



Review article

Impact of irradiation on physico-chemical and nutritional properties of fruits and vegetables: A mini review

Pooja Bhatnagar^a, Prateek Gururani^{b,*}, Bhawna Bisht^a, Vinod Kumar^{a,c,**}, Navin Kumar^b, Raja Joshi^d, Mikhail S. Vlaskin^e^a Department of Life Sciences, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, 248002, India^b Department of Biotechnology, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, 248002, India^c Peoples' Friendship University of Russia (RUDN University), Moscow, 117198, Russian Federation^d School of Agriculture, Uttaranchal University, Dehradun, Uttarakhand, 248007, India^e Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, 117198, Russian Federation

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ABSTRACT

Background: Fruits and vegetables are healthy because they contain good nutrients and secondary metabolites that keep the body healthy and disease-free. Post-harvest losses of fresh fruits and vegetables limit access and availability as a result of foodborne infections and poor storage technologies. The selection of fruits and vegetables depend on the starting microbial load, the size of fruits and vegetables, and the type of infrastructure.

Scope and approach: Despite the positive impacts of conventional thermal (roasting, boiling, blanching) and some non-thermal processing techniques such as High Pressure Processing (HPP), Pulse Electric Field (PEF), Cold Plasma Technology (CPT) on shelf-life extension, their use is commonly associated with a number of negative consequences on product quality such as cold plasma treatment increases the acidity and rate of lipid oxidation and further decrease the colour intensity and firmness of products. Similarly, in high pressure processing and pulse electric field there is no spore inactivation and they further limit their application to semi-moist and liquid foods. On that account, food irradiation, a non-thermal technique, is currently being used for post-harvest preservation, which could be very useful in retaining the keeping quality of various fresh and dehydrated products without negatively affecting their versatility and physico-chemical, nutritional and sensory properties.

Conclusion: Existing studies have communicated the effective influence of irradiation technology on nutritional, sensory, and physico-chemical properties of multiple fruits and vegetables accompanying consequential deduction in microbial load throughout the storage period. Food irradiation can be recognized as a prevalent, safe and promising technology however, still is not fully exploited on a magnified scale. The consumer acceptance of processed products has always been a significant challenge for innovative food processing technologies such as food irradiation. Therefore, owing to current review, additional scientific evidences and efforts are still demanded for increasing its technological request.

1. Introduction

Food insecurity, malnutrition, lifestyle diseases, and food-borne illness are among the major worldwide challenges driving up demand for healthy foods (Gogo et al., 2017). It is predicted that one-third of the population in affluent countries will be afflicted up to food borne diseases each year due to the ingestion of causative agents, with the figure likely to be higher in developing countries (Mostafidi et al., 2020; Delorme et al., 2020). According to recent statistics of World Health Organization

(2020), consumption of food contaminated with pathogenic micro-organisms and viruses can cause around more than 200 diseases ranging from diarrhoea to cancer. The ever-increasing consumer demand for healthy and safe food has compelled the scientific community of food processing to employ advance food processing technologies for ensuring product acceptance, quality and safety as well as high nutritional content and fresh flavour (Troy et al., 2016). Fruits and vegetables are a fantastic source of highly nutritious nutrients (like dietary fibres, phenolic compounds, minerals and vitamins) keeping the body healthy and

* Corresponding author.

** Corresponding author.

E-mail addresses: prateekguru25@gmail.com (P. Gururani), vinodkhatwalia@gmail.com (V. Kumar).<https://doi.org/10.1016/j.heliyon.2022.e10918>

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disease-free (Alegbeleye et al., 2022; Salehi and Kashaninejad, 2018). However, due to their high perishability, they incur significant post-harvest losses during storage, making long-term storage of these agricultural products a considerable concern (Salehi, 2020). It has been stated that every year, over 1.3 billion tonnes of food in the globe is wasted due to spoilage, with fruits and vegetables accounting for nearly 40% of the losses (Jiang et al., 2020). Earlier research approaches content that thermal food processing methods for instance, drying, roasting, boiling and frying (Cai et al., 2016; Zhang et al., 2016, 2018; Lamberti et al., 2021; Amini et al., 2021) provide adequate food safety and quality; however, they are dramatically influencing the physical, nutritional and sensory characteristics of food product along with generation of harmful uncontrollable by-products (Pi et al., 2021; Bisht et al., 2021). These methods, for example, can result in vitamin or bioactive ingredient loss, protein denaturation, lipid oxidation, colour, flavour, or textural changes of food product (Salehi and Satorabi, 2021).

In addition to consumer demand and resolving the above-mentioned challenges, several innovative non-thermal food processing methods have evolved, allowing these losses to be reduced (Bisht et al., 2021). When compared to thermal methods, these non-thermal food processing methods not only require less energy but also significantly reduce processing time while maintaining nutritional, sensory and physicochemical properties along with a significant reduction of allergenicity of the food product (Pi et al., 2021). As a result, they can be effectively applied on an industrial scale (Delorme et al., 2020). Currently, these revolutionary techniques have piqued the curiosity of a wide range of researchers in the field of food science and technology (Jiang et al., 2020). Ohmic heating (Roobab et al., 2022a), food irradiation (Bisht et al., 2021), cold plasma technology (Asgar et al., 2022), pulsed electric field (Ranjha et al., 2021), high-pressure processing (Roobab et al., 2022b, 2022c), and ultrasonic technology (Jiang et al., 2020) are examples of such emerging non-thermal techniques. However, the use of emerging technologies has been linked to a number of vulnerabilities. For instance, pulsed electric field is confined to minute particles and liquid foods, with no spore destruction. Similarly, high-pressure processing necessitates the use of heat or pressure pulsing in order to ensure total spore eradication (Bisht et al., 2021). Furthermore, this technology also demands more than 40% free water in food medium for significant microbial inactivation which makes its application highly limited (Hinds et al., 2019). Similarly, cold plasma technology necessitates additional safety considerations when high voltage is used to generate plasma, which might reduce the colour intensity and stiffness of the product. It can also accelerate the rate of lipid oxidation in meals due to the production of reactive oxygen species (Bhatnagar, 2019; Pankaj et al., 2018).

