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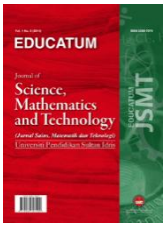
Synergistic Effects of Radiotherapy and Capsaicin on Colorectal Cancer (CaCo-2) and Normal Fibroblast (HDFn) Cell Lines In Vitro



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Article History
Received
10 August 2025
Received in revised form
1 October 2025
Accepted
15 November 2026
Published Online
30 April 2026

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Abstract
Colorectal cancer is the second most frequent kind of cancer worldwide. The treatment may comprise surgery, chemotherapy, and radiation therapy. More than half of cancer treatments are derived from natural sources, such as capsaicin. The biggest challenge is to get the disease under control as much as possible while causing as little harm to the healthy tissues around it. Cells were treated with an extract, Capsaicin of (chili peppers) and irradiated at 1 Gy, 3 Gy and 5 Gy. The MTT test was used to determine viability, and absorbance was measured at 570 nm using a Counter reader (Mutiskan EX, Thermo Lab systems). Capsaicin extract has shown a potential radiosensitizing effect in vitro for colorectal cancer. The inhibition effect in the cell lines was not selective and is significantly different from conventional radiotherapy. Capsaicin extract from chili peppers concerted with radiation proved more effective in colorectal cancer cells than radiotherapy alone.

Keywords Digital Transformation in Education; Education Digitalization; Higher Education; Smart Campus; Virtual Desktop Infrastructure (VDI)

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To cite this article (APA): Abbas R. Hatif et al., (2026) Synergistic Effects of Radiotherapy and Capsaicin on Colorectal Cancer (CaCo-2) and Normal Fibroblast (HDFn) Cell Lines In Vitro. EDUCATUM Journal of Science, Mathematics and Technology, 13(1), 109–119

INTRODUCTION

Cancer is the main cause of mortality in advanced nations in 2020, surpassing heart disease [1]. Human colorectal cancer is the fourth most often diagnosed kind of cancer globally. It manifests as a malignant tumor in the colon or rectum mucosa [2]. CRC is also one of the main causes of mortality, and although our understanding of the illness has improved in recent years, existing therapies are insufficient to control metastatic types of CRC [3]. Surgery is the primary option for individuals with possibly curable CRC, however depending on the stage of the illness, neoadjuvant chemotherapy and/or radiation may be administered before or after surgery. However, these treatment regimens are insufficient to control CRC since 30% of patients with stage I-III and up to 65% of patients with stage IV will acquire recurrent illness, emphasizing the need of developing new and more effective treatment approaches [4].

Radiotherapy has long been the conventional treatment technique for several malignancies, including colorectal cancer. Although an acceptable response to radiation therapy is obtained during the first phase of cancer treatment, many cancer patients exhibit radiation resistance [5]. Today, radiation therapy ratings can be based on how well radiosensitizers improve the effectiveness of treatment. The potential of nutraceutical natural chemicals such as flavonoids, anthocyanidins, carotenoids, and terpenoids for cancer prevention has been extensively studied, and there is enough evidence to suggest that moderate fruit and vegetable diet is associated with a lower risk of CRC [6]. Some members of these families of chemicals have the capacity to control signaling pathways and to affect the expression of genes involved in cell [7]. In addition to their potential for prevention, certain of these molecules may also be beneficial for the treatment of CRC, particularly when used in conjunction with other medications.

Combination treatment allows for the simultaneous targeting of several cancer pathways, leveraging various mechanisms of action to diminish tumor drug resistance [8]. The DNA mismatch repair phenotype (around 15% of CRC cases), chromosomal instability versions (CIN; around two-thirds of cases), and other less common CRC versions like abnormal DNA methylation, colon inflammation status, and microRNA triggering effects all contribute to CRC development [9]. Several studies published in recent years have indicated that cancer therapy by combinatorial strategy is far more successful than the usage of medications separately [10]. Furthermore, chemosensitization by means of phytochemicals, based on the use of a natural substance to boost the effectiveness of a medication by modification of its resistance pathways, is one of the treatments recommended to overcome chemoresistance, one of the primary obstacles in CRC therapy [11, 27]. The aim of this research was to assess the cytotoxic effect of a plant extract (Capsaicin) combined with radiation in colorectal cancer cell lines.

