.25
C	**10 ppm**	250	1000	2.5
D	**20 ppm**	100	1000	2
E	**50 ppm**	100	1000	5

The stock solution was prepared at 1000 ppm by dissolving 100 mg of methylene blue in 0.1 L of distilled water. Additional concentrations of the stock were included to test the maximum threshold of irradiation feasibility, ensuring that the degradation behavior could be evaluated across a wider concentration range. Subsequent dilutions were prepared to obtain the target working concentrations used for analysis.

Table 6.1

Calibration Curve Data and Absorbance (λmax = 664 nm) for Gamma and Electron Beam Irradiation

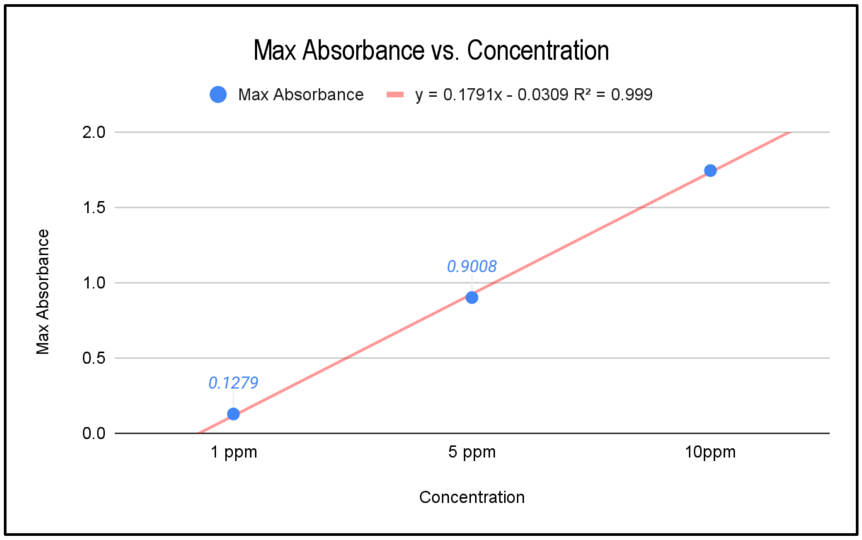
Concentration (ppm)		Absorbance (664 nm)
A	**1**	0.1279 au
B	**5**	0.9008 au
C	**10**	1.7434 au

au = absorbance units

The table details the initial absorbance of methylene blue solution across varying concentrations. At λmax = 664 nm, the noticeable increase in the absorbance can be related to the increase in the dye concentration. This data is then used in order to create a calibration curve for the methylene blue concentration against its max absorbance

Figure 4.1

Calibration Curve of Methylene Blue Absorbance vs. Concentration

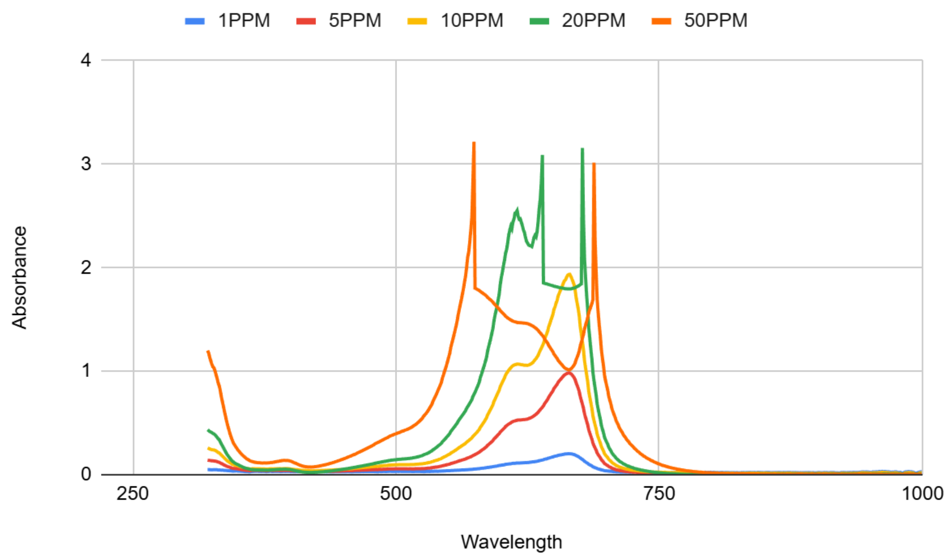


The table shows the calibration curve of Methylene blue, specifically the concentration of methylene blue against its max absorbance. The data points were used to construct the calibration curve that confirms the solution's adherence to the Beer-Lambert law within the experimental range. The R^2 of 0.999 denotes that the concentration and max absorbance of methylene blue demonstrated a linear relationship. This result as well the linear equation of y = 0.1791x - 0.309 is essential in quantifying the dye concentration and the percent degradation after the irradiation process.

Objective 1: Effects of Varying Concentration on Methylene Blue Degradation

Figure 5.1

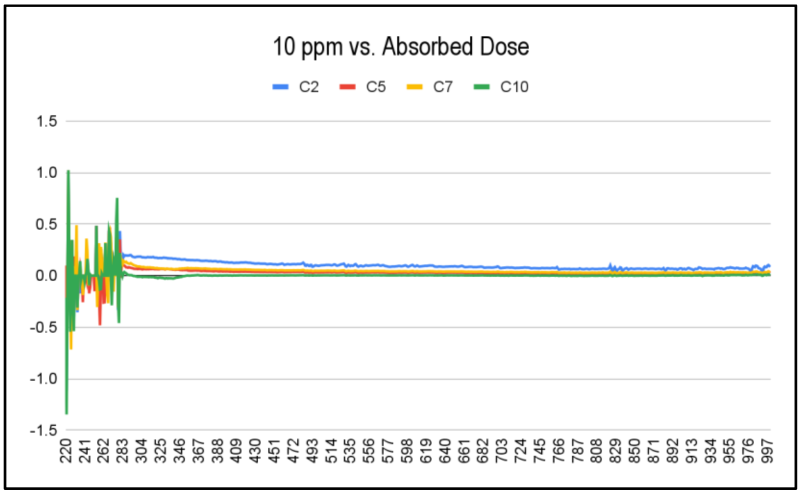
Concentration vs. Absorbance of Methylene Blue (λ_{max} = 664 nm)

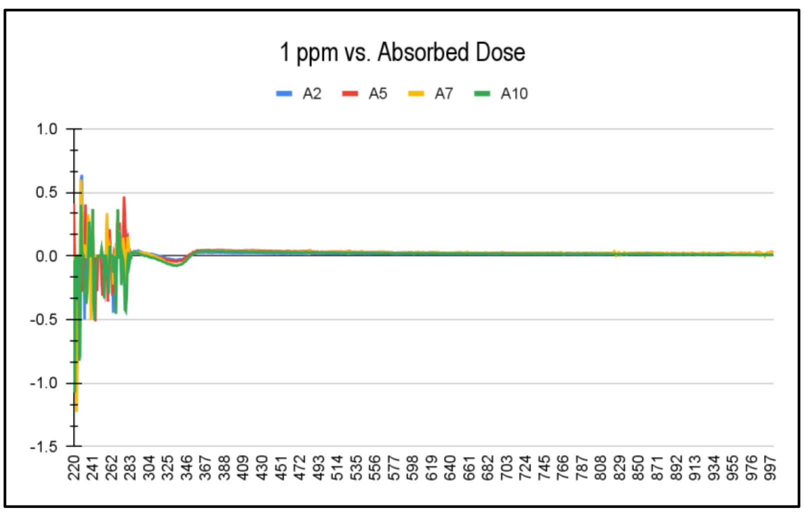


The figure shows the initial UV-Vis absorbance spectra for Methylene Blue solutions across the five experimental concentrations before any radiation treatment was applied. The presence of a dominant peak near 664 nm confirms the expected characteristic light absorption wavelength of Methylene Blue dye. The linear increase in the peak absorbance with increasing concentration validates the solutions' suitability for degradation analysis based on the Beer-Lambert law.