Despite significant efforts to reduce outbreaks of foodborne diseases and preserving the general quality and safety of fruits and vegetables, the most adaptable non-thermal processing technology among all remains the food irradiation technology (Barkai-Golan and Follett, 2017). There is a growing interest in the use of food irradiation for preservation of fresh produce where no other acceptable technique exists (Bisht et al., 2021). Food irradiation is a non-thermal and physical process in which the food is subjected to the controlled amounts of either non-ionizing or ionizing radiations (mostly used), which have a positive influence on pathogenic and spoilage microorganisms, including viruses, without compromising the product's quality or nutritional properties (Pathak et al., 2018; Nair and Sharma, 2016; Kalaiselvan et al., 2018). No toxicological, microbiological or nutritional problem occurred with the use of up to 10 kG y irradiation in food has been reported by joint venture of Food and Agriculture Organization (FAO)/International Atomic Energy Agency (IAEA)/World Health Organization (WHO) Expert Committee (Cho and Ha, 2019; WHO, 1981). The Food and Drug Administration (FDA) approves the use of up to a level 4.5 kG y ionizing radiation for preventing foodborne microorganisms and increasing the self-life of refrigerated meat products (FDA, 2017). Food irradiation has been studied as a successful alternative for microbial inactivation and enhancing the quality of various fresh as well as dehydrated products

without adversely affecting their physico-chemical, nutritional and sensory characteristics as well as the versatility of foods that may be treated (Cho and Ha, 2019; Bisht et al., 2021).

It is important to increase the consumer confidence in food irradiation as a safer method to preserve foods, maintain adequate nutrients and reduce the incidence of food-borne diseases, the purpose of this review was to summarize the mechanism of both type radiations (ionizing and non-ionizing) and access and discuss its effect on physico-chemical, nutritional and microbial characteristics of fruits and vegetables.

2. Mechanisms of different type of radiations

2.1. Non-ionizing radiations

Non-ionizing radiations often referred to as ultraviolet radiations which are the part of electromagnetic spectrum ranging from 10 to 400 nm wavelengths, between visible light and X-rays. Based on wavelength UV light is further categorized into four types, namely UV-A (315–400nm), UV-B (280–315 nm), UV-C (200–280 nm) and UV-V (10–200 nm). However, in among all these, UV-C is termed as the germicidal wavelength because highest DNA absorption takes place in this range leading to substantial damage of pathogenic micro-organisms. Particularly, for microbial inactivation, UV-C light in the range between 260–265nm is the most lethal range due to peak absorption of genetic material. As UV-C hits the target point, it initiates the production of DNA photoproducts which are pyrimidine 6-4 pyrimidone (6–4 P P) and cyclobutane pyrimidine dimers (CPDs) inhibiting the process of replication and transcription. Moreover, the indirect effects are associated with membrane damage, increase in concentration of ROS like hydrogen peroxide, hydroxyl radicals etc (Hinds et al., 2019). Figure 1 represents an overview of steps involved behind inactivation of micro-organisms by non-ionizing radiations.

2.2. Ionizing radiations

Ionizing radiations are defined as those radiations which cause excitation and ionization in the absorbed substance. Such radiations include gamma rays, X-rays and electron beams. For food processing purposes using ionizing radiations, gamma rays from cobalt-60 sources up to 5 MeV, X-rays from X-ray machines up to 5 MeV and electron beams from electron accelerators from up to 10 MeV are considered as radiologically safe (Pi et al., 2021).

Generally, ionizing radiations exerts their influence on micro-organisms by means of two major mechanism namely, direct effect and indirect effect (Fan, 2012). In direct effect, these radiations directly induce the destruction to microbial cell components like lipids, carbohydrates and DNA whereas, in indirect effect, free radicals and reactive species including hydroxyl radicals, hydrogen atoms and hydrated electrons from radiolysis of water act with cells components (Fan and Wang, 2021). Besides this, the cellular injury might further include reactive nitrogen species (RNS) and other species and can also take place because of the ionization of atoms on essential molecules as in DNA (Wardman, 2009). Moreover, in case of fresh products, inactivation of micro-organisms through indirect effect is the main mechanism because water is the principal component in such products (Bisht et al., 2021). The final outcome of indirect and direct effects, is the occurrence of physiological, genetic, epigenetic and biological alterations (Desouky et al., 2015). Figure 2 delineates detrimental effect of ionizing radiations on nucleic acid of micro-organisms.

3. Process parameters affecting the efficiency of food irradiation

Multiple factors represent an essential role in elimination of different micro-organisms by irradiation technology. Such type of factors involve composition and physical state of foodstuffs, type and dose of radiation used, exposure time, species, number, age, type and location of micro-organisms, inoculation time, ability of micro-organisms to regenerate