METHODOLOGY

Capsaicin extraction from hot pepper

Several organic solvents may be used to extract capsaicin from spicy peppers, but only ethanol is adequate to produce pharmaceutical-grade material [12,13]. The capsaicin was extracted from dried and crushed Capsicum annuum, which was stored in desiccators [14, 27]. Extraction was carried out in a water bath at 40°C for 5 hours using 96% (v/v) ethanol and 0.1-0.5 g of powdered plant material. Then, water vacuum fi, ltration for obtaining an ethanol extract of capsaicin [15]. The extract was concentrated under reduced pressure and dried to a constant weight to determine the extraction yield, calculated as:

$$\text{Yield (\%)} = \frac{Weight\ of\ dried\ extract}{Weight\ of\ starting\ material} \times 100$$

Capsaicin content in the extract was quantified using high-performance liquid chromatography (HPLC) with a standard curve generated from pure capsaicin. Purity was confirmed by comparing the retention time and UV spectra of the sample with those of the standard. All experiments were performed in triplicate to ensure reproducibility.

Cell lines and Cell Cultures

Human colorectal cancer cells (CaCo-2) and normal human dermal fibroblasts (HDFn) were obtained from Pasteur Institute, Iran. Cells were cultured in RPMI 1640 medium supplemented with 10% fetal bovine serum (FBS) and 100 U/mL penicillin–100 µg/mL streptomycin at 37°C in a humidified incubator with 5% CO_2. Cells were maintained in the exponential growth phase by replacing the culture medium every 2–3 days. Upon reaching approximately 80% confluence, cells were detached using 0.25% trypsin-EDTA, collected, and reseeded into new tissue culture flasks at an appropriate density. For all experiments, cells between passages 5–15 were used to ensure consistency. Prior to experimentation, cultures were authenticated by STR profiling or supplier validation and routinely tested for mycoplasma contamination using [state detection method, e.g., PCR-based assay]. For viability assays cells were seeded in 96-well plates at a density of 5×10^3 cells/well for CaCo-2, and 1×10^4cells/well for HDFn and allowed to adhere for 24 hours. Following adherence, cells were exposed to the experimental treatments. Cell survival rates were subsequently assessed using the MTT assay.

Irradiation Setup

After 24 hours of incubation at 37°C, giving the cells enough time to fully attach to the surface, the cells were treated with Plant extract (Capsaicin) and radiation in linear accelerator (Elekta Synergy 3630, LINAC, Warith International Cancer Institute, Iraq). Calibration of the LINAC was performed according to international protocols (e.g., IAEA TRS-398), using an ionization chamber and water phantom to verify absolute dose output. Beam uniformity and flatness were checked across the treatment field to ensure consistent dose distribution. Additionally, dose verification was conducted using thermoluminescent dosimeters (TLDs) or radiochromic films to confirm the planned doses delivered to the cell cultures. These procedures ensure reproducibility and reliability of radiation exposure in experimental setups. Cells were treated with 6 Mev photons at a dosage rate of 3 Gy/min. The cells were subjected to total doses of 1, 3, and 5 Gy with a 10×10 cm^2 field size. 3 cm thickness of a Perspex sheet was placed on top of the six wells plate and three centimetres of a Perspex sheet was utilized under the bottom of plate as a source of backscatters and Source surface distance (SSD) 100 cm photons. After irradiation, the cells were cultured for two days at 37°C in a humidified 5% CO2 environment. The cells were then frozen and stained with 0.4% crystal violet, and visible colonies containing more than 50 cells were counted. The inhibition rate was computed based on the survival of the non-treated group and the survival percentage of the treatment group by following formula Inhibition rate = [(O.D (control) − O.D (sample)/ O. D (control) 100%].

MTT Assay

The MTT test was measured as previously reported (Mosmann, 1983). After irradiation, cells were treated with MTT reagent for one to two days. The Mutiskan EX microplate reader (Thermo Lab systems) was employed to measure the absorbance at 570 nm. The viability of control cells (untreated cells) was assumed to be 100%.

Statistical Analysis

Statistical analysis was conducted using GraphPad Prism version 9.2 (GraphPad Software Inc., La Jolla, CA). Data were first assessed for normality using the Shapiro–Wilk test. Quantitative parametric data are presented as mean ± standard deviation (SD). One-way ANOVA followed by Tukey's post hoc test was used to compare differences among multiple groups. Statistical significance was defined as *$p < 0.05$ and **$p < 0.01$.