Figure 6.1

Concentration vs. Absorbed Dose for Gamma Irradiated Methylene Blue Samples (λ_{max} = 664 nm)





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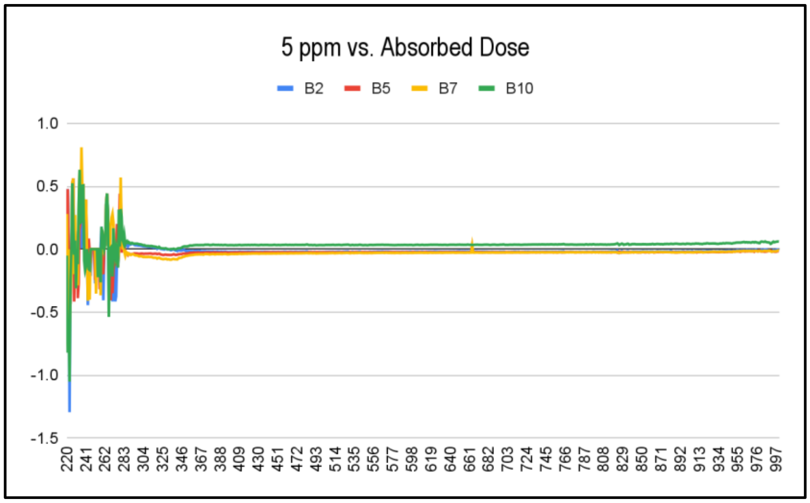
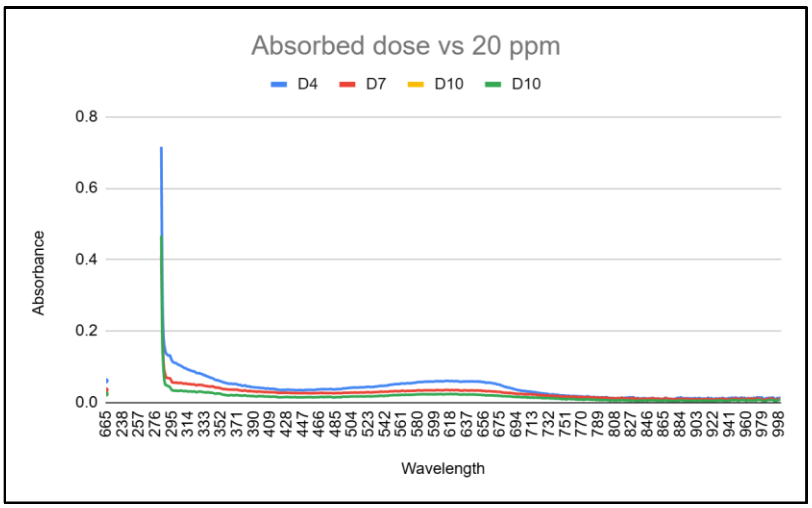
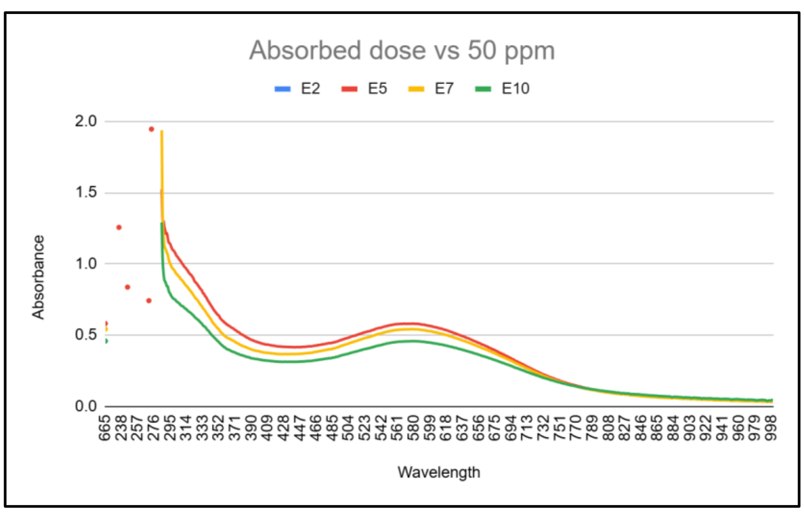


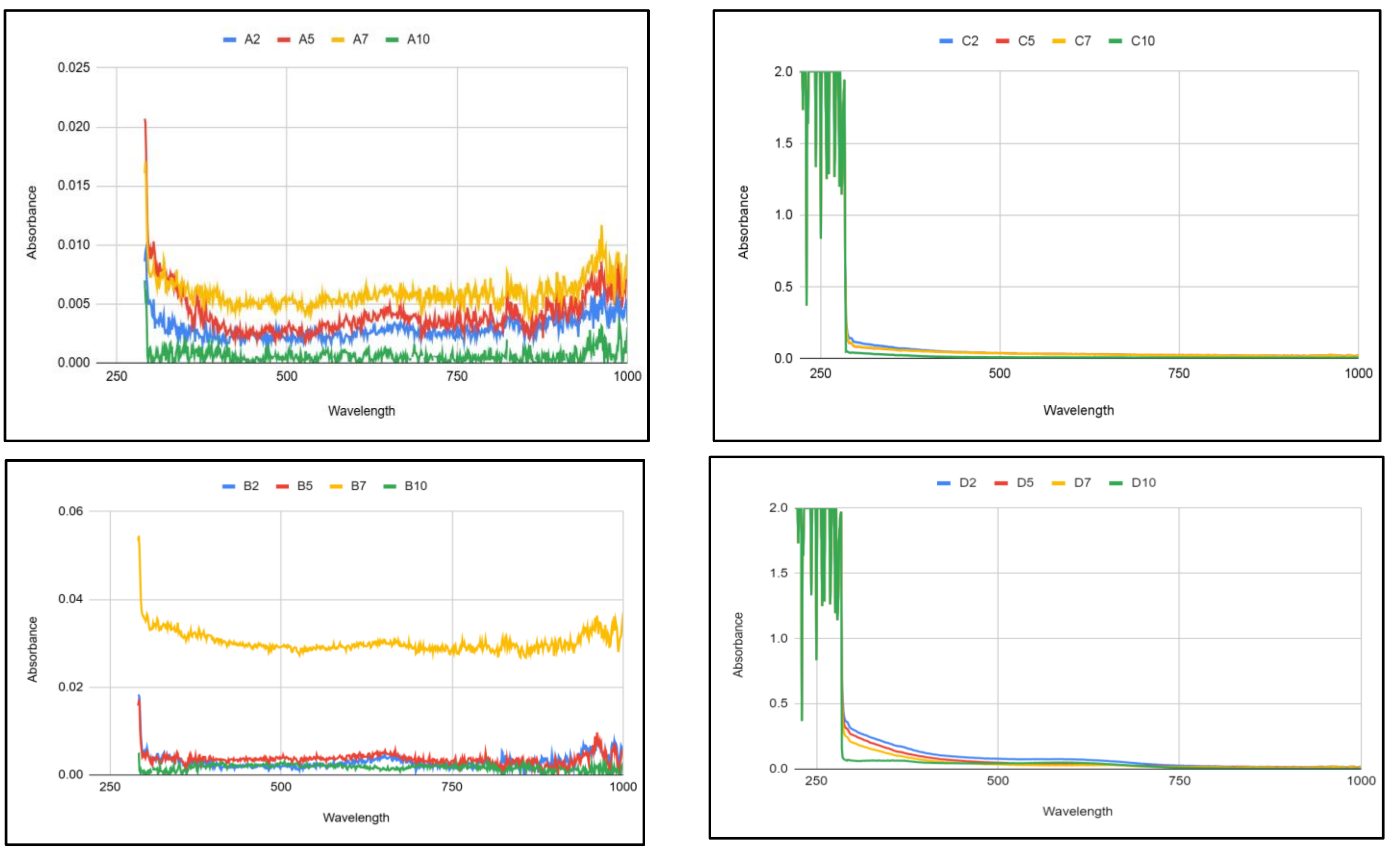




The composite figure illustrates the full UV-Vis absorbance spectra of Methylene Blue at various concentrations after exposure to different doses of Gamma Irradiation. The consistent and significant reduction in the characteristic absorbance peak across all conditions confirms that the irradiation process successfully induced dye degradation and decolorization. The varying shapes of the spectral curves across different concentrations qualitatively demonstrate that the radiolysis mechanism and efficiency are influenced by the initial dye concentration.

Figure 7.1

Uv-Vis of Concentration vs Absorbed Dose for Electron Beam Irradiated Samples



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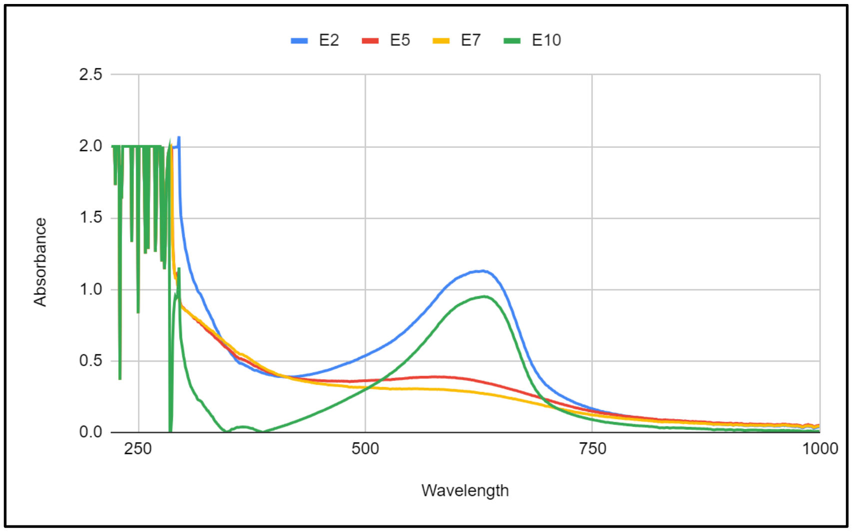

The composite figure displays the full UV-Vis absorbance spectra of Methylene Blue solutions after treatment with varying doses of Gamma Irradiation across five different concentrations. The consistent and significant reduction in the characteristic absorbance peak after irradiation confirms the successful degradation and decolorization of the dye in all tested samples. The degradation profile, as shown by the changes in the spectral curves, qualitatively demonstrates that the removal rate is influenced by the initial dye concentration.