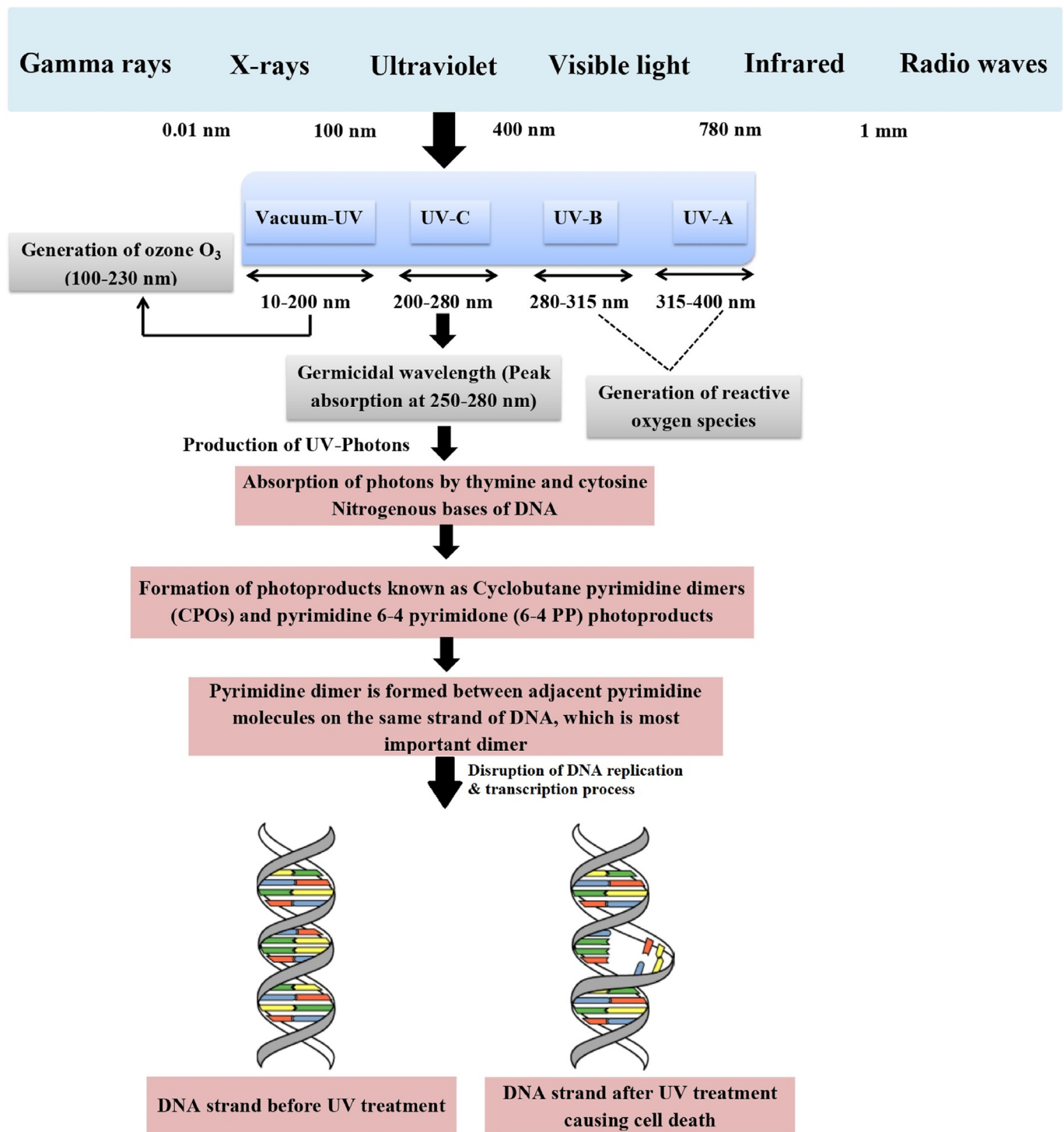


Figure 1. Steps involved in inactivation of micro-organisms by non-ionizing radiations.

and environmental factors (Delorme et al., 2020; Bozoglu and Erkmen, 2016; Pi et al., 2021). Hence, appropriate understanding of these factors and their influence on micro-organisms longevity or death is crucial to decide the acceptable radiation so that a beneficial inactivation can be achieved (Fan et al., 2017).

3.1. type and dose of radiation

Gamma rays possess the efficacy for economical and effective utilization in food preservation as compared to β and X-rays. Cobalt-60 is principally utilized as a source of gamma rays in food irradiation process

because of its economical and equipped accessibility. Moreover, it has been stated that the antimicrobial potential of ionizing radiation increases with an increase in dosage rate (Bozoglu and Erkmen, 2016). Similarly, in case of UV-irradiation, dose and wavelength are important factors influencing the potency of microbial inactivation associated with the process. Additionally, other physical parameters like geometry and conformation of UV equipment and flow pattern also have crucial importance (López et al., 2005). Higher lethal efficiency is attained at wavelengths adjacent to the peak of DNA absorption. Moreover, the emission of wavelength depends up on the UV lamp utilized in treatment (Gayán et al., 2011).

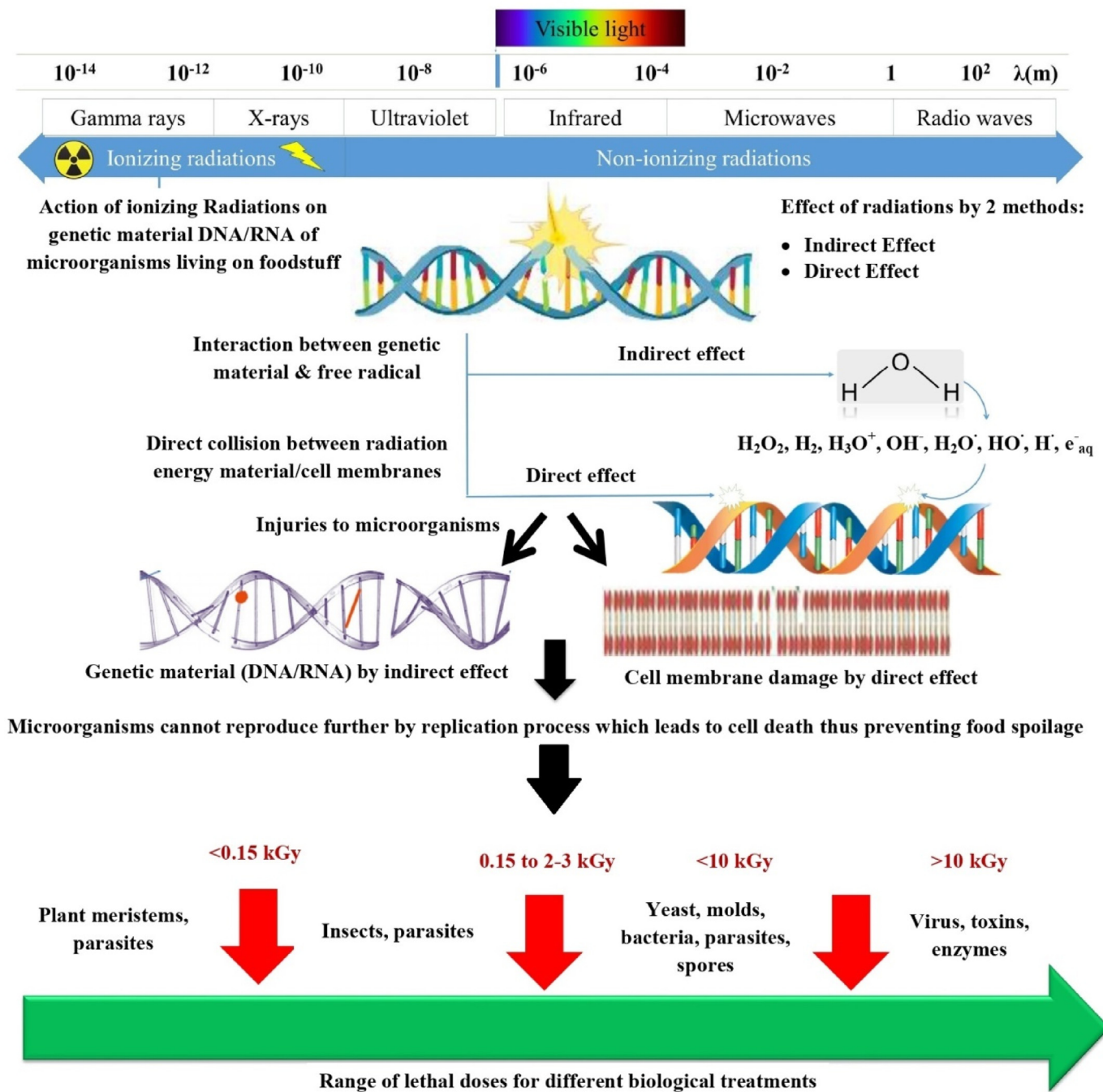


Figure 2. Action of ionizing radiations on nucleic acid of micro-organisms.

