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Evaluation of Tartrazine Solution as a Potential Gamma Dosimeter Material

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Abstract

Radiation dosimetry plays a crucial role in various fields, including medical, industrial, and environmental applications. Accurate and reliable dosimeters are essential for measuring and controlling radiation exposure. This study aims to evaluate the stability of the food dye tartrazine as a potential gamma radiation dosimeter. The need for accessible and cost-effective dosimetric materials motivates the exploration of tartrazine's capabilities in this regard. This research investigates the response of tartrazine solutions under varying gamma radiation doses (0 to 3.118 kGy) using UV-Vis spectrophotometry to measure absorbance at a wavelength of 424 nm. The results demonstrate a significant decrease in absorbance with increasing radiation doses, indicating decolorization due to oxidative reactions triggered by hydroxyl radicals (OH·) generated during irradiation. Tartrazine, which imparts a yellow color through its diazenedyl (-N=N-) bonds, undergoes bond cleavage upon gamma radiation exposure, resulting in a permanent color change. Further analysis reveals that tartrazine-based dosimeters exhibit optimal stability for less than four weeks. Therefore, tartrazine solution can serve as an effective gamma radiation dosimeter for short-term applications. This study provides a foundation for developing new dosimetric materials, emphasizing the importance of ongoing research to enhance radiation safety and measurement accuracy.

Keywords: Dosimeter, Gamma Irradiation, Radiation, Stability, Tartrazine.

1 Introduction

Radiation dose measurement is conducted using dosimeters. Essentially, any material that undergoes changes due to irradiation can be used as a dosimeter, provided these changes can be measured with available instruments, are stable, have good reproducibility, are easy to manufacture, and are easy to use [1]. Based on their quality and relative usage, dosimeters can be categorized into four main classes [2], [3]:

1. Primary Standard Dosimeter

   These dosimeters are used by national standard laboratories to calibrate radiation fields. This category includes calorimeter dosimeters and ionization chamber dosimeters.
2. Reference Standard Dosimeter

   These dosimeters are used to calibrate radiation fields and for routine dosimetry. Since not all laboratories or irradiation facilities have primary standard dosimeters, reference standard dosimeters can be used for calibrating radiation fields.
3. Routine Dosimeter

   These dosimeters are used for routine measurement of absorbed radiation doses. Common examples include red/clear Perspex (PMMA) dosimeters, cellulose triacetate (CTA) dosimeters, radiochromic film dosimeters (FW-Technology), and alanine dosimeters.
4. Transfer Standard Dosimeter

   These dosimeters are mainly selected from reference standard dosimeters or routine dosimeters that can be exchanged between different laboratories. This is important for the accreditation of irradiation facilities, allowing national laboratories to verify the validity of specific radiation processes carried out by an irradiation facility.

Gamma radiation is energy emitted by an element as it releases excess energy to achieve stability. It originates from the nuclei of radioactive atoms, which are typically beta emitters, though many also emit alpha particles. When these nuclei emit beta or alpha radiation, their energy decreases. However, if the nucleus still has excess energy beyond the lowest energy required to emit beta or alpha radiation, this excess energy is emitted as gamma radiation. Gamma radiation can also come from excited atomic nuclei, which can be achieved by bombarding the nucleus with neutrons. The excited nucleus returns to its original state by emitting gamma radiation [4]

Gamma radiation is not affected by magnetic fields, indicating it is uncharged. Additionally, gamma radiation has no mass, giving it greater range and penetration power compared to alpha and beta radiation. Gamma radiation falls under the category of electromagnetic radiation. There are three possible interactions of gamma rays with matter: the photoelectric effect, Compton scattering, and pair production. These interactions produce charged particles (electrons or positrons) with energy. These electrons or positrons ionize the atoms they pass through, meaning electromagnetic waves can ionize matter indirectly [5].

When ionizing radiation, such as an electron beam, interacts with water, it produces electronically excited species and ionized molecules. This leads to the formation of reactive species (eaq^-, OH*, H*, and HO2* or O2*) and molecular products (H2 and H2O2). These species are primary products of water radiolysis that react with dissolved substances and decompose them. These primary products tend to react with the functional groups of organic molecules rather than the entire molecule [6].