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Table 7.1

Initial and Post-Gamma Irradiation of pH Values of Methylene Blue Solutions

Concentration (ppm)		Initial (0 kGy)	2kGy	5kGy	7 kGy	10 kGy
A	1 ppm	9.21	T1 - 8.66 T2 - 8.28 T3 - 7.73	T1 - 8.04 T2 - 7.66 T3 - 7.60	T1 - 7.38 T2 - 7.46 T3 - 7.25	T1 - 7.26 T2 - 7.24 T3 - 7.17
			$\bar{X}$ = 8.22	**$\bar{X}$ = 7.77**	**$\bar{X}$ = 7.36**	**$\bar{X}$ = 7.22**
B	5 ppm	8.64	T1 - 5.68 T2 - 5.36 T3 - 5.28	T1 - 5.92 T2 - 5.52 T3 - 5.22	T1 - 5.35 T2 - 5.66 T3 - 5.15	T1 - 5.58 T2 - 4.77 T3 - 5.57
			$\bar{X}$ = 5.44	**$\bar{X}$ = 5.55**	**$\bar{X}$ = 5.39**	**$\bar{X}$ = 5.31**
C	10 ppm	7.82	T1 - 4.56 T2 - 5.06 T3 - 4.58	T1 - 4.64 T2 - 4.03 T3 - 4.12	T1 - 4.20 T2 - 4.43 T3 - 4.08	T1 - 4.67 T2 - 4.17 T3 - 4.61
			$\bar{X}$ = 4.73	**$\bar{X}$ = 4.26**	**$\bar{X}$ = 4.24**	**$\bar{X}$ = 4.48**

D	**20 ppm**	**8. 14**	T1 - 4.21 T2 - 4.32 T3 - 4.35	T1 - 3.72 T2 - 3.71 T3 - 3.70	T1 - 3.99 T2 - 4.13 T3 - 3.89	T1 - 3.43 T2 - 4.55 T3 - 4.38
			$\bar{X}$ = 4.29	**$\bar{X}$ = 3.71**	**$\bar{X}$ = 4**	**$\bar{X}$ = 4.12**
E	**50 ppm**	**8.08**	T1 - 5.05 T2 - 5.11 T3 - 4.28	T1 - 4.30 T2 - 5.13 T3 - 4.78	T1 - 3.94 T2 - 4.16 T3 - 3.84	T1 - 4.28 T2 - 3.88 T3 - 4.76
			$\bar{X}$ = 4.81	**$\bar{X}$ = 4.74**	**$\bar{X}$ = 3.98**	**$\bar{X}$ = 4.31**

This table summarizes the pH of the Methylene Blue solutions after treatment with increasing doses of Gamma Irradiation across five distinct concentration levels. The pH generally decreased across most concentrations and doses compared to the initial reading, indicating an overall increase in solution acidity after irradiation. This shift toward a lower pH suggests the formation of acidic byproducts resulting from the radiation-induced degradation of Methylene Blue.

Table 8.1

% Degradation of Methylene Blue for Absorbed Dose vs Concentration post-Gamma Irradiation

	Post Concentration							
Concentration	**2 kGy**	**% Degradation**	**5 kGy**	**% Degradation**	**7 kGy**	**% Degradation**	**10 kGy**	**% Degradation**
A	0.2501	74.9860	0.3004	69.9609	0.2954	70.4634	0.2741	72.5851
B	0.2680	94.6399	0.3049	93.9028	0.3188	93.6237	0.3640	92.7192
C	0.6376	93.6237	0.3797	96.2032	0.3836	96.1642	0.1854	98.1463
D	1.0547	94.7264	0.4830	97.5851	0.3518	98.2412	0.2864	98.5678
E	2.1128	95.7744	2.5410	94.9179	2.4082	95.1837	2.1128	95.7744

This table summarizes the quantitative effectiveness of the Gamma Irradiation treatment by showing the calculated percentage of Methylene Blue degradation achieved at various doses and initial concentrations. The results indicate that degradation was highly efficient across all conditions, generally achieving close to perfect removal. The minor variations in efficiency suggest that while the degradation is robust, the initial concentration has a subtle influence on the overall percentage of dye removed.

Table 9.1

% Degradation of Methylene Blue for Absorbed Dose vs Concentration post-Electron Beam Irradiation

	Post Concentration							
Concentration	**2 kGy**	**% Degradation**	**5 kGy**	**% Degradation**	**7 kGy**	**% Degradation**	**10 kGy**	**% Degradation**
A	0.1893	81.0720	0.1954	80.4578	0.2049	79.5087	0.1742	82.5796
B	0.1921	96.1586	0.1988	96.0246	0.3395	93.2105	0.1815	96.3707
C	0.3250	96.7504	0.3149	96.8509	0.3143	96.8565	0.2066	97.9341
D	0.4886	97.5572	0.3412	98.2942	0.3378	98.3110	0.3585	98.2077
E	4.6510	90.6979	1.8208	96.3585	1.4796	97.0408	3.8079	92.3841

The low post-irradiation absorbance values across all concentrations and doses confirm that EBI is an extremely efficient method for dye degradation, often achieving near-complete removal. The degradation efficiency appears to be inversely related to the initial concentration, with the highest initial concentrations (D and E) exhibiting the highest post-treatment absorbance readings, indicating less complete removal.

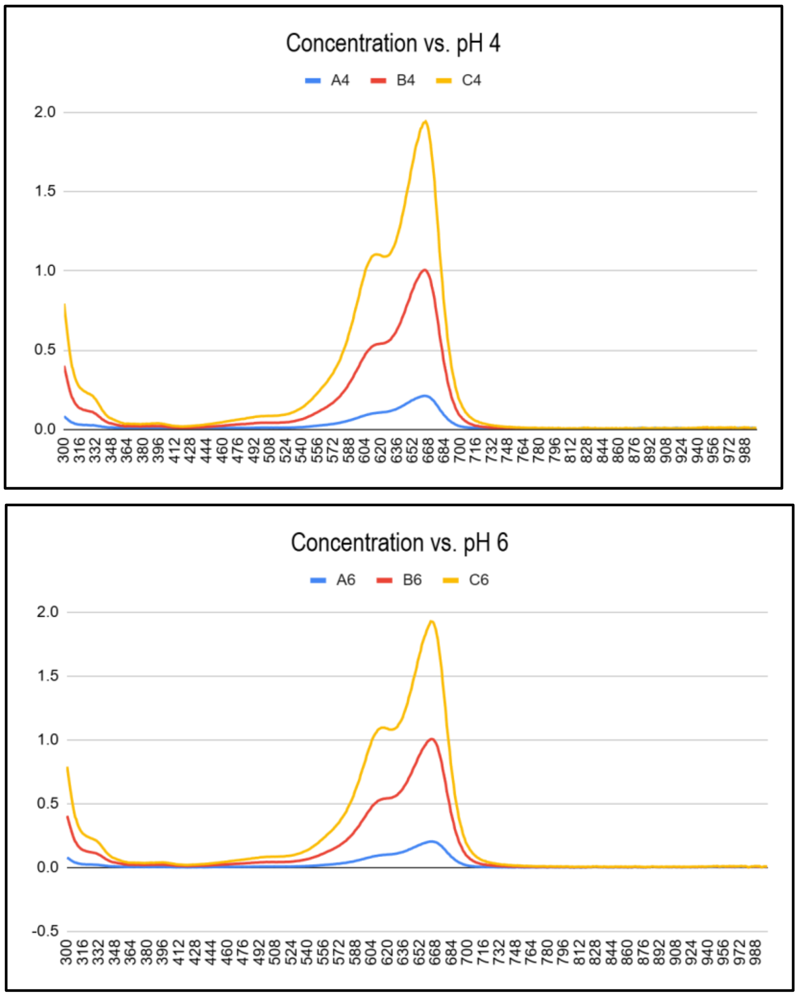
Both Tables 8 and 9 shows the quantitative effectiveness of both irradiations respectively, among the detailed data, it is also observable that the increase in concentration also has an effect on the overall degradation of the methylene blue dye, with increase in concentration, resulting in a solution with a much lower degradation rate. In other studies, Higher concentrations of methylene blue create greater molecular resistance and reduce the availability of reactive species needed for radiolytic breakdown (Mishra & Maiti, 2018). Both gamma and electron beam irradiation depend on highly reactive radicals such as •OH, $e^{-}aq$, and H• to attack the aromatic structure of MB (Arshad et al., 2020), and lower concentrations generally degrade more readily due to reduced radical scavenging (Bhuiyan et al., 2015). Ye et al. (2022) similarly demonstrated that electron beam irradiation becomes less efficient at elevated MB concentrations unless supported by catalytic materials, reinforcing that concentration strongly shapes degradation pathways. In this experiment, the dilution scheme and calibration curves ensured accurate concentration gradients prior to treatment, and subsequent UV–Vis spectra and percent-degradation outputs showed consistent reductions in absorbance across all concentrations, with slightly higher residuals at 10 ppm. These trends align with literature indicating that while irradiation is highly effective, degradation efficiency remains subtly influenced by the initial dye load.