3.2. Species and types of micro-organisms

Micro-organisms substantially vary in their responsiveness to irradiation technology and a particular organism demands a definite lethal dose of radiation, therefore the properties of micro-organisms are crucial for treatment efficacy because their sensitivity to irradiation differ remarkably between various species, strains and types of microorganisms (Bozoglu and Erkmen, 2016; Koutchma, 2009). Additional essential parameters involve cell size of microbe, DNA reparability, irradiation-produced photoproducts, pigment production and conformation, size and composition of genetic material (Tran and Farid, 2004). Generally, the main foodborne pathogens of unlike species are sensitive to irradiation and might be eliminated by medium and low dose of radiation ranging between 1 and 7 kG y. Moreover, moulds reveal

increased sensitivity to irradiation followed by yeasts, bacteria and viruses. In addition, cocci are more opposed to irradiation than rods and similarly gram positive bacteria are more opposed to irradiation than gram negative bacteria. The extents of lethal dose for microbial inactivation are as follows: 0.5–10 kG y for yeast, mould and bacterial cells; 10–50 kG y for bacterial spores and 10–200 kG y for viruses. Normally, *Listeria* and *Salmonella* are more resistant to irradiation than *Staphylococcus* and *E. coli* (Bozoglu and Erkmen, 2016). Similarly, studies have further stated the higher potential of UV-irradiation in eliminating gram negative bacteria as compared to gram positive bacteria because of the thick peptidoglycan layer present on the outside of gram positive bacteria cell wall, and subsequently yeast, bacterial spores, fungi, viruses, and protozoa (Delorme et al., 2020). In addition, yeasts own huge sized cells and lesser pyrimidine content in genetic material that is related to greater

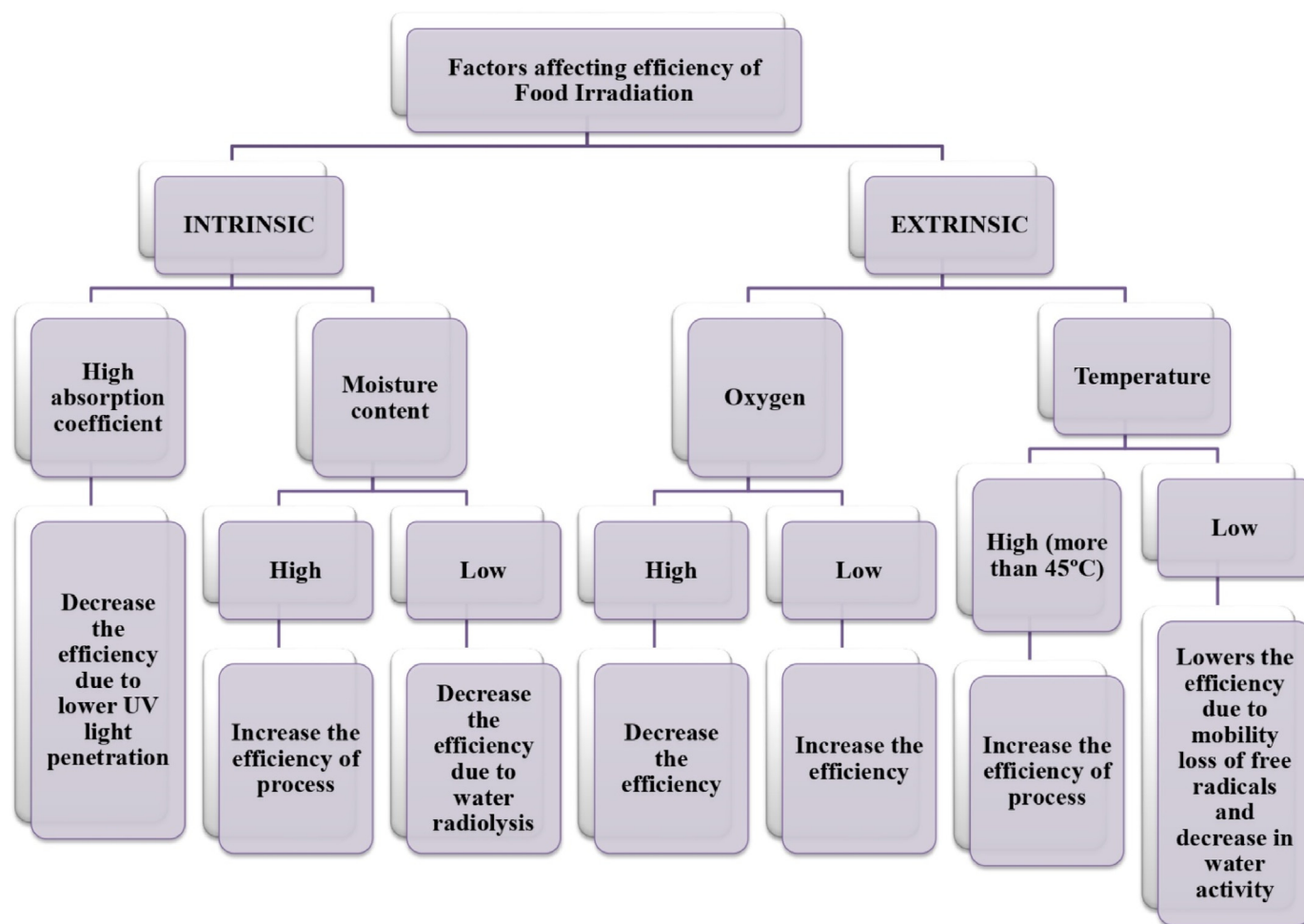


Figure 3. Effect of different parameters on the efficiency of food irradiation.

resistance for UV as compared to bacteria, majorly due to increased probability of photons absorption by other components before affecting the genetic material. Likewise, bacterial spores are more resistant to UV irradiation than vegetative cells, principally due to the dehydrated state of core that decreases the pyrimidine dimerization; efficient action of spore photoproducts lyase at the time of germination and the existence of a thick protein coating in spore (Gayán et al., 2014b). Besides this, the physiological stage of cells, like their growth conditions, growth phase, stressors prior to UV treatment and recovery of cell after processing, could further influence the sensitivity of micro-organisms for irradiation (Wassmann et al., 2011).