RESULTS

Effect of radiotherapy and Capsaicin on CaCo-2 and HDFn cells proliferation for 24 h

To assess the effect of radiotherapy and Capsaicin on cell viability in CaCo-2 colorectal cancer cells, we used MTT assay. Cell viability and proliferation were evaluated at 24 h after exposure at 1, 3, and 5 Gy and Capsaicin at a concentration of 100 µM/ml using one assays. The viability of Caco-2 cells was significantly ($p < 0.05$) reduced following radiotherapy irradiation and add Capsaicin. As shown in table 1, the reduction in cell viability between the three doses, extract of capsaicin and Combining radiotherapy and plant extract was different 24 h after treatment. Notably, 24 h after irradiation and treatment by Capsaicin, cell viability gradually decreased in a dose-dependent manner by 93.27 %, 86.01, and 79.84 % in the 1, 3, and 5 Gy and 51.06% with Capsaicin at concentration 100 µM/ml groups compared to untreated cells, respectively. while, the MTT assay revealed combination radiation with and Capsaicin affected the viability of Caco-2 cells 24 h after exposure to three doses with Capsaicin In addition, as shown in Table 1, and Figure 1 the growth rate of radiotherapy-exposed cells decreased compared to that of non-irradiated cells.

In HDFn normal cells, the results of the MTT test after 24 hours showed that the use of radiation was inhibited cells by 5.27%, 7.31%, and 8.76% at doses (1, 3 and 5 Gy), respectively, while Capsaicin inhibited normal cells with an inhibition rate of 25.71 %, while the decrease in the percentage of vitality of cells exposed to the three doses of radiotherapy was with Capsaicin 35.17%, 40.34% and 48.75% in doses, respectively. as shown in table 1. Exposing normal cells HDFn to radiotherapy showed a significant effect (p value < 0.0001), and Capsaicin alone showed a significant toxic effect (p value < 0.0001), with a greater decrease observed in colorectal cancer cells line when combination with capsaicin at a concentration of 100 µg/ml, these findings are shown in Figure 2.

Induction of apoptosis by radiotherapy and Capsaicin alone and in combination in CaCo-2 colorectal cancer cells and HDFn normal cells for 48 h

The MTT assay was used to examine the effects of CAP and radiotherapy on the viability of two cell lines (CaCo-2 colorectal cancer and HDFn normal cells) in vitro. one concentration of CAP and three doses of radiotherapy were used to treat cells lines for 48 h. As shown in table 2. Both CAP treatment alone and radiotherapy treatment alone caused a dose and concentration-dependent decrease in the viability of the cell lines. After 48 hours of treatment, the rate of CAP inhibition was 28.49% in HDFn cell lines and 52.18% in CaCo-2 colorectal cancer.

Table 1 Effect of different doses of radiotherapy and Capsaicin the HDFn viability and cells ofCaCo-2 using the MTT assay for 24 hours exposure at a temperature of 37 °C.

	Cell Viability % ± SD		Sig.	*p* Value
	HdFn	Caco-2		
"Untreated Cells"	96.55 ± 1.06 [a]	94.73 ± 0.94 [a]	ns	0.96
"1 Gy"	94.73 ± 0.72 [a]	93.27 ± 0.77 [a]	ns	0.99
"3 Gy"	92.69 ± 1.33 [a]	86.01 ± 2.39 [b]	**	0.01
"5 Gy"	91.24 ± 2.09 [a]	79.84 ± 3.03 [c]	**	<0.0001
Capsaicin	74.29 ± 2.78 [b]	51.06 ± 2.49 [d]	**	<0.0001
"1 Gy + Capsaicin "	64.83 ± 5.26 [c]	59.24 ± 3.69 [d]	*	0.03
"3 Gy + Capsaicin "	59.66 ± 6.16 [c]	49.63 ± 3.82 [e]	**	<0.0001
"5 Gy + Capsaicin "	51.25 ± 5.22 [d]	41.78 ± 3.59 [f]	**	<0.0001

Different letters (a, b, c, d, e, f) in raw are significant at $p \leq 0.05$. **: $p \leq 0.01$, * $p \leq 0.05$, NS: Non-Significant, SD: Standard Deviation.