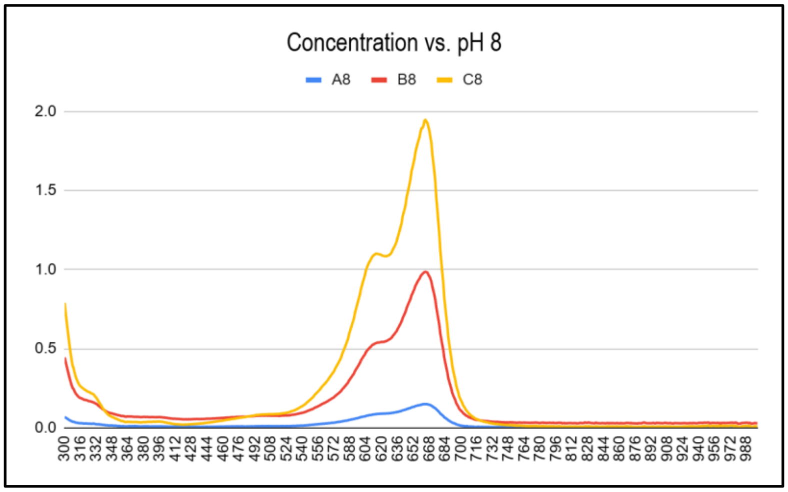
Objective 2: pH-Dependent Irradiation

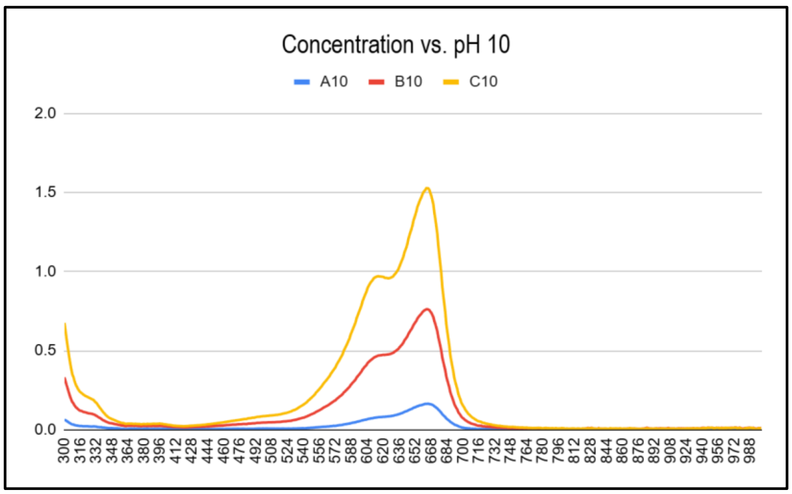
In this section, pH level is studied as a factor of the radiolytic process of methylene blue degradation, across three concentration (1ppm,5ppm, and 10ppm), the initial pH level was varied to four levels pH: 4, 6, 8 and 10 in order to determine the rate of degradation across acidic and basic solutions.

Figure 8.1

pH-Dependent Degradation of Methylene Blue After Gamma Irradiation





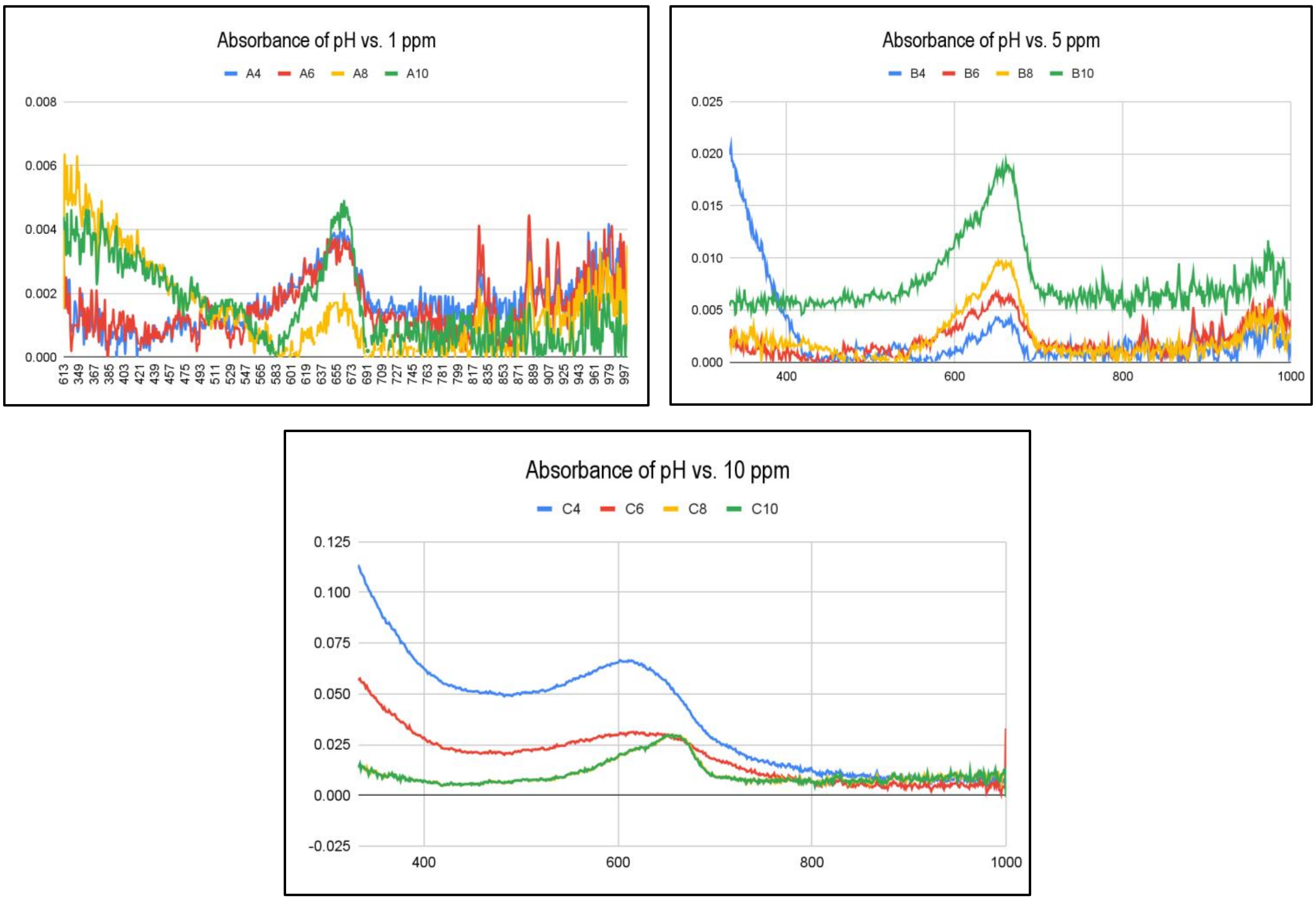


The composite figure displays the UV-Vis absorbance spectra of Methylene Blue solutions after Gamma Irradiation across four different initial pH conditions. A clear and significant reduction in the characteristic absorbance peak is visible in all four pH conditions, confirming the effective degradation of the dye regardless of the initial acidity or alkalinity. The similar degree of reduction across the different pH plots qualitatively suggests that the

Gamma Irradiation degradation mechanism is not substantially dependent on the initial pH of the solution.

Figure 9.1

Concentration vs. pH Level of Gamma Irradiated Methylene Blue Samples



This composite figure illustrates the UV-Vis absorbance spectra of Methylene Blue solutions after Gamma Irradiation across different initial pH conditions at three key concentrations. The degradation profile, as indicated by the reduction of the absorbance peak, demonstrates that the Gamma Irradiation is highly effective in removing the dye regardless of the solution's initial pH. This set of figures qualitatively supports the conclusion that the degradation mechanism's efficiency is not significantly dependent on the initial pH of the Methylene Blue solution.

Table 10.1

Initial and Post-Gamma Irradiation pH Values Across Controlled Initial pH Levels

Concentration	***pH 4***		***pH 6***		***pH 8***	
	Before	***After***	***Before***	***After***	***Before***	***After***
A	3.82	T1 - 3.72 T2 - 3.70 T3 - 3.69 $\bar{X}$ = **3.7**	5.54	T1 - 4.58 T2 - 4.58 T3 - 4.50 $\bar{X}$ = **4.6**	8.53	T1 - 4.88 T2 - 8.85 T3 - 5.20 $\bar{X}$ = **6.31**
B	3.81	T1 - 3.64 T2 - 3.61 T3 - 3.56 $\bar{X}$ =**3.6**	5.72	T1 - 4.14 T2 - 4.13 T3 - 4.09 $\bar{X}$ = **4.12**	8.58	T1 - 4.19 T2 - 4.19 T3 - 4.21 $\bar{X}$ = **4.2**
C	3.66	T1 - 3.59 T2 - 3.56	5.68	T1 - 3.91 T2 - 3.97	8.39	T1 - 4.01 T2 - 4.01

T3 - 3.55	T3 - 3.60	T3 - 4.01
$\bar{X}$ = **3.57**	$\bar{X}$ = **3.83**	$\bar{X}$ = **4.01**

This table summarizes the change in the pH level of the Methylene Blue solutions after they were subjected to Gamma Irradiation at three distinct initial pH settings. A general pH increase (reduction in acidity) was observed across all tested conditions, suggesting the consumption of H^+ ions or the formation of alkaline degradation products. The magnitude of this pH shift appears to be dependent on the initial pH of the solution and the concentration group.