Exposure is the ability of X-rays or gamma rays to cause ionization in air within a specific volume. The unit of measurement is the Roentgen. One Roentgen is the radiation intensity of X-rays or gamma rays that can produce 1.61 x 10^15 ion pairs per kilogram of air. However, the Roentgen unit does not fully describe the extent of radiation exposure received by a medium [4].

Dosimetry is the activity of measuring radiation dose based on the ionization caused by radiation in specific materials. To measure the energy of radiation absorbed by a material, it is necessary to determine a quantity that does not depend on the type of radiation, its energy, or the properties of the absorbing material, but only on the amount of radiation energy per unit mass of the material [7]. Radiation dosimetry is a method for measuring the amount of radiation energy, whether in the form of electromagnetic waves or charged particle currents emitted by a radiation source at a specific point and absorbed by irradiated material. Materials that undergo changes due to irradiation can be used as dosimeters if the changes can be measured by instruments, are stable, have good reproducibility, and are easy to manufacture and use. Based on their quality and function, dosimeters are categorized into four main classes: primary standard dosimeters, reference standard dosimeters, routine dosimeters, and transfer standard dosimeters [1].

Radiochromic dosimeters are a type of dosimeter that utilize color change (chromatic change) in special polymers as a response to exposure to ionizing radiation. Gamma radiation is energy emitted by an element to release excess energy and achieve stability. When gamma radiation is used, dyes can decompose into organic compounds with lower molecular weights, such as organic acids[8]. The primary material used is a polymer containing chromogenic compounds, which undergo photochemical reactions and permanently change color when exposed to radiation such as X-rays, gamma rays, or electron beams. This color change occurs due to modifications in the chemical structure of the polymer caused by the radiation.

Radiochromic dosimeters allow for direct observation based on the color change that occurs. These dosimeters are among the types of radiation dose monitoring systems that are easier and more practical to manufacture and use. Dosimetry observation is conducted directly by observing the color change that occurs. The color change reaction is caused by the interaction between ionizing radiation and the material used as the radiochromic agent. The characteristic color change of the radiochromic material is used as the basis for monitoring radiation dose, as the change in absorption spectra is proportional to the absorbed dose [9]. Radiochromic dosimeters are available in various forms such as liquids, gels, and thin labels. In the process of making liquid radiochromic dosimeters, solvents, dyes, and additives are required in the correct formulation. The type of solvent depends on the characteristics of the dye to be used, which can be obtained from synthetic or natural sources. Radiochromic dosimeters are widely employed for monitoring low to medium dose ranges, such as in food irradiation. Its use as a dosimeter for food irradiation necessitates the selection of radiochromic dosimeter materials that are safe for health. One potential material for use as a radiochromic dosimeter is food coloring, which is inherently safe for human consumption.

Tartrazine is a synthetic lemon yellow azo dye used as a food coloring. The yellow color of tartrazine is produced by the azo group that connects two benzene rings within its molecule. This azo group contains a nitrogen double bond (N=N) capable of absorbing specific wavelengths of visible light. Tartrazine absorbs light at a wavelength of approximately 427 nm, which lies within the blue region of the visible spectrum. Its structure is shown in the Fig. 1 below:

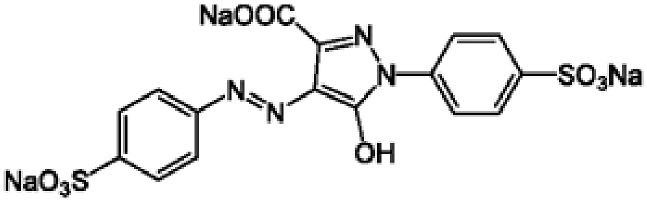

Figure 1 Chemical Structure of Tartrazine

Tartrazine is an orange-yellow powder that is easily soluble in water, producing a golden-yellow solution. Its solubility in 95% alcohol is limited, but it dissolves easily in glycerol and glycol. Tartrazine is resistant to light, acetic acid, HCl, and 10% NaOH. However, 30% NaOH will turn the color reddish. It fades easily in the presence of oxidizers; FeSO4 makes the dye solution cloudy, although aluminum (Al) does not affect it. The presence of copper (Cu) will change the yellow color to reddish[10]. Tartrazine was selected for this study due to its widespread use as a food dye, ensuring its safety and accessibility. Moreover, its distinct chemical structure, which allows for noticeable color changes under gamma irradiation, makes it a suitable candidate for dosimetry.