3.3. Composition of foodstuffs

Multiple food matrices might absorb light distinctively; hence they would possess contrasting absorption coefficients (Hinds et al., 2019). For instance, micro-organisms are more responsive to irradiation when disclosed in buffer solutions than organic components (like proteins) constituting solutions. Organic components possess protective influence against radiations. Antimicrobial agents, like nitrite, enhance the sensitivity of micro-organisms for irradiation (Bozoglu and Erkmen, 2016). Similarly, the penetrability of UV radiations in solid foods is dependent upon various factors, involving surface, compositional and physical properties namely, roughness, viscosity, thickness, colour, density and optical characteristics (Koca et al., 2018). The product properties that majorly influence the lethal efficiency are optical characteristics, especially the medium turbidity and UV absorbance. Soluble and colour components and solids in suspension can decrease the number of photons

accessible to inactivate microorganisms by scattering, reflecting and absorbing incidental light (Koutchma, 2009). Contrastingly, other properties like water activity and pH are not applicable in regulating the microbial resistance towards UV irradiation (Müller et al., 2015) that is of extreme importance formerly this technology could be used for several products regardless of these factors (Gayán et al., 2014a).

3.4. Environmental factors

Various environmental factors namely, temperature, oxygen, moisture and pH further possess a significant influence on consequences of food irradiation (Pi et al., 2021). For instance, under the presence of oxygen, the lethal influence of ionizing radiations on micro-organisms increases, while in absence of oxygen and under wet environment, the radiation resistance generally enhances by a factor of 2–4 (Bisht et al., 2021). Similarly, temperature also owns a significant effect on efficiency of irradiation technology like, in vegetative cells, the lethal influence of irradiation is increased with an increase in temperature usually ranging above 45 °C (Ashraf, 2019). Moreover, it has also been stated that a reduction in moisture content might intercept the lethal influence of radiation on micro-organisms (Bisht et al., 2021). Figure 3 represents effect of different parameters on the efficiency of food irradiation process.

4. Effect of ultraviolet radiation on nutritional quality of different fruits and vegetables

From the last few years, application of ultraviolet irradiation for preservation of postharvest fruits and vegetables has attracted the

Table 1. Effect of ultraviolet irradiation of different Fruits and Vegetables.

S. No.	Fruit/Vegetable	Treatment	Dose and Time	Observed Effects	References
1.	Tomatoes (breaker)	UV-C light	1h & 1.0 kJ/m ²	<ul style="list-style-type: none"> Total lycopene content was increased (59.91 ± 1.47^a) during storage at room temperature for 8 days. An increment in lipophilic antioxidant activity was also observed (0.43 mmol Trolox/kg). 	Bravo et al. (2012)
2.	Strawberry	UV-C light	1min & 0.43 kJ/m ²	<ul style="list-style-type: none"> ORAC values were increased (30.33 mmol kg⁻¹). Activity of GSH-POD and GR was the lowest. Higher SOD activities were observed as compared to that in controlled samples after 15 days of storage at 10 °C. 	Erkan et al. (2008)
3.	Strawberry	UV-C light	5min & 2.15 kJ/m ²	<ul style="list-style-type: none"> Highest total phenolic content, ORAC values (32.21 mmol kg⁻¹) & high activity of G-POD was observed. Similarly, the activity of SOD was also high as compared to that in controlled samples after 15 days of storage at 10 °C. 	Erkan et al. (2008)
4.	Banana	UV-C light	0.03 kJ/m ²	<ul style="list-style-type: none"> MDA content and LOX activity was lowered. PPO activity was also decreased, at 8 °C it was high but reduced at 25 °C. Respiration rate and ethylene production were reduced at 25 °C during storage. UV-C also maintained high chlorophyll content after 14d of storage. The activity of chlorophyll degrading enzymes was reduced. There was increase in pulp firmness, TSS & Hue angle values. 	Pongprasert et al. (2011)
5.	Tomatoes (breaker)	UV-C light	12h & 12.2 kJ/m ²	<ul style="list-style-type: none"> Total phenolic content was increased by 42%. Hydrophilic antioxidant activity was also increased (1.74 & 1.88 mmol Trolox/kg). But a decrease in total lycopene content (42.56 ± 2.42^b) was observed. 	Bravo et al. (2012)
6.	Tomatoes (breaker)	UV-C light	3h & 3.0 kJ/m ²	<ul style="list-style-type: none"> Lipophilic antioxidant activity was increased (0.48 mmol Trolox/kg). Total lycopene content was also enhanced (63.17 ± 1.90^b). 	Bravo et al. (2012)
7.	Strawberry	UV-C light	10min & 4.30 kJ/m ²	<ul style="list-style-type: none"> ORAC values were increased (29.65 mmol kg⁻¹). The activity of (GSSG & GSH), (GSH-POD & GR) was the highest. Similarly, the activity of SOD was also high as compared to that in controlled samples after 15d of storage at 10 °C. 	Erkan et al. (2008)
8.	Lemon peel	UV-B light	22 kJ m ⁻² d ⁻¹ (0,0.5,1.0,2.0,3.0 & 5.0 min)	<ul style="list-style-type: none"> In flavedo, UV-B absorbing compounds enhanced by 28.5% & 54.7% after treatment of 2 & 3 min, respectively & TPC was enhanced by 31.3% at 2min & 19.3% at 3min while, no significant changes were observed in albedo. Concentrations of soluble sugars were higher in albedo than in flavedo. In flavedo, sucrose & fructose content was enhanced by 30.1 & 52.4 μmol g⁻¹FW at 3min-dose, but glucose content was lower 56.4 μmol/g FW. However, at 5min-dose sucrose content was decreased. In albedo, sucrose & glucose content was increased by 38.5 & 116.8 μmol g⁻¹FW at 3 min-doses & no change was observed in fructose. But at 1min-dose fructose content was enhanced (27.5 μmol g⁻¹FW). 	Interdonato et al. (2011)

ORAC- Oxygen radical absorbance capacity; GSH-POD- Glutathione peroxidase; TSS- Total soluble solids; TPC- Total phenolic content; h- Hour; min- Minutes; KJ/m² – Kilojoule per meter square; ±- Standard deviation; GR- Glutathione reductase; PPO- Polyphenol oxidase; FW- Fresh weight; SOD- Superoxide dismutase; GSSG- Oxidized glutathione; G-POD- Guaiacol peroxidase; MDA- Malondialdehyde content; LOX- Lipoxigenase.

interest of many researchers and technologists. Furthermore, researches have shown an exponential growth on the implementation of UV light particularly in area of postharvest fruits and vegetables (Bisht et al., 2021). Various existing studies have revealed the promising outcomes of ultraviolet irradiation for preservation of different fruits and vegetables without adversely affecting their quality parameters like in pineapple, tomato, mangoes, leafy vegetables, broccoli, lily bulb etc.