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Table 11.1

pH-Dependent Degradation: Initial Absorbance of Samples Across pH Levels for Gamma Irradiation

Concentration (ppm)		Max Absorbance (664 nm)				
		Before	After			
		Initial Absorbance	pH 4	pH 6	pH 8	pH 10
A	**1**	.1279 au	.2125	.2041	.1504	.165580
B	**5**	.9008 au	1.0058	1.0061	.9861	.7628
C	**10**	1.7434 au	1.9346	1.9255	1.9454	1.5276

This table presents the final Max Absorbance readings (664 nm) after Gamma Irradiation which demonstrates the degree of dye removal across solutions with controlled initial pH levels. The consistency of the post-treatment absorbance values within each concentration group indicates that the degradation efficiency is independent of the initial pH of the solution. This finding suggests that Gamma Irradiation is an effective degradation method that performs robustly across varying environmental pH conditions.

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Table 12.1

% Degradation of Methylene Blue for ph-Dependent post-Gamma Irradiation

Concentration	Post Concentration							
	pH 4	% Degradation	pH 6	% Degradation	pH 8	% Degradation	pH 10	% Degradation
A	0.1949	80.5137	0.1932	80.6812	0.1837	81.6304	0.1999	80.0112
B	0.1954	96.0916	0.2083	95.8347	0.2256	95.4886	0.2781	94.4389
C	0.4405	95.5946	0.3277	96.7225	0.3356	96.6443	0.3361	96.6387

A consistent increase in pH was observed across all tested concentration groups after irradiation, indicating a reduction in the solution's acidity. The results suggest that the post-treatment pH shift is dependent on the initial pH of the solution and the concentration group (A, B, or C).

Table 13.1

Initial and Post-Electron Beam Irradiation pH Values of Methylene Blue Solutions

Concentration (ppm)	pH 4		pH 6		pH 8		pH 10	
	Before	After	Before	After	Before	After	Before	After
A	4.16	3.98	5.80	6.64	8.98	7.66	10.96	7.16
B	4.06	4.27	5.38	4.31	8.80	4.20	10.25	4.21
C	4.05	6.52	5.01	7.11	8.64	4.44	10.82	6.63

This table summarizes the pH values of the Methylene Blue solutions before and after treatment with Electron Beam Irradiation (EBI) across four controlled initial pH levels, pH 4 to pH 10. The results indicate that the EBI treatment generally caused a shift in pH towards neutrality or alkalinity across all pH conditions, with the largest increases seen in the strongly acidic and basic starting points. This effect suggests that the EBI process either consumed H^+ ions or produced basic degradation byproducts in the solution.

Table 14.1

% Degradation of Methylene Blue for pH-dependent post-Electron Beam Irradiation

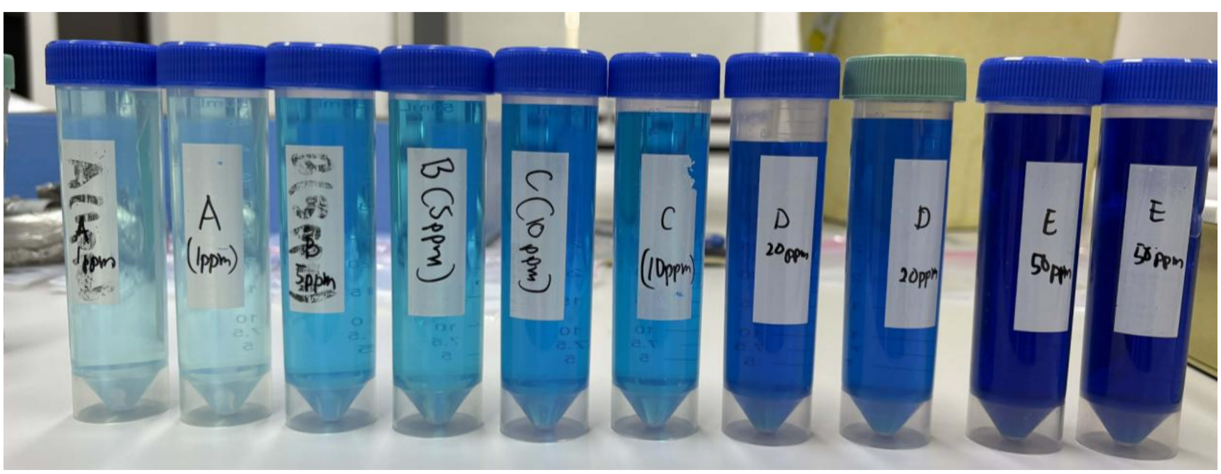
Concentration	pH 4	% Degradation	pH 6	% Degradation	pH 8	% Degradation	pH 10	% Degradation
A	0.4093	59.0731	0.3205	67.9509	0.2937	70.6309	0.2245	77.5544
B	0.3021	93.9587	0.2915	94.1709	0.2970	94.0592	0.1848	96.3037
C	0.4433	95.5667	0.3389	96.6108	0.3004	96.9961	0.1887	98.1128

The degradation was consistently highly efficient for all tested concentrations, generally achieving near-maximal removal regardless of the starting pH. This finding suggests that the Gamma Irradiation degradation mechanism is highly robust and largely independent of the initial acidity or alkalinity of the solution.

Initial pH is a critical parameter in dye remediation because it influences both the ionization behavior of methylene blue and the formation of reactive species generated during irradiation (Suresh & Sundaramoorthy, 2014; Arshad et al., 2020). Prior studies emphasize that the stability and degradation pathways of cationic dyes vary across acidic and alkaline conditions, as pH alters molecular charge distribution and reaction kinetics (John, 2024). However, irradiation-based treatments such as gamma rays and electron beams generate highly reactive radicals—including •OH and e^{-}_{aq}—that can effectively degrade dye structures across a wide pH range, making them less sensitive to initial acidity or alkalinity (Bhuiyan et al., 2016; Parvin et al., 2015). In this study, pH levels were systematically varied and combined with controlled concentrations and absorbed doses using a factorial design, enabling clear detection of pH-related trends and interactions (Oimoen, 2019). The resulting UV–Vis spectra, absorbance tables, and degradation percentages consistently showed substantial dye removal regardless of starting pH, supporting literature that irradiation-driven degradation mechanisms remain robust across diverse environmental conditions (Alkhatib et al., 2017).

Objective 3: Variation of Absorbed dose

Figure 10.1



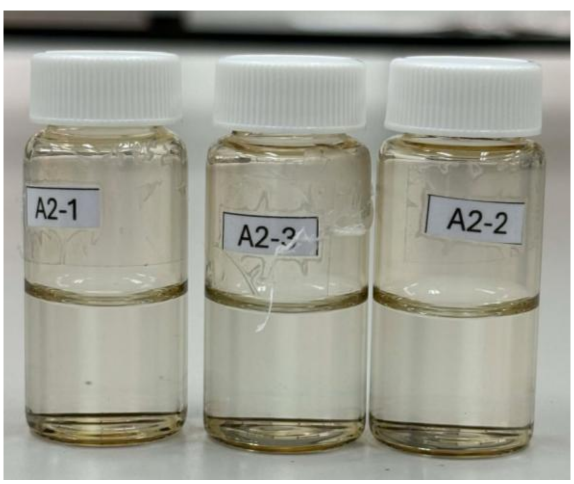
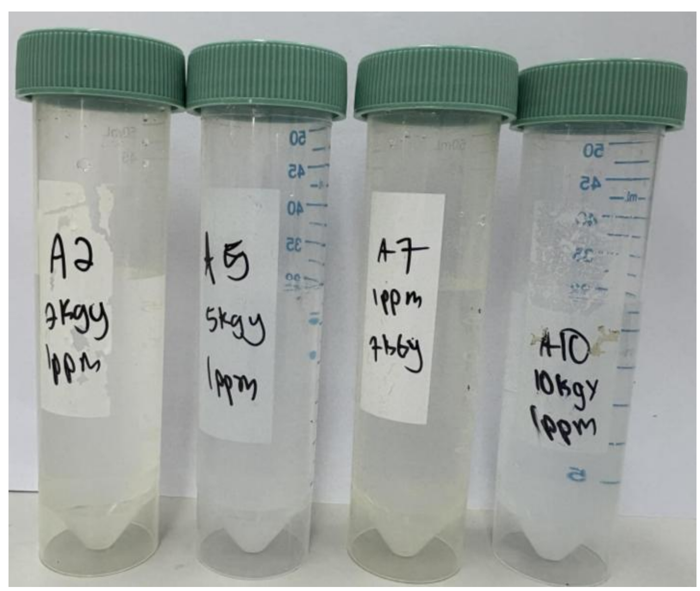
Methylene Blue Solution (before gamma and electron beam irradiation)

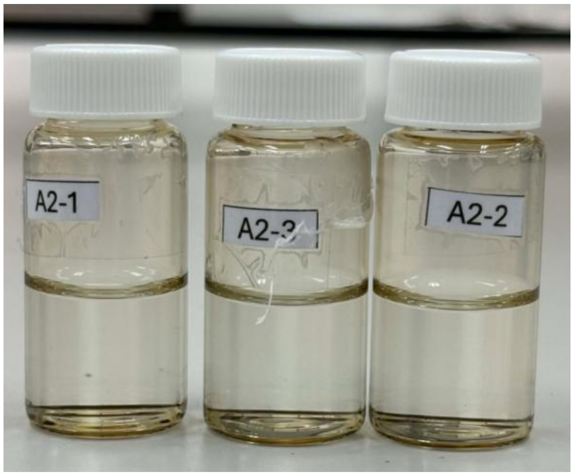
The figure shows the initial states of all methylene blue solutions in increasing concentration order from 1ppm, 5ppm, 10ppm, 20ppm, and 50ppm. Each concentration is

labelled from A to E. These solutions will be subjected to both irradiation in varying Absorbed doses from 2 to 10 kGy.