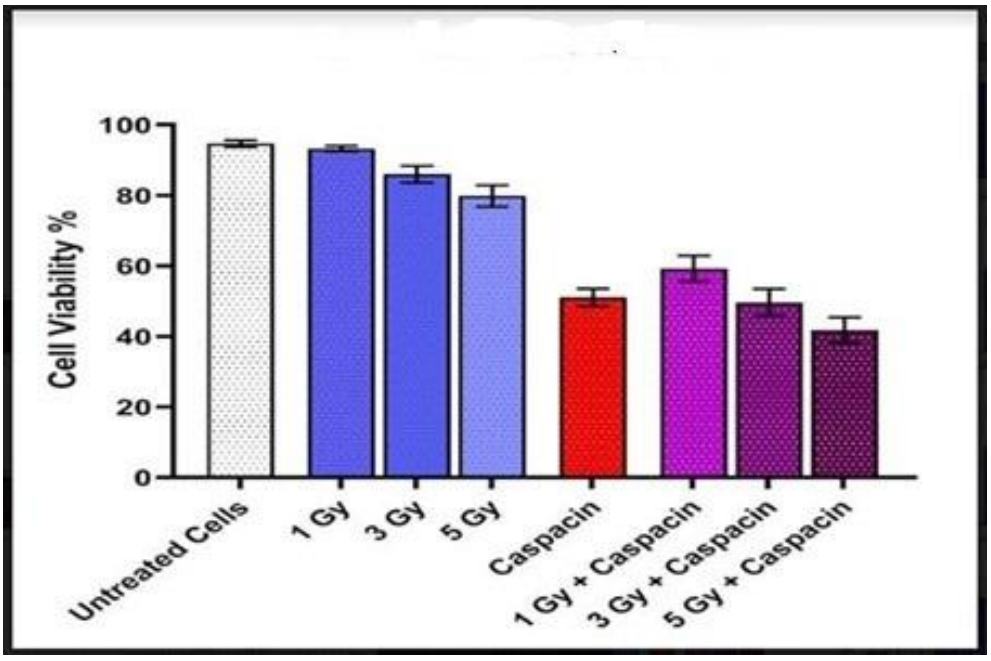

Figure 1 The different doses Effect of radiotherapy and Capsaicin on the CaCo-2 cells viability during using MTT assay for 24 hours exposure period at a temperature of 37 °C.

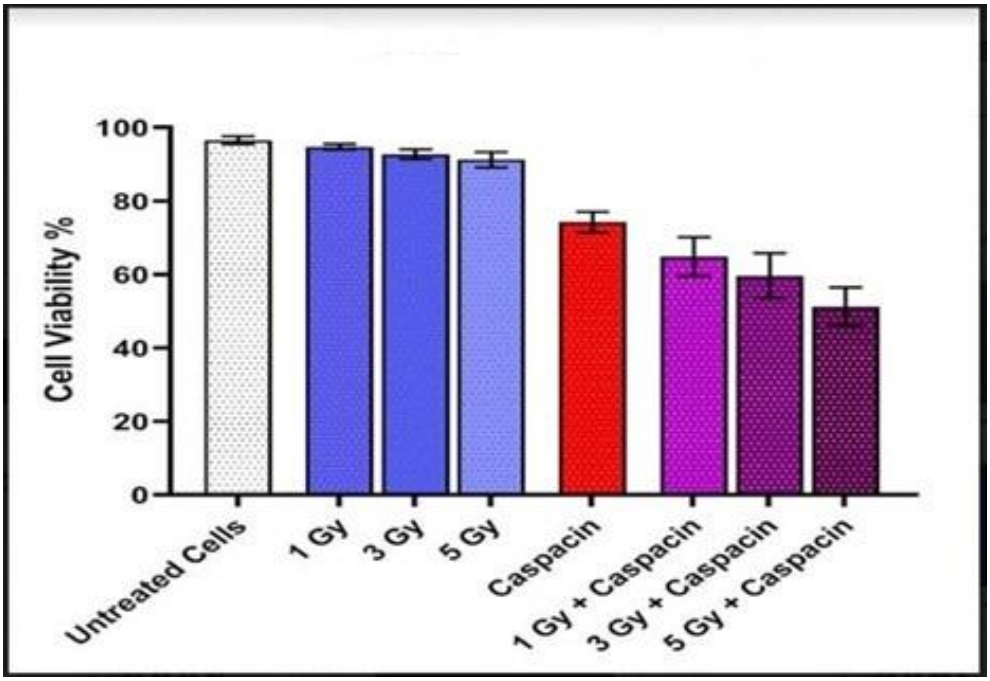

Figure 2 The different doses Effect of radiotherapy and Capsaicin on the HDFn cells viability during using MTT assay for 24 hours exposure period at a temperature of 37 °C

In addition, the values inhibition of radiotherapy (1, 3 and 5 Gy) in CaCo-2 and HDFn cell lines were 11.86%, 15.8% and 21.3% in CaCo-2 and 7.16%, 9.2% and 9.5% in, respectively. MTT assay was used to evaluate whether a concentration of CAP can enhance the radiotherapy-induced toxicity in CaCo-2 and HDFn cells. As our previous results indicated that relatively low doses of radiotherapy exhibited mild cytotoxicity and could not induce significant apoptosis in Colorectal cancer cells and normal cells, we performed viability tests of CaCo-2 and HDFn cells treated with concentration of CAP (100 μM/ml) in combination with radiotherapy (1, 3 and 5 Gy) for 48 h to explore the effects of the combination. As shown in Fig.3 and 4, compared to radiation alone, the combination of radiation and CAP induced significantly higher cytotoxicity in the cell lines.