2 Material and Methods

In this study, we used distilled water (aquadest) and food coloring (Koepoe Light Yellow). The instruments included a 10 ml volumetric pipette, a measuring cylinder, a beaker, a stirrer, vial bottles, and cuvettes.

The sample solution was prepared by adding one drop of food coloring to 150 ml of aquadest. This solution was then divided into six different vial bottles, ensuring that each vial contained a sufficient volume for analysis in a UV-Visible spectrophotometer. Each vial was irradiated for different durations (0, 15, 30, 45, 60, and 75 minutes), and the vials were labeled accordingly. The gamma radiation dose rate was recorded during the experiment, and the estimated gamma radiation dose absorbed by the solution was calculated using the formula: radiation dose = dose rate × irradiation time. The irradiator used in this research is the Servo Ignis irradiator at KSE Ahmad Baequni from a Co-60 radioactive source (gamma ray source) with a dose rate of 2,494 kGy/h

The absorbance of each irradiated vial was measured using a Shimadzu UV Mini-1240 UV-Visible spectrophotometer within the wavelength range of 300-650 nm, with aquadest used as the blank. The maximum absorbance observed for each vial was recorded. The data were then used to plot a curve of wavelength (nm) against absorbance for the different radiation doses (six variations). Additionally, a curve of gamma radiation dose versus the change in maximum absorbance ($\Delta A = Ai - A0$) was plotted, where Ai represents the maximum absorbance at a specific radiation dose and A0 represents the maximum absorbance of the non-irradiated solution.

The stability of the tartrazine solution as a radiochromic dosimeter was evaluated by measuring the solution's absorbance every week over a 4-week period. The decrease in absorbance was recorded weekly to assess whether the solution remained stable during this time. The difference in absorbance (ΔA) was calculated as the difference between the absorbance at dose 0 and other doses each week. The average %Error of each absorbance measurement in weeks 2, 3, and 4 was then compared to the first week.

3 Results and Discussions

1. UV-Vis Absorbance Analysis

The irradiated sample solution was analyzed using a UV-Vis spectrophotometer at a maximum wavelength (λ) of 424 nm. This maximum wavelength was determined by analyzing the highest absorbance of the non-irradiated tartrazine solution. Typically, the absorption spectrum of tartrazine shows two main peaks: one in the near-UV range at 250-260 nm and another in the visible range at 420-430 nm. The peak at 250-260 nm is characteristic of individual aromatic rings, while the peak at 420-430 nm is responsible for the yellow color of the dye, caused by π–π^* transitions of the N=N, C=N, and C=O groups [11]. Table 1 shows the absorbance and ΔA of the six sample solutions at a wavelength of 424 nm.

Table 1 UV-Vis Analysis in The First Week

Time (minutes)	Dose (kGy)	Absorbance (nm)	ΔA
0	0	0,650	0
15	0,62	0,409	0,241
30	1,25	0,293	0,357
45	1,87	0,191	0,459
60	2,49	0,153	0,497
75	3,12	0,082	0,568