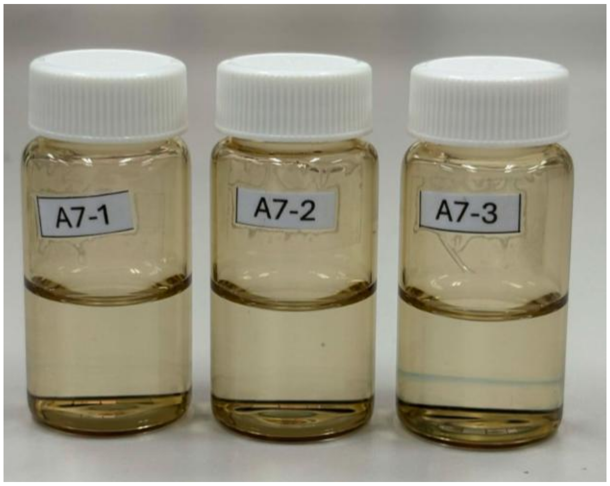
Figure 11.1

Color Transformation of Irradiated Methylene Blue

Gamma Treatment	Electron Beam Treatment
	


A2-1
A2-3
A2-2


A10-1
A10-2
A10-3

 A7-1 A7-2 A7-3	

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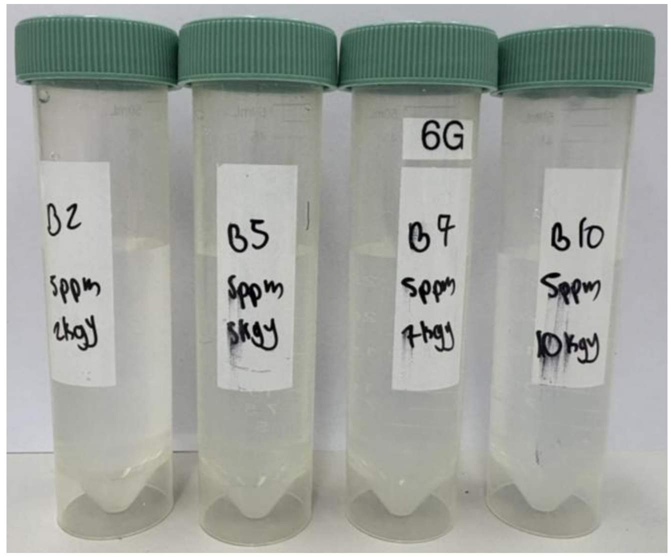
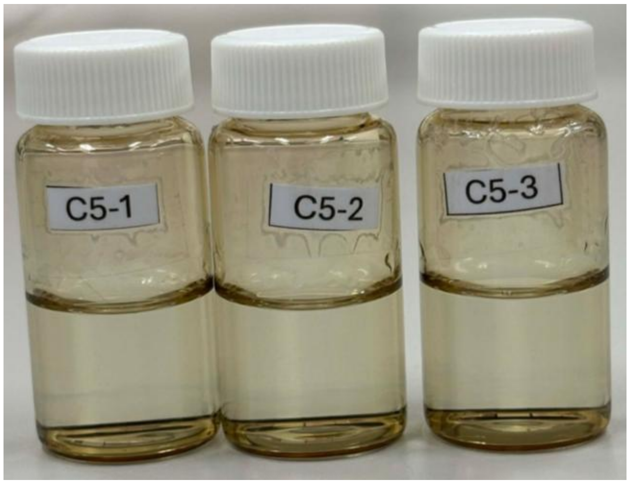
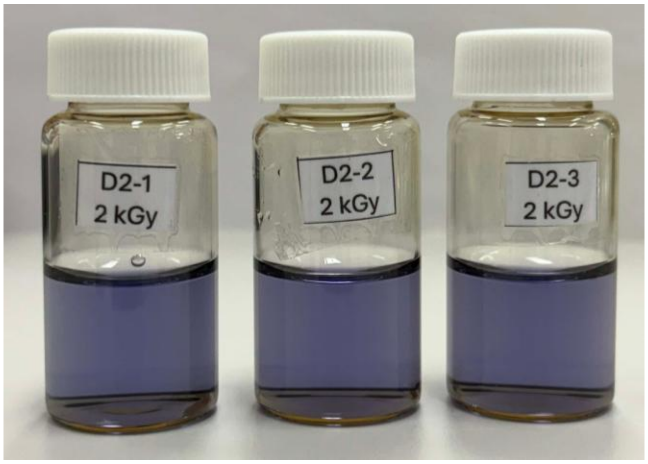


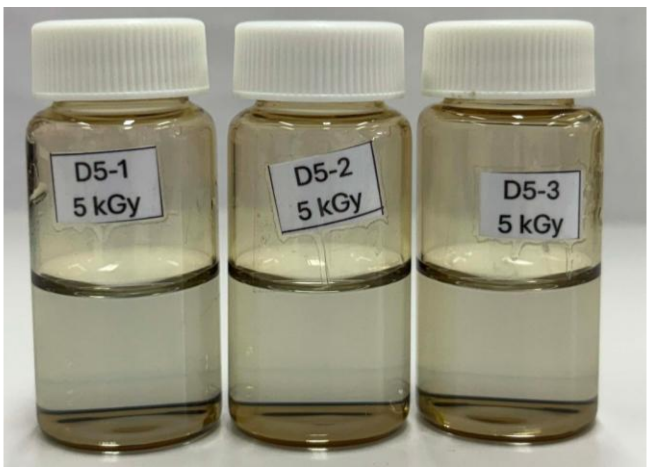

C5-1
C5-2
C5-3

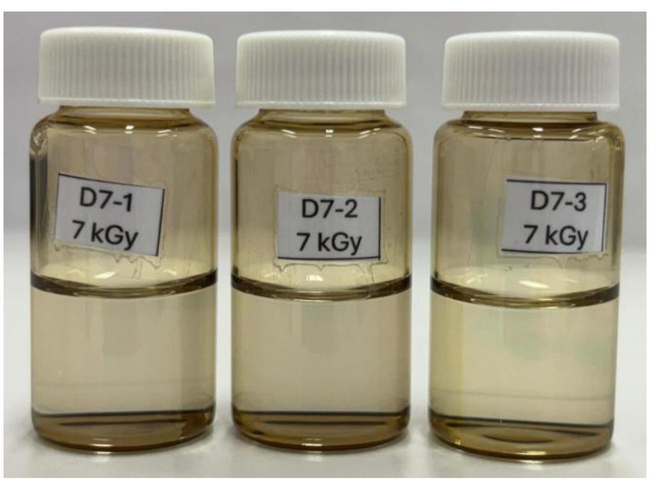

61
C2
10ppm
C5
10ppm
5kgy
C7
10ppm
C10
10ppm
10kgy

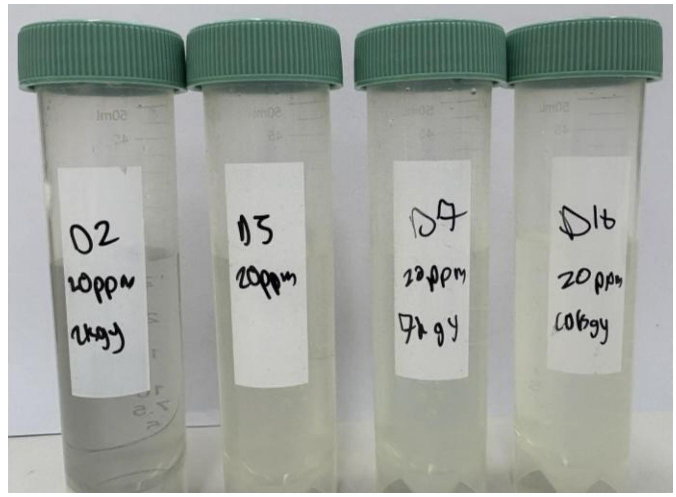

C7-1
C7-2
C7-3


C10-1
C10-2
C10-3


D2-1
2 kGy
D2-2
2 kGy
D2-3
2 kGy


D5-1
5 kGy
D5-2
5 kGy
D5-3
5 kGy


D7-1
7 kGy
D7-2
7 kGy
D7-3
7 kGy


D2
20ppm
D5
20ppm
20ppm
20ppm

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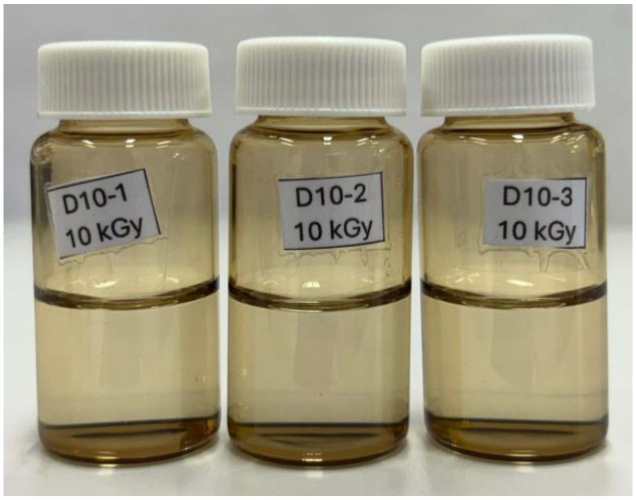	