Dissection

In the context of the preceding information and drawing on previously collected data on the various cell lines, this study presents an integrated investigation of the response of Caco-2 and HDFn cells to X-ray doses up to 5 Gy. Radiation-induced cell viability is a crucial metric in biological research. MTT test is a simple and effective technique for evaluating cell growth and viability. According to statistics, more than 50% of cancer patients need radiation treatment, with pelvic and abdominal malignancies accounting for more than half [16]. Radiation therapy, one of the major therapeutic approaches for cancer treatment, may be considered a "double- edged sword" in that it may lead to genetic alterations in exposed normal tissue, but it may also cause tumor cell death by destroying the DNA of exposed tumor tissue [17]. That is, even if radiation treatment targets tumor cells as anticipated, it may unavoidably kill healthy cells [18].

Table 2 Effect of different doses of radiotherapy and Capsaicin the HDFn viability and cells of CaCo-2 using the MTT assay for 48 hours exposure at a temperature of 37 °C.

Cell Viability % ± SD			**Sig.**	***p* Value**
	HdFn	**Caco-2**		
"Untreated Cells"	93.92 ± 1.52 [a]	92.63 ± 1.64 [a]	ns	0.9965
"1 Gy"	92.84 ± 1.27 [a]	88.14 ± 1.79 [ab]	ns	0.1324
"3 Gy"	90.8 ± 1.4 [a]	84.2 ± 3.1 [b]	ns	0.0694
"5 Gy"	90.5 ± 2.1 [a]	78.7 ± 3.9 [c]	**	<0.0001
Capsaicin	71.51 ± 2.49 [b]	47.18 ± 2.15 [d]	**	<0.0001
"1 Gy + Capsaicin "	62.5 ± 5.9 [bc]	56.1 ± 4.9 [e]	*	0.0231
"3 Gy + Capsaicin "	57.8 ± 7.72 [c]	47.9 ± 2.8 [d]	**	<0.0001
"5 Gy + Capsaicin "	48.9 ± 4.4 [d]	40.9 ± 3.51 [f]	**	0.0022

Different letters (a, b, c, d, e, f) in raw are significant at $p \leq 0.05$. **: $p \leq 0.01$, * $p \leq 0.05$, NS: Non-Significant, SD: Standard Deviation.

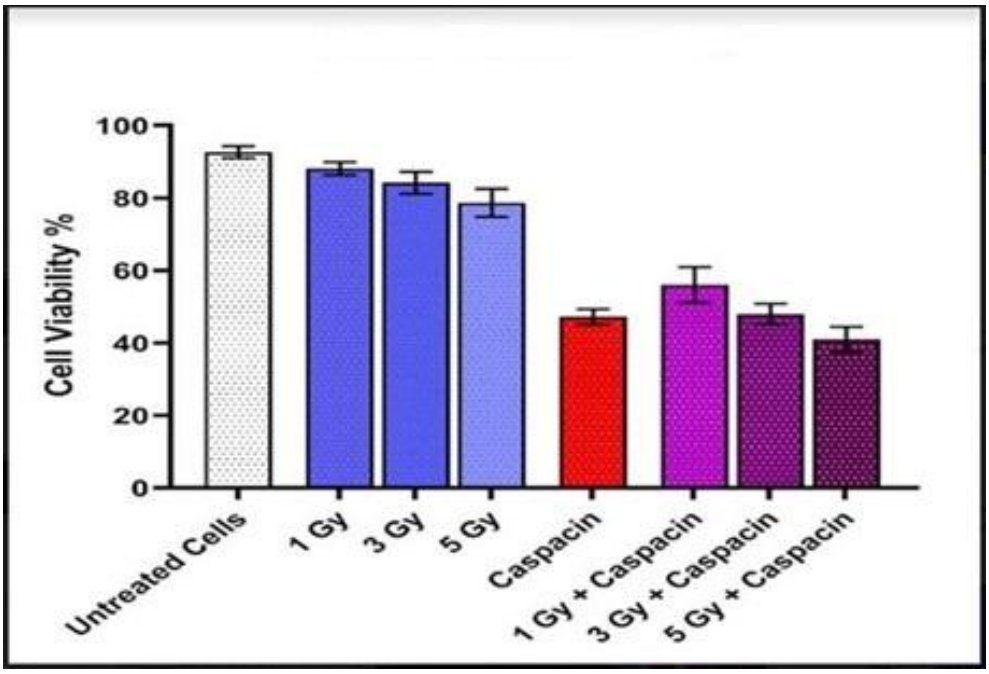

Fig 3: The different doses Effect of radiotherapy and Capsaicin on the CaCo-2 cells viability during using MTT assay for 48 hours exposure period at a temperature of 37 °C.