More specifically, Charles et al. (2008) revealed that low doses of UV-C can improve the resistance of tomatoes to fungi by producing defences. The reason behind the resistance was the increase in phytoalexin-rishitin at the initial stage and the long-term resistance was developed due to an increment in the lignin and phenolic compounds which increased the inhibitory effects of CWSZ (cell wall stacking zone) on fungi colonization. Likewise, Obande et al. (2011) studied that the ripening process in tomatoes were retarded on treating with UV-C and the growth of *Penicillium digitatum* was also inhibited. Similarly, Bravo et al. (2012) revealed that UV-C irradiation increased the lycopene content, phenolic compounds, ascorbic acid, and antioxidants at the time of storage in tomatoes. Tiecher et al. (2013) further concluded that the UV-C treated tomato fruits were having high concentration of polyamines.

Additionally, D'Hallewin et al. (2012) studied that treatment with UV-C for 5–10 min can reduce the chances of strawberry decay at a storage temperature of 10 °C and could also inhibit the formation of brown stain in grapes. Also, Cote et al. (2013) demonstrated that using high intensity of UV-C (4.1 kJ/m²) in strawberries is more effective as compared to low intensity in reducing postharvest losses and softening.

The positive results of UV-C treatment with strawberry fruit and its leaves were reported by Jin et al. (2017) which revealed that treatment increases proteins content such as beta-1,3-glucanase and chitinase that are vital for plant defence in leaves attacked by *Colletotrichum acutatum* and fruits impacted by *B. cinerea*. According to Dyshlyuk et al. (2020), using UV-A irradiation in tomatoes as a post-harvest treatment increased the total content of phenolic compounds, flavonoids and carotenoids and increases at all the investigated wavelengths while the content of chlorophylls reacts the antioxidant activity ambiguously. UV-C has been shown to be beneficial in the post-harvest phase of horticultural products in terms of reducing respiration rate, controlling depreciation products, delaying maturation, minimizing browning and ripening processes, and increasing antioxidant content in new and freshly cut fruits and vegetables. The effect of UV irradiation on different fruits and vegetables is shown in Table 1.

5. Effect on different ionizing irradiation on nutritional quality of different fruits and vegetables

5.1. Gamma rays

Currently, gamma ray irradiation has been identified as a safer tool for ensuring food safety due to its high penetration strength, which allows it to easily target harmful microorganisms, resulting in microbial load reduction, as well as being an environmentally friendly and chemical-free technology (Zarbaksh and Rastegar, 2019). Moreover,

Table 2. Effect of gamma irradiation on different Fruits and Vegetables.

S. No.	Fruit/Vegetable	Treatment	Dose rate	Observed Effects	Reference
1.	Pomegranate	γ -rays	0, 0.4, 1 & 2 kG y	<ul style="list-style-type: none"> The pomegranate fruits were exposed to irradiation and then its juice was extracted. Treatment at 0.4 kG y does not affect the TA of juice but it was decreased at 1 and 2 kG y. pH was unaffected up to 1 kG y but at higher doses it was enhanced. TSS remains unaffected at all the applied doses. Similarly, total sugar content remains unaffected in the fruit at all the applied doses but reducing sugar content varied with the applied doses. TPC was decreased with increase in the dose. 	Shahbaz et al. (2014)
2.	Litchi	γ -rays	0, 0.3 & 0.5 kG y	<ul style="list-style-type: none"> Two varieties of the fruits were taken 'Shahi' & 'China'. The pH of 'Shahi' fruits was about 4.3 on day 1 & it remain unaffected on day 12 & the pH of 'China' fruits was about 4 on day 1 & was increased up to 4.7 on day 12. Doses of 0.3 & 0.5 kG y do not cause significant changes in pH. TA of 'Shahi' fruit juice was 0.3% which remains unaffected on day 10. Additionally, increase in TA was found on day 28 at 0.3 kG y & on day 20 at 0.5 kG y. While, in 'China' fruits TA was higher at day 1 & decreased at day 10 in both (treated & controlled samples). It was found similar on day 20 at 0.3 & 0.5 kG y & on day 28 TA was increased but it was less as compared to day 1. 	Hajare et al. (2010)
3.	Apple	γ -rays	0.0, 300, 600, 900 & 1200Gy	<ul style="list-style-type: none"> After the treatment, an inverse relation was noticed between moisture content and TSS of the samples. As, the moisture content was decreased, TSS was increased. STPC and antioxidant activity was higher in the control ones and samples treated with (300 & 600Gy) doses, while samples treated with (900–1200Gy) were having lower TPC & antioxidant activity. The firmness of fruits was decreased as storage period and irradiation dose was increased. Doses of 0–600Gy were having no negative effect on firmness while (900–1200Gy) negatively affect the firmness of the fruit during storage. 	Mostafavi et al. (2012)
4.	Green onion	γ -rays	1.2 kG y	<ul style="list-style-type: none"> After the treatment, concentration of polyphenols was increased (163-188μM Trolox eq.). The ascorbic acid content was negatively affected. Initially it was found to be 364μM but after the treatment it was decreased by 213 μM. The ORAC-FL was also decreased from 245 to 200. 	Jimenez et al. (2011)
5.	Prata bananas	γ -rays	0.0, 1.0, 1.5 & 2.0 kG y	<ul style="list-style-type: none"> During storage of 21d, no significant changes were observed in total amines concentration of controlled and irradiated samples. It was (3.07–3.52mg/100g) & (3.12–3.37mg/100g) in green and ripened bananas, respectively but was lower (1.99–2.03mg/100g) in over-ripened bananas [35d storage]. Dosage of 1.5 kG y decreased the rate of starch degradation [providing firmness to the fruits] whereas at 2.0 kG y it was increased. Dose of 1.0 kG y was most effective in delaying the change in colour during storage while 1.5 kG y & 2.0 kG y were not viable. 	Gloria and Adão (2013)
6.	Lettuce	γ -rays	0.5, 1.0 & 1.5 kG y	<ul style="list-style-type: none"> Total vitamin C content was decreased in all the samples (controlled and treated) with increase in storage period. At the end of storage period (after 9d) the samples irradiated with 1.0 kG y were found to have high vitamin C content (3.30a\pm2.20) as compared to all the other samples. Rate of browning was effectively prevented at 1.0 kG y & 1.5 kG y dosage. PPO activity was highest in 1.0 kG y (10.50b \pm 0.49) & in 1.5 kG y (11.81a\pm0.02) as compared to controlled & 0.5 kG y treated samples at the 9th day of storage at 4 °C. 	Zhang et al. (2006)
7.	Sun dried apricots	γ -rays	1.0, 1.5, 2.0, 2.5 & 3.0 kG y	<ul style="list-style-type: none"> β-carotene was decreased with increase in storage period in both treated and controlled samples. But at the end of storage (18months), controlled samples retained about 63.9% of β-carotene, whereas fruits irradiated at 2.5 & 3.0 kG y retain about 71.2% & 72.6% of total β-carotene content. Among all the doses, 3.0 kG y was recorded as the best in maintaining high β-carotene. Samples treated with 2.5 kG y were having the lowest acid content (1.5 \pm 0.01a,1) at the end of storage. Loss of ascorbic acid was maximum in controlled samples (58.6%) while in treated samples this loss ranged from 55.1% & 46.2%. 	Hussain et al. (2011)
8.	Red beetroot	γ -rays	1 & 2 kG y	<ul style="list-style-type: none"> After treatment, the concentration of β-cyanin & β-xanthin pigments got decreased. β-cyanin reduced by 35% at 2.0 kG y, while β-xanthin was increased at 1.0 kG y & decreased at 2.0 kG y in a ratio of 11% & 19%, respectively. No significant changes were observed in the colour of samples. The activity of PPO was enhanced at 2 kG y & POX activity was also enhanced. 	Latorre et al. (2010)
9.	Kiwi	γ -rays	0, 1, 2 & 3 kG y	<ul style="list-style-type: none"> After treatment, a delay in the ripening process was observed as TSS was decreased in treated samples with increase in storage time. Irradiated fruits were softer than controlled ones. Ascorbic acid content was found to be low in irradiated samples & was lowest at 3 kG y. Initially antioxidant activity was low at 2 & 3 kG y dose as compared to controlled and 1 kG y treated samples. But with increase in storage period, antioxidant activity was decreased in controlled samples & no significant difference was observed in the antioxidant activity of 1 & 2 kG y treated samples. 	Yook (2009)