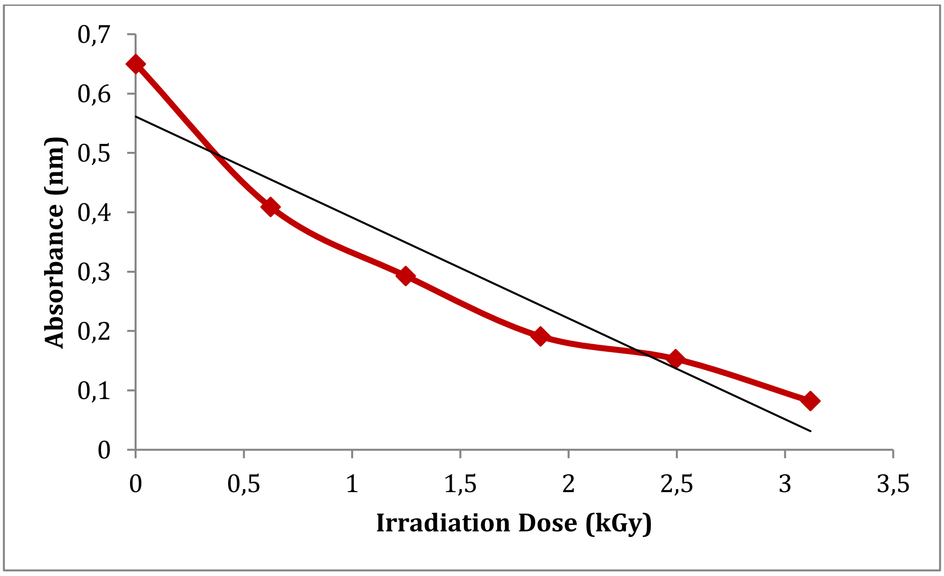

Figure 2 Dose Radiation Effect on Tartrazine Solution Absorbance

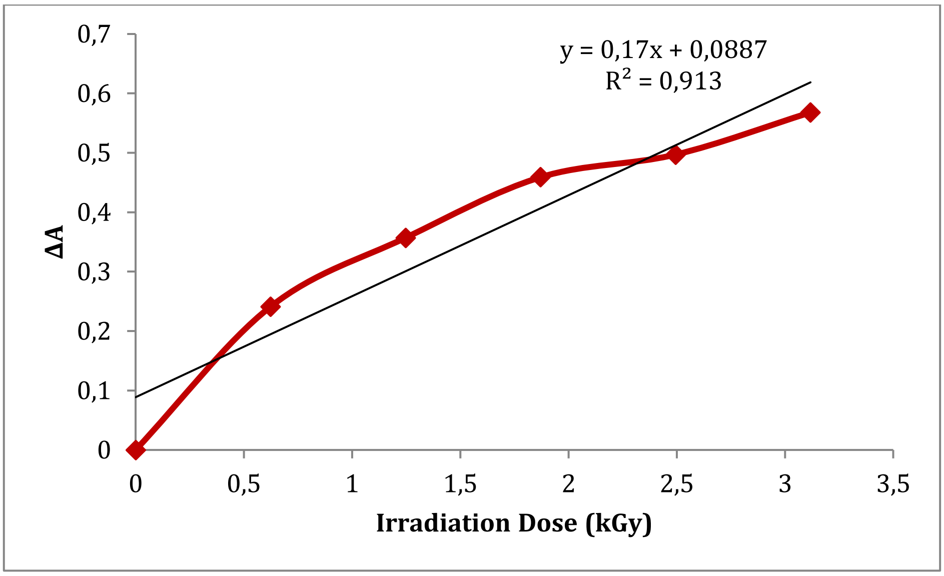

Figure 3 Dose Radiation Effect on Difference in Absorbance

From the research results, it was found that there was a decrease in the absorbance of the tartrazine solution with the increase in gamma radiation dose, as shown Fig. 2. This decrease is interpreted as the result of the degradation of tartrazine molecules into products that absorb less at the wavelength (λ) of 424 nm. The reduction in absorbance indicates that tartrazine undergoes molecular structure degradation due to radiation exposure. This change is consistent with the theory that gamma radiation causes the breaking of azo/diazenedyl (-N=N-) bonds in tartrazine molecules, resulting in compounds with lower absorbance [11], [12].