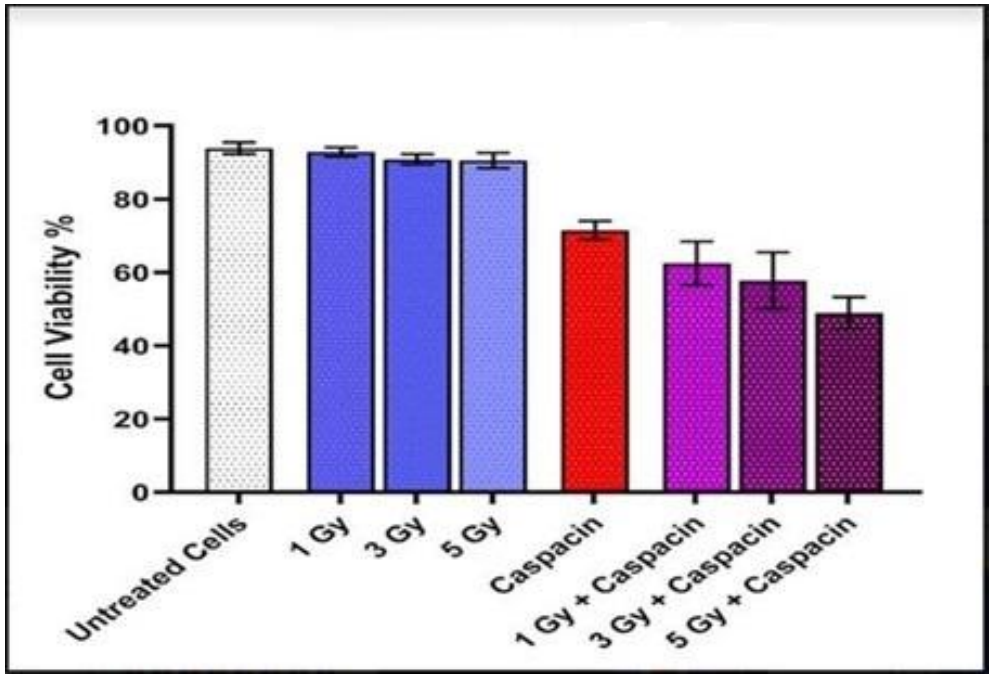

Fig 4: The different doses Effect of radiotherapy and Capsaicin on the CaCo-2 cells viability during using MTT assay for 48 hours exposure period at a temperature of 37 °C.

Many research have demonstrated that abdominal radiation treatment may cause radioactive intestine illnesses, which present mostly as acute and chronic intestinal injuries [19]. In the present research, 24 hours after radiation exposure, cell viability decreased in a dose-dependent manner compared to non-irradiated cells. However, the MTT assay showed that cell proliferation was significantly reduced only 24 hours after radiation exposure compared to non-irradiated cells. These findings might be due to the properties of cell growth tests [20]. Communicated that radiotherapy (1, 3, and 5 Gy) stimulates the break or eliminate of continuously strained lines of occluding in cells lines [21]. Caco-2 viability was assessed using the MTT test and found to be as high as in the sham condition for cells irradiated with varying dosages of radiation and followed for up to 48 hours after exposure. The proportion of dead cells was discovered to increase in a dose-dependent way. Findings at 5 Gy are highly consistent with what was seen in a prior study following X-ray exposure of Caco-2 cells seeded 48 h before irradiation [22, 27].

In a prior study, we discovered that capsaicin administration dramatically increased growth arrest and apoptosis in human colorectal cancer cells [23]. However, the fundamental processes by which capsaicin impacts human colorectal cancer are still poorly understood. This study's concentration (100 μM) corresponds with prior studies on human colorectal cancer cells in vitro [24,25]. The combination of CAP with chemotherapeutic medications or radiation treatment may give techniques for increasing chemotherapy or radiation therapy sensitivity, lowering harmful side effects, and overcoming chemotherapy resistance and radiotherapy tolerance. In light of the aforesaid results, it may be hypothesized that CAP may become an auxiliary technique to established treatment approaches like as chemotherapy or radiation in the near future [26]. Capsaicin has been shown to have anti-cancer properties, including anti-proliferation, activation of apoptosis and autophagy, anti-angiogenesis, and anti-metastasis. More studies is required to

determine the safety and effectiveness of capsaicin, as well as its potential anti- tumor effects when coupled with other conventional medicines or radiation [26].