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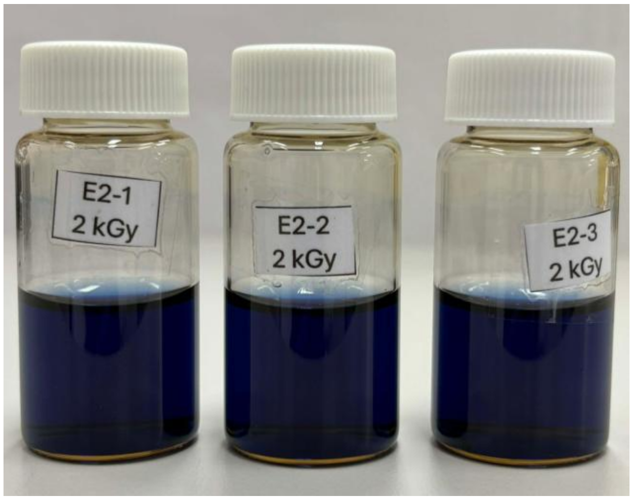

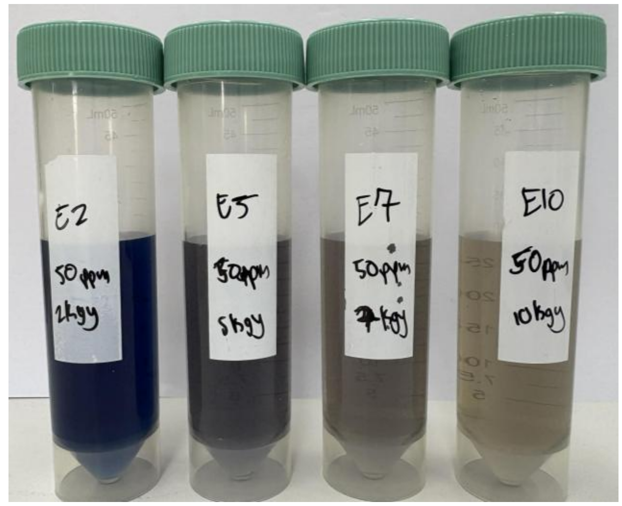

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The increase in the absorbed dose in both irradiation techniques has a positive effect on the degradation rate of the methylene blue dye. Based on the table 8 to 9, it can be seen that for as low as 2kGy, it is visible there is more than 70% degradation rate of the methylene blue dye. Additionally, it is visible that in both electron beam and gamma irradiation, higher concentration of methylene blue dye has the potential to be degraded in doses such as 10 kGy. It is worth noting that during the irradiation of 50 ppm concentration, formation of precipitate has occurred and additionally, rather than turning clear, the samples have turned in either brown, grey or violet hue in low absorbed doses. Which indicates that apart from degrading the methylene blue dye. There is also the possibility that along degradation of methylene blue, the degradation also takes a different pathway which causes the dye to be converted into a chemical compound that can produce a different hue, evidently a violet hue.

Objective 4: Changes in Parameters of Methylene Blue Effluent after Gamma and Electron Beam Treatment Compared to Existing Water Standards

Table 15.1

Analysis of Variance (ANOVA) for Initial pH Level Across Controlled Groups

	Sum of Squares	Degrees of Freedom (df)	Mean Square	F-statistic (F)	P-value (p)
Gamma Irradiation	0.0790	2	0.0395	0.00454	0.995
Residuals	286.8875	33	8.6936		

The analysis indicated no statistically significant difference in the initial pH level across the three Methylene Blue concentration groups designated for gamma irradiation. The non-significant result confirms that the solutions were homogeneous at baseline before treatment began, validating the experimental setup for internal consistency. This finding is crucial because it ensures that any differences observed in post-treatment pH can be attributed solely to the effects of the irradiation and not to initial variations.

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Table 16.1

Analysis of Variance (ANOVA) for Post-Treatment pH Level as a Function of Gamma Irradiation Concentration

	Sum of Squares	Degrees of Freedom (df)	Mean Square	F-statistic (F)	P-value (p)
Gamma Irradiation	102.37	4	25.593	168	< .001
Residuals	8.36	55	0.152		

The analysis indicated a highly statistically significant effect of the Methylene Blue concentration on the post-treatment level. This significant finding confirms that the degradation process is concentration-dependent, meaning the initial amount of dye strongly influences the final pH observed after irradiation. The statistical significance necessitates the use of a post-hoc comparison test to identify which specific concentration pairs exhibited different post-treatment pH values.

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Table 17.1

Tukey's Post-hoc Comparison of Mean Post-Treatment pH Differences Across Methylene Blue Concentration Groups

Comparison				
Comparison Group 1 (Initial pH)	Comparison Group 2 (Initial pH)	Mean Difference	T-statistic (t)	p-tukey (p)
7.82	8.08	*0.7400*	-0.0300	1.000
	8.14	*1.0425*	0.3975	0.106
	8.64	*0.9500*	-0.9925	< .001
	9.21	*0.9125*	-3.2150	< .001
8.08	8.14	*0.3025*	0.4275	0.069
	8.64	*0.2100*	-0.9625	< .001
	9.21	*0.1725*	-3.1850	< .001

8.14	8.64	*-0.0925*	-1.3900	< .001
	9.21	*-0.1300*	-3.6125	< .001
8.64	9.21	*-0.0375*	-2.2225	< .001

This table summarizes the pH of the Methylene Blue solutions after treatment with increasing doses of Gamma Irradiation across five distinct concentration levels. The pH generally decreased across most concentrations and doses compared to the initial reading, indicating an overall increase in solution acidity after irradiation. This shift toward a lower pH suggests the formation of acidic byproducts resulting from the radiation-induced degradation of Methylene Blue.

Table 18.1

Analysis of Variance (ANOVA) for Post-Electron Beam Irradiation pH Level in Methylene Blue Solutions

	Sum of Squares	Degrees of Freedom (df)	Mean Square	F-statistic (F)	p-value (p)
Electron Beam Irradiation	2.47	3	0.822	0.317	.813
Residuals	20.78	8	2.597		

A consistent increase in pH was observed across all tested concentration groups after irradiation, indicating a reduction in the solution's acidity. This overall change suggests the degradation process produces basic byproducts or consumes H+ ions. However, statistical analysis using ANOVA indicated no statistically significant effect of the Electron Beam Irradiation dose on the post-treatment pH level ($(F)(3, 8) = 0.317$, $p = 0.813$). The results suggest that the final pH shift is dependent on the initial pH of the solution and the Methylene Blue concentration group (A, B, or C), rather than the dose applied.

Table 19.1

Analysis of Variance (ANOVA) for Post-Treatment pH Level as a Function of Methylene Blue Solution Concentration After Electron Beam Irradiation

	Sum of Squares	Degrees of Freedom (df)	Mean Square	F-statistic (F)	P-value (p)
Concentration	2.85	4	0.7124	8.57	< .001
Residuals	1.25	15	0.0831		

The analysis indicated a highly statistically significant effect of the Methylene Blue concentration on the post-treatment pH level ($(F)(4, 15) = 8.57$, $p < .001$). This strong finding confirms that the initial concentration of the dye is a dominant factor influencing the final acidity or alkalinity of the solution after Electron Beam Irradiation. The statistical significance necessitates the use of a post-hoc comparison test to precisely identify which specific concentration groups' final pH values differed from one another.

Table 20.1

Tukey's Post-hoc Comparison of Mean Post-Treatment pH Differences Across Methylene Blue Concentration Groups After Electron Beam Irradiation

Comparison				
Comparison Group 1 (Concentration in ppm)	**Comparison Group 2 (Concentration in ppm)**	**Mean Difference**	**T-statistic (t)**	**p-value (p)**
1	5	*0.7400*	*3.630*	0.018
	10	*1.0425*	*5.114*	*0.001*
	20	*0.9500*	*4.660*	*0.002*
	50	*0.9125*	*4.476*	*0.003*
5	10	*0.3025*	*1.484*	*0.587*
	20	*0.2100*	*1.030*	*0.838*

	50	*0.1725*	*0.846*	*0.912*
10	20	*-0.0925*	*-0.454*	*0.990*
	50	*-0.1300*	*-0.638*	*0.966*
20	20	*-0.0375*	*-0.184*	*1.000*

Tukey's post-hoc test was performed to determine which Methylene Blue concentration groups significantly differed in their final pH after Electron Beam Irradiation. The results showed that the lowest concentration group (1 ppm) had a post-treatment pH that was statistically different from all other higher concentrations ($p < .02$). Conversely, no significant differences in pH were found among any of the higher concentration groups (5 ppm, 10 ppm, 20 ppm, and 50 ppm), indicating they all altered the solution's pH similarly.