TA- Titratable acidity; TSS- Total soluble solids; TPC- Total phenolic content; ORAC-FL- Oxygen radical absorbance capacity-fluorescein; PPO- Polyphenol oxidase; POX- Peroxidase.

various existing studies have demonstrated the potency of gamma irradiation on reducing the microbial load in different fruits and vegetables without adversely affecting their nutritional and sensory parameters like in garlic, date fruits, pomegranate, mandarin, cherry and many more.

Particularly, Zaman et al. (2007) reported that the gamma irradiation treatment in bananas increased the shelf-life of the fruit by 20 days and the ripening process was also delayed. Similarly, Majeed et al. (2014) found that there was an increase in the shelf-life of gamma irradiated (1

Table 3. Effect of X-rays on different Fruits and Vegetables.

S.No.	Fruit/ Vegetable	Pathogens	Irradiation source	Irradiation dose (kGy)	Log reduction achieved	Quality attributes	Observed effects on quality attributes	Reference
1.	Cantaloupes	<i>E. coli</i> O 157:H7	X-rays	0.1	1.7 log CFU 5 cm ⁻²	<ul style="list-style-type: none"> • Colour • Firmness 	<ul style="list-style-type: none"> • No significant difference was observed in colour and firmness of controlled and X-rays irradiated (0.1–2.0 kG y) samples. 	Mahmoud, (2012b)
		<i>Listeria monocytogenes</i>			0.6 log CFU 5 cm ⁻²			
		<i>Salmonella enterica</i>			1.3 log CFU 5 cm ⁻²			
		<i>Shigella flexneri</i>			1.8 log CFU 5 cm ⁻²			
		<i>E. coli</i> O 157:H7	X-rays	0.5	2.7 log CFU 5 cm ⁻²			
		<i>Listeria monocytogenes</i>			1.6 log CFU 5 cm ⁻²			
		<i>Salmonella enterica</i>			3.8 log CFU 5 cm ⁻²			
		<i>Shigella flexneri</i>			3.1 log CFU 5 cm ⁻²			
		<i>E. coli</i> O 157:H7	X-rays	1.0	4.8 log CFU 5 cm ⁻²			
		<i>Listeria monocytogenes</i>			2.5 log CFU 5 cm ⁻²			
		<i>Salmonella enterica</i>			5.0 log CFU 5 cm ⁻²			
		<i>Shigella flexneri</i>			3.7 log CFU 5 cm ⁻²			
<i>E. coli</i> O 157:H7	X-rays	1.2, 2.0, 2.5	UD (2 log CFU 5cm ⁻²)					
<i>Listeria monocytogenes</i>			UD (2 log CFU 5cm ⁻²)					
<i>Salmonella enterica</i>			UD (2 log CFU 5cm ⁻²)					
<i>Shigella flexneri</i>			UD (2 log CFU 5cm ⁻²)					
2.	Shredded iceberg lettuce	<i>E. coli</i> O 157:H7	X-rays	0.1	1.3 log CFU g ⁻¹	<ul style="list-style-type: none"> • Visual colour 	<ul style="list-style-type: none"> • No signific. 	Mahmoud, (2010a)
		<i>Listeria monocytogenes</i>			1.6 log CFU g ⁻¹			
		<i>Salmonella enterica</i>			1.0 log CFU g ⁻¹			
		<i>Shigella flexneri</i>			1.4 log CFU g ⁻¹			
		<i>E. coli</i> O 157:H7	X-rays	1.0	4.4 log CFU g ⁻¹			
		<i>Listeria monocytogenes</i>			4.1 log CFU g ⁻¹			
		<i>Salmonella enterica</i>			4.8 log CFU g ⁻¹			
		<i>Shigella flexneri</i>			4.4 log CFU g ⁻¹			
		<i>E. coli</i> O 157:H7	X-rays	2.0	More than 5 log CFU			
		<i>Listeria monocytogenes</i>			More than 5 log CFU			
		<i>Salmonella enterica</i>			More than 5 log CFU			
		<i>Shigella flexneri</i>			More than 5 log CFU			
3.	Roma tomatoes	<i>E. coli</i> O 157:H7	X-rays	0.75	4.2 log CFU g ⁻¹	-	-	Mahmoud, (2010b)
		<i>Listeria monocytogenes</i>			2.3 log CFU g ⁻¹			
		<i>Salmonella enterica</i>			3.7 log CFU g ⁻¹			
		<i>Shigella flexneri</i>			3.6 log CFU g ⁻¹			
		<i>E. coli</i> O 157:H7	X-rays	1.0, 1.5	UD (2logCFUtomato ⁻¹)			
		<i>Listeria monocytogenes</i>			UD (2logCFUtomato ⁻¹)			
		<i>Salmonella enterica</i>			UD (2logCFUtomato ⁻¹)			
		<i>Shigella flexneri</i>			UD (2logCFUtomato ⁻¹)			