CONCLUSION

Our findings demonstrate that natural compounds such as capsaicin, when combined with radiotherapy, significantly enhanced the cytotoxic effects on colorectal cancer cells in vitro compared to either treatment alone. The combined approach reduced the required drug concentration and radiation dose while increasing cancer cell sensitivity and selectivity against normal cells. These results suggest a potential role for natural compounds in overcoming resistance and minimizing side effects of conventional therapies. However, the study is limited by its in vitro design and short observation period; therefore, further in vivo and clinical investigations are needed to confirm the therapeutic relevance and safety of these combinations.

ACKNOWLEDGEMENT

Many thanks to all who have contributed to declare this issue, and special thanks to the staff of the school of physics, Universiti Sains Malaysia.

AUTHOR CONTRIBUTIONS

Abbas R. Hatif: Writing—draft the original, conceptualized the study, developed the research framework, designed the methodology, data collection, data cleaning, conducted data analysis, prepared figures and tables, and drafted the manuscript. **Azhar Abdul Rahman**: Writing—performed statistical analysis, contributed to the manuscript literature review, validation and provided expertise support; while **Talib A. Abdulwahid** and Naser M. Ahmed: Writing—interpreted results, discussion the manuscript, and validation. All authors reviewed, and edited this final approved manuscript.

FUNDING

The authors did not receive support from any funding agency for the submitted work.

DATA AVAILABILITY

The dataset used for this research paper could be provided upon reasonable request from the corresponding author.

DECLARATIONS

ETHICAL APPROVAL AND CONSENT TO PARTICIPATE

None

CONSENT TO PUBLICATION

In this paper, the results/data/figures/tables have not previously been published, or are not under consideration for publication elsewhere.

COMPETING INTERESTS

The authors declare no competing interest

REFERENCES

[1] Ahmed, M., Askar, S., Muheden, K., & Bilal, N. (2024). Enhancing Educational Bray, F., Laversanne, M., Weiderpass, E., & Soerjomataram, I. (2021). The ever-increasing importance of cancer as a leading cause of premature death worldwide. Cancer, 127(16), 3029– 3030.

[2] Torre, L. A., Bray, F., Siegel, R. L., Ferlay, J., Lortet-Tieulent, J., & Jemal, A. (2015). Global cancer statistics, 2012. CA: A Cancer Journal for Clinicians, 65(2), 87–108.

[3] Santandreu, F. M., Valle, A., Oliver, J., & Roca, P. (2011). Resveratrol potentiates the cytotoxic oxidative stress induced by chemotherapy in human colon cancer cells. Cellular Physiology and Biochemistry, 28(2), 219–228.

[4] van der Stok, E. P., Spaander, M. C. W., Grünhagen, D. J., Verhoef, C., & Kuipers, E. J. (2017). Surveillance after curative treatment for colorectal cancer. Nature Reviews Clinical Oncology, 14(5), 297–315.

[5] Park, S.-Y., Kim, J.-Y., Jang, G.-B., Choi, J.-H., Kim, J.-H., Lee, C.-J., Lee, S., Baek, J.-H., Park, K.-K., & Kim, J.-M. (2021). Aberrant activation of the CD45-Wnt signaling axis promotes stemness and therapy resistance in colorectal cancer cells. Theranostics, 11(18), 8755.

[6] Fernández, J., Redondo-Blanco, S., Gutiérrez-del-Río, I., Miguélez, E. M., Villar, C. J., & Lombo, F. (2016). Colon microbiota fermentation of dietary prebiotics towards short-chain fatty acids and their roles as anti-inflammatory and antitumour agents: A review. Journal of Functional Foods, 25, 511–522.

[7] Pan, M., Lai, C., Wu, J., & Ho, C. (2011). Molecular mechanisms for chemoprevention of colorectal cancer by natural dietary compounds. Molecular Nutrition & Food Research, 55(1), 32–45.

[8] Housman, G., Byler, S., Heerboth, S., Lapinska, K., Longacre, M., Snyder, N., & Sarkar, S. (2014). Drug resistance in cancer: an overview. Cancers, 6(3), 1769–1792.

[9] Colussi, D., Brandi, G., Bazzoli, F., & Ricciardiello, L. (2013). Molecular pathways involved in colorectal cancer: implications for disease behavior and prevention. International Journal of Molecular Sciences, 14(8), 16365–16385.

[10] Singh, C. K., George, J., & Ahmad, N. (2013). Resveratrol-based combinatorial strategies for cancer management. Annals of the New York Academy of Sciences, 1290(1), 113–121.