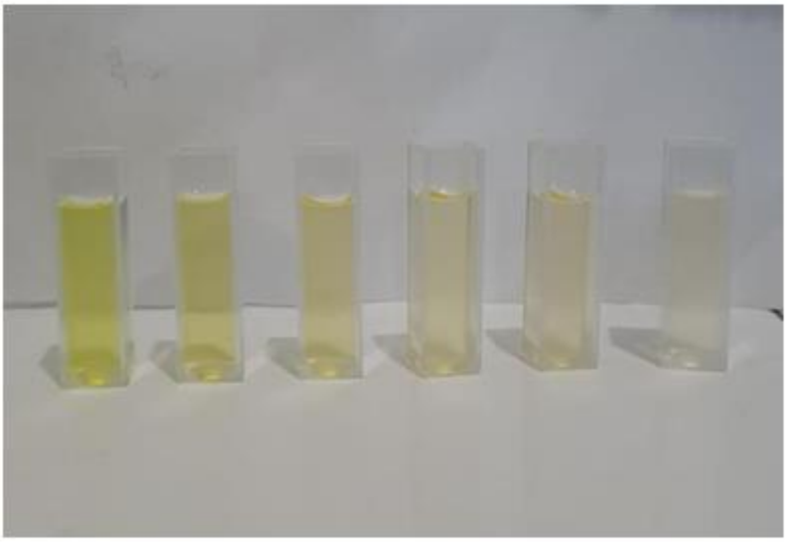

Figure 4 Change in Color of Tartrazine Solution after Irradiation with Dose (from left to right) 0; 0.62 ; 1.24 ; 1.87 ; 2.49 ; 3.11 kGy

The color degradation in tartrazine compounds due to gamma irradiation is caused by the breaking of bonds in the tartrazine molecules. Tartrazine produces a yellow color because of the azo/diazenedyl (-N=N-) bonds that form two aromatic rings in the compound. The OH· radicals generated by the hydrolysis during gamma irradiation cause oxidative decolorization by reacting with the diazenedyl bonds. This reaction ultimately fades the color of the sample solution and reduces the absorbance at the wavelength of 424 nm. Furthermore, the degradation products of tartrazine typically do not have the same conjugated structure, so they do not absorb light at the same wavelength, resulting in a paler or colorless solution, as shown in Fig. 3. The longer and higher the irradiation dose, the more OH· radicals are produced, leading to an increased oxidative decolorization reaction in the solution.

The graph of absorbance decrease against radiation dose shows a nearly linear relationship. In Fig. 2, it can be seen that the absorbance decrease is quite linear in the dose range of 0 - 2 kGy, while data instability occurs at doses above 2 kGy. This indicates that a radiocromic dosimeter using tartrazine solution can be effectively used for radiation doses up to 2 kGy. For higher doses, adjustments in composition, irradiation conditions, and methods, or the replacement of the dosimeter material with a more stable compound at high doses, are required.

2. Stability and Potential Use Of Tartrazine as a Dosimeter

The stability study of the tartrazine solution was conducted by measuring the solution's absorbance weekly over a four-week period. This measurement aimed to determine whether the tartrazine solution remained stable in preserving optical changes due to gamma radiation exposure over a longer duration at room temperature.

The results, presented in Table 2 and Fig. 5, indicate that the absorbance difference (ΔA) between the 0 dose and other doses from week to week is relatively consistent. The average percentage error (%Error) obtained from comparing the absorbance of weeks 2, 3, and 4 with week 1 is 2.16%. This low %Error value demonstrates that the tartrazine solution maintains good stability over four weeks at room temperature.

The good stability of tartrazine indicates that tartrazine-based dosimeters can be used for radiation dose measurements that require storage time before analysis. This extends its potential application in situations where immediate measurement is not always feasible. With an average %Error of 2.16%, the tartrazine solution demonstrates that changes in absorbance remain within acceptable limits for dosimeter applications. This shows that tartrazine-based dosimeters are stable not only in the short term but also in the medium to long term.

The results of this study demonstrate that tartrazine, a widely available and safe food dye, exhibits promising potential as a gamma radiation dosimeter, particularly for low to medium doses. The linear decrease in absorbance up to 2 kGy indicates that tartrazine can effectively measure radiation doses within this range. Furthermore, the stability study showed that the tartrazine solution maintained its dosimetric properties over a four-week period, with an average percentage error of only 2.16%. This suggests that tartrazine-based dosimeters can be stored and used reliably over time, extending their practical applicability.

The significance of this research lies in the potential for tartrazine to be used in various fields requiring radiation dose measurement, such as food irradiation, medical applications, and environmental monitoring. Given its cost-effectiveness, ease of use, and safety profile, tartrazine could provide a practical alternative to more expensive or complex dosimetric materials currently in use.