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Table 21.1

Analysis of Variance (ANOVA) for Post-Treatment Absorbance Unit (λmax = 664 nm) as a Function of Concentration

	Sum of Squares	Degrees of Freedom (df)	Mean Square	F-statistic (F)	P-value (p)
Gamma Irradiation	0.3798	4	0.09495	72.0	< .001
Residuals	0.0198	15	0.00132		

The analysis indicated a highly statistically significant effect of the Gamma Irradiation absorbed dose on the measured post-treatment property ($F(4, 15) = 72.0$, $p < 0.001$). This finding confirms that the dose of Gamma Irradiation is a dominant factor controlling the outcome of the experiment, whether it is absorbance or degradation. The high statistical significance necessitates the use of a post-hoc comparison test to precisely identify which specific dose increments resulted in statistically different effects.

Table 22.1

Tukey's Post-hoc Comparison of Mean Post-Treatment Absorbance Unit Differences Across Methylene Blue Concentration Groups After Gamma Irradiation

Comparison Group 1 (Concentration in ppm)	Comparison Group 2 (Concentration in ppm)	Mean Difference	T-statistic (t)	p-value (p)
1	5	-0.00607	-0.237	0.999
	10	-0.02087	-0.813	0.923
	20	-0.04727	-1.840	0.388
	50	-0.36065	-14.041	< .001
5	10	-0.01480	-0.576	0.977
	20	-0.04120	-1.604	0.517
	50	-0.35458	-13.804	< .001
10	20	-0.02640	-1.028	0.839
	50	-0.33978	-13.228	< .001

20	20	-0.31338	-12.200	< .001

This table summarizes the maximum absorbance of Methylene Blue solutions, which quantifies the amount of dye remaining after treatment with varying doses of Gamma Irradiation. The low post-irradiation absorbance values across most conditions confirm that Gamma Irradiation is a **highly efficient method** for dye degradation, often achieving near-complete removal. The data strongly suggests that the degradation efficiency is **inversely related to the initial concentration** but less clearly dependent on the absorbed dose.

Table 23.1

Analysis of Variance (ANOVA) for Initial Absorbance Level (λmax = 664 nm) Across pH-Controlled Solutions

	Sum of Squares	Degrees of Freedom (df)	Mean Square	F-statistic (F)	P-value (p)
Gamma Irradiation	0.112	3	0.0374	0.0543	0.982
Residuals	5.516	8	0.6895		

The analysis indicated no statistically significant effect of the Gamma Irradiation absorbed dose on the final measured property ($p = .982$). This finding suggests that applying different irradiation doses does not significantly alter the final outcome of the experiment, at least within the tested dose range. The lack of statistical significance validates that the primary variable affecting the final result is not the radiation dose itself.

Overall, the analysis of variance across the three parameters have proven to be significant enough to affect the degradation of methylene blue dye in both gamma and electron beam irradiation, proving that the variation between the Initial pH, Absorbed dose and Dye concentration has a direct effect on the degradation rate and percentage of degradation done. This highlights the importance of determining the proper initial state of the methylene blue solution before irradiation, in order to ensure that the most effective technique, and absorbed dose would suit best and fully degrade the contaminant.

CHAPTER 4

CONCLUSION, IMPLICATIONS, AND RECOMMENDATIONS

Conclusion

Methylene blue solutions were successfully degraded at relatively low absorbed doses, while pH variation was found to enhance the degradation of higher dye concentrations. Both electron beam and gamma irradiation are effective for methylene blue degradation. However, electron beam irradiation offers a distinct advantage due to its faster processing.

Implications

Both methods of irradiation are proven to be effective in breaking down contaminants, particularly the methylene blue from the textile industries. The factors of choice to utilize on either irradiation method are the cost, scale and degree of degradation required that the water effluents require. In wastewater treatment, these methods can be used for decolorizing the water and degrading pollutants into smaller and more manageable molecules.

Practical Applications

The result of this study may support existing or future irradiation facilities in promoting gamma and electron beam irradiation as viable treatment technologies for textile effluent-generating private industry and government-initiated sanitation programs. Moreover, the date generated by this research may contribute to future national or local guidelines recommending irradiation as an alternative or complementary method for treating dye-laden effluents. And lastly, practically speaking, this may serve as baseline data for future researchers who will test irradiation on real MB-rich wastewater, enabling transition from laboratory-scale to pilot or full-scale treatment systems.

Future Research Directions

Future research should adopt an experimental design that simultaneously evaluates both gamma and electron-beam irradiation within a unified framework, rather than treating them as separate systems. This approach would allow direct comparison of their interactive effects and potential complementarities. Additionally, the application of these irradiation treatments—either individually or in combination—should be expanded to other major pollutants commonly found in textile wastewater in addition to the assessment of treatment performance in complex effluent matrices. Future studies should demonstrate how gamma and electron beam irradiation-based dye degradation can be practically translated into full-scale wastewater treatment systems. And lastly, further studies are necessary to identify the optimal pH conditions and minimum effective radiation dose required for each methylene-blue concentration to ensure that treatment efficiency is maximized while minimizing energy input and operational cost.

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Philippine Normal University

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APPENDIX A

GANTT CHART

Research Phase		Assigned Member(s)	Month 1 (February 2025)	Month 2 (March 2025)	Month 3 (August 2025)	Month 4 (Sept. 2025)	Month 5 (Oct. 2025)	Month 6 (Nov. 2025)
I. Preparation & Preliminary Studies	• Finalize Research Protocol & Literature Review	Caasi, Calunod, Farenas, and Magana						
	• Procurement & Preparation of Materials (Dye, reagents, etc.)	Caasi and Farenas						
	• Solution Preparation: Calculation and Creation of stock solutions of Methylene Blue at varying concentrations	Caasi and Farenas						

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II. Pre-Irradiation Analysis & Characterization	• Baseline Analysis: Measure initial parameters: pH and Absorbance Level per concentration	Caasi and Farenas						
III. Electron Beam Irradiation Treatment	• Scheduling of Gamma and Electron Beam Facility	Calunod and Magana						
	• Stage 1 Irradiation: Treat samples (varying Concentrations) at a fixed pH and Dose and Treat samples (varying Absorbed Doses - kGy) at fixed Concentration /pH	Caasi and Farenas						

	• Stage 2: Irradiation: Treat samples (varying pH Levels) at a fixed Concentration and Dose	Caasi and Farenas						
IV. Post-Irradiation Analysis	• Post-Treatment Analysis: Measure pH, and Absorbance Level	Caasi and Farenas						
	• Spectroscopic Analysis: Measure degradation efficiency via Absorbance/Concentration change	Caasi and Farenas						
V. Data Analysis &	• Tabulation, Interpretation, and Statistical	Calunod and Magana						

Synthesis	Analysis of all data							
	• Computation of Treatment Cost & Feasibility Analysis	Caasi and Farenas						
VI. Research Compilation	• Finalize the Research Paper	Calunod and Magana						

APPENDIX B

LINE-ITEM BUDGET

Philippine Normal University

The National Center for Teacher Education

UNIT	ITEM/SERVICE	QUANTITY	UNIT COST *in pesos*	TOTAL COST *in pesos*
Trip	Transportation Fee	8	80	640
Test	Laboratory Cost	3	250	750
Expense	Incidental Fee	1	1, 500	1500
Page/Batch	Printing Cost	250	5	1250
Person/Meal	Token/Food	6	100	600
Gigabyte	Cellular Data	15	100	1500
			Subtotal in peso	29240
			Contingency Funds	2909
			Total *in pesos*	32149

APPENDIX C

EXPECTED OUTCOMES AND IMPACT

Publication

The researchers are open to presenting it at conference presentations at scientific gatherings to disseminate findings and promote discussions on innovative wastewater treatment.

Product

The research expects that there will be an enhancement of MB solution quality through gamma and electron beam irradiation technology.

Policy

With the study, it may provide some recommendations for integrating gamma irradiation and EBI technology into local or, in supposition, national policies on water sanitation and quality assurance.

People Service

There could be implementation of educational workshops and awareness campaigns for students, faculty, admin and staff at PNU-Manila regarding innovative wastewater treatment. Additionally, it fosters engagement with local communities to share knowledge and clarify misconceptions on irradiation technology and its potential benefits for public water safety.

Partnerships

Expectation of collaborations with the Department of Science and Technology-Philippine Nuclear Research Institute (DOST-PNRI) for technical support and further research on gamma and electron beam technology applications is anticipated in commencing this research.

Patent/Copyright

It is important to have copyright protection for the reviewed research (and possibly published) and the methodology developed from the study.

Social Impact

The study aims for sustainable and access to safe and reusable water for textile factories, reducing health risks associated with dye effluent. It also aims to increase public awareness about the importance of water quality and the role of advanced technologies in ensuring water quality. This also serves to contribute to the SDG Goal 6: Clean Water and Sanitation, by promoting innovative solutions for wastewater treatment.

Economic Impact

One of the goals of this research is to exploit potential cost savings for institutions through reduced dependence on traditional water purification methods that require frequent chemical treatment. This could also promote local gamma irradiation and EBI technology development, creating opportunities for job generation in the water treatment sector.