[11] Amiri, F., Zarnani, A.-H., Zand, H., Koohdani, F., Jeddi-Tehrani, M., & Vafa, M. (2013). Synergistic anti-proliferative effect of resveratrol and etoposide on human hepatocellular and colon cancer cell lines. European Journal of Pharmacology, 718(1–3), 34–40.

[12] Fattorusso, E., & Taglialatela-Scafati, O. (2007). Modern alkaloids: structure, isolation, synthesis, and biology. John Wiley & Sons.

[13] Perucka, I., & Oleszek, W. (2000). Extraction and determination of capsaicinoids in fruit of hot pepper Capsicum annuum L. by spectrophotometry and high-performance liquid chromatography. Food Chemistry, 71(2), 287–291.

[14] Koleva-Gudeva, L., Mitrev, S., Maksimova, V., & Spasov, D. (2013a). Content of capsaicin extracted from hot pepper (Capsicum annuum ssp. microcarpum L.) and its use as an ecopesticide. Hemijska Industrija, 67(4), 671–675.

[15] Koleva-Gudeva, L., Mitrev, S., Maksimova, V., & Spasov, D. (2013b). Content of capsaicin extracted from hot pepper (Capsicum annuum ssp. microcarpum L.) and its use as an ecopesticide. Hemijska Industrija, 67(4), 671–675.
[16] Chen, G., Han, Y., Zhang, H., Tu, W., & Zhang, S. (2021a). Radiotherapy-induced digestive injury: diagnosis, treatment and mechanisms. Frontiers in Oncology, 11, 757973.
[17] Lomax, M. E., Folkes, L. K., & O'neill, P. (2013). Biological consequences of radiation-induced DNA damage: relevance to radiotherapy. Clinical Oncology, 25(10), 578–585.
[18] Chen, G., Han, Y., Zhang, H., Tu, W., & Zhang, S. (2021b). Radiotherapy-induced digestive injury: diagnosis, treatment and mechanisms. Frontiers in Oncology, 11, 757973.
[19] Qu, W., Zhang, L., & Ao, J. (2020). Radiotherapy induces intestinal barrier dysfunction by inhibiting autophagy. Acs Omega, 5(22), 12955–12963.
[20] Chung, D. M., Kim, J. H., & Kim, J. K. (2015). Evaluation of MTT and Trypan Blue assays for radiation-induced cell viability test in HepG2 cells. International Journal of Radiation Research, 13(4), 331.
[21] Shukla, P. K., Gangwar, R., Manda, B., Meena, A. S., Yadav, N., Szabo, E., Balogh, A., Lee, S. C., Tigyi, G., & Rao, R. (2016). Rapid disruption of intestinal epithelial tight junction and barrier dysfunction by ionizing radiation in mouse colon in vivo: protection by N-acetyl-l- cysteine. American Journal of Physiology-Gastrointestinal and Liver Physiology, 310(9), G705–G715.
[22] Suetens, A., Moreels, M., Quintens, R., Soors, E., Buset, J., Chiriotti, S., Tabury, K., Gregoire, V., & Baatout, S. (2015). Dose-and time-dependent gene expression alterations in prostate and colon cancer cells after in vitro exposure to carbon ion and X-irradiation. Journal of Radiation Research, 56(1), 11–21.
[23] Lee, S.-H., Krisanapun, C., & Baek, S. J. (2010). NSAID-activated gene-1 as a molecular target for capsaicin-induced apoptosis through a novel molecular mechanism involving GSK3β, C/EBPβ and ATF3. Carcinogenesis, 31(4), 719–728.
[24] Kim, M. Y., Trudel, L. J., & Wogan, G. N. (2009). Apoptosis induced by capsaicin and resveratrol in colon carcinoma cells requires nitric oxide production and caspase activation. Anticancer Research, 29(10), 3733–3740.
[25] Yang, K., Pyo, J., Kim, G.-Y., Yu, R., Han, I., Ju, S., Kim, W., & Kim, B.-S. (2009). Capsaicin induces apoptosis by generating reactive oxygen species and disrupting mitochondrial transmembrane potential in human colon cancer cell lines. Cellular and Molecular Biology Letters, 14(3), 497–510.
[26] Zhang, S., Wang, D., Huang, J., Hu, Y., & Xu, Y. (2020). Application of capsaicin as a potential new therapeutic drug in human cancers. Journal of Clinical Pharmacy and Therapeutics, 45(1), 16–28
[27] Hatif, A. R., Abdul Rahman, A., Abdulwahid, T. A., Ahmed, N. M., Mahdi Badi, K., Jumaah Mhawes, A., Khaled Albadarneh, L., & Rashid Hatif, A. (2024). *Combined radiotherapy, plant extracts, and chemotherapy in colorectal cancer cells*. PQ.