Future research should explore the response of tartrazine at low to medium doses with a more narrowly defined dose range under longer storage conditions, allowing for the precise determination of the optimal dose range, capabilities and limitations. Additionally, investigating other azo dyes with similar chemical structures may lead to the development of a broader range of dosimetric materials suitable for different applications.

Table 2 Measurement of The Difference in Absorbance Each Week and The Average % Error Obtained

Dose (kGy)	ΔA 1st Week	ΔA 2nd Week	ΔA 3rd Week	ΔA 4th Week
0	0	0	0	0
0,62	0,241	0,235	0,247	0,2389
1,25	0,357	0,356	0,369	0,3807
1,87	0,459	0,452	0,454	0,4633
2,49	0,497	0,518	0,522	0,5002
3,12	0,568	0,561	0,566	0,5606
Average %Error				2,16%

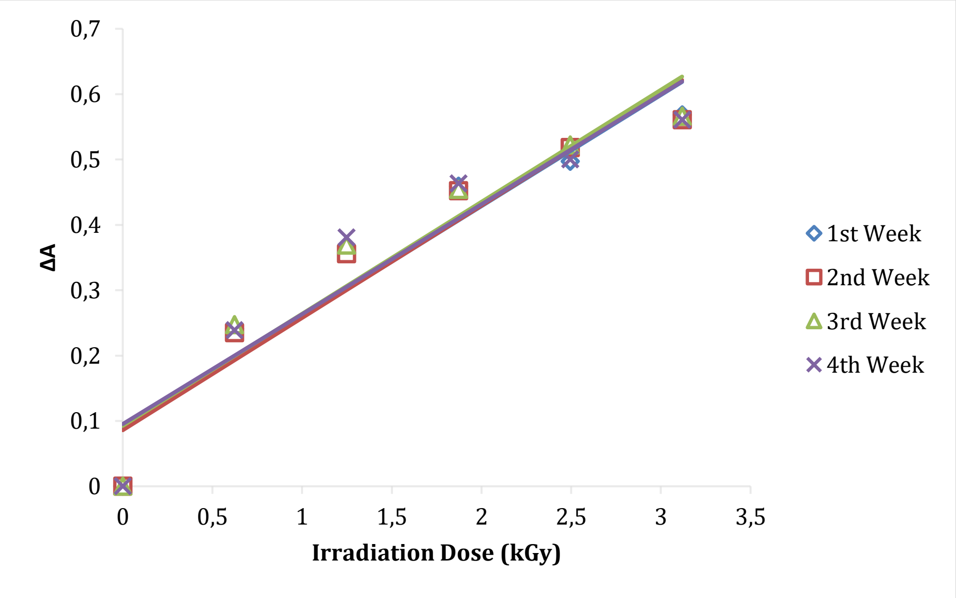

Figure 5 Absorbance Difference Stability of The Irradiated Tartrazine Solution

4 Conclusions

Based on the data obtained in this study, the following conclusions can be drawn:

1. Colorants exposed to radiation such as X-rays, gamma rays, or electron beams undergo photochemical reactions resulting in permanent color changes. These alterations occur due to radiation-induced modifications of the chemical structure within the polymer.
2. The color degradation of tartrazine compounds due to gamma irradiation is likely caused by bond cleavage. Tartrazine produces a yellow color due to the diazenedyl (-N=N-) bond forming two aromatic rings in the compound. OH- · radicals generated by gamma irradiation-induced hydrolysis cause oxidative decolorization by reacting with the diazenedyl bond. This reaction ultimately fades the color of the sample solution. The duration and magnitude of the irradiation dose are directly proportional to the OH- · radicals produced, thus increasing the oxidative decolorization reaction in the solution.

The dye (tartrazine) used as a dosimeter material in this experiment, containing tartrazine compound, demonstrates usage stability for less than four weeks. The tartrazine solution demonstrated good stability as a radiochromic dosimeter for applications at low to medium radiation doses. The time stability shown by tartrazine in this study reinforces its potential for use in dosimeter applications that require storage and analysis over a certain period. Further research may be needed to explore the response of tartrazine at higher radiation doses and under longer storage conditions.

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