(continued on next page)

Table 3 (continued)

S.No.	Fruit/ Vegetable	Pathogens	Irradiation source	Irradiation dose (kGy)	Log reduction achieved	Quality attributes	Observed effects on quality attributes	Reference
4.	Spinach leaves	<i>E. coli</i> O 157:H7	X-rays	0.1	0.2 log CFU g ⁻¹	• Colour	• No significant effects were observed on the colour of X-rays irradiated (0.1 up to 2.0 kG y) spinach leaves during storage.	Mahmoud et al. (2010)
		<i>Listeria monocytogenes</i>			0.9 log CFU g ⁻¹			
		<i>Salmonella enterica</i>			0.6 log CFU g ⁻¹			
		<i>Shigella flexneri</i>	1.2 log CFU g ⁻¹					
		<i>E. coli</i> O 157:H7	X-rays	1.0	3.5 log CFU g ⁻¹			
		<i>Listeria monocytogenes</i>			5.4 log CFU g ⁻¹			
<i>Salmonella enterica</i>	3.4 log CFU g ⁻¹							
		<i>Shigella flexneri</i>		5.2 log CFU g ⁻¹				

CFU- Colony forming unit; UD- Undetectable limit.

Table 4. Exposure Dose Rate of Irradiation for various fruits and vegetables for Different Purpose.

S. No.	Irradiated fruit or vegetable	Type of irradiation used	Purpose of irradiation	Range of exposed dose rate	Reference
1.	Litchi “Shahi” & “China”	Gamma irradiation	<ul style="list-style-type: none"> Reduction in microbial load Extension of shelf-life 	0–2 kG y at 2.4 kG y/h dose rate	Hajare et al. (2010)
2.	Pomegranate	Gamma irradiation	<ul style="list-style-type: none"> Disinfection of pests Quarantine treatment 	0.4, 1 & 2 kG y at 1.5 kG y/h dose rate	Shahbaz et al. (2014)
3.	Date fruits “Piarom”, “Zahedi” & “Deiri”	Gamma irradiation	<ul style="list-style-type: none"> Reduction in microbial and fungal growth Extension of storage period duration 	1, 3 & 5 kG at 0.4G/sec dose rate	Zarbaksh and Rastegar (2019)
4.	Prata banana	Gamma irradiation	<ul style="list-style-type: none"> Reduction in rate of starch degradation Delay in ripening process Reducing post-harvest losses 	1.0 kG y at 4.43 ± 0.16 kG y/h dose rate	Gloria and Adão (2013)
5.	Strawberry & raspberry	Gamma irradiation	<ul style="list-style-type: none"> Reduction in viral load of Human adenovirus type 5 and Murine norovirus type 1 	Between 0.9 & 7.6 kG y; 3.6 & 11.3 kG y at 1.6 kG y/h dose rate	Pimenta et al. (2019)
6.	Strawberry	Gamma irradiation	<ul style="list-style-type: none"> Extension of shelf-life No adverse effect on chemical quality 	0.5, 1.0 and 1.5 kG y	Majeed et al. (2014)
7.	Blueberries	UV-C coupled with aqueous chlorine dioxide	<ul style="list-style-type: none"> Inhibition of increased respiration rate Extension of postharvest life Enhanced shelf-life 	4 kJ/m ² with 2 mg/L of aqueous chlorine dioxide	Xu et al. (2016)
8.	Fresh cut cauliflower	UV-C coupled with gamma irradiation & anti-microbial formulations	<ul style="list-style-type: none"> Controlling the growth of foodborne pathogenic microbes namely, <i>E. coli</i>, <i>Listeria monocytogenes</i> & total yeast mould count Extension of shelf-life 	5 kJ/m ² & 10 kJ/m ² followed by gamma irradiation at 0.5 & 1 kG y with 16.74 kG y/h dose rate	Tawema et al. (2016)
9.	Apple skin	UV-B	<ul style="list-style-type: none"> Modulating concentration of bioactive compounds (phenolic components) 	219 kJ/m ²	Assumpção et al. (2018)
10.	“Phulae” pineapple	UV-C	<ul style="list-style-type: none"> Reduction in disease incidence and internal browning Extension of shelf-life 	13.2 kJ/m ² , 26.4 kJ/m ² and 39.6 kJ/m ²	Sari et al. (2016)
11.	Spinach leaves	X-rays coupled with citric acid	<ul style="list-style-type: none"> Reduction in foodborne pathogenic microbes namely <i>E. coli</i> and <i>Listeria monocytogenes</i> Applicable for food sanitation purposes 	0.1, 0.2 & 0.3 kG y with citric acid (1%)	Jeon and Ha, (2020a)
12.	Lettuce	X-rays coupled with gallic acid	<ul style="list-style-type: none"> Improving microbial safety of food products Synergistic bacterial effect against <i>E. coli</i> 	0.1, 0.2 & 0.3 kG y with gallic acid (0.5%)	Jeon and Ha, (2020b)
13.	Peach	UV-B	<ul style="list-style-type: none"> Resulted aggregation of antioxidant components Exploitation as nutraceutical enhancing tool can be a possibility 	10.7026 W/m ²	Santin et al. (2018)
14.	Spinach	UV-A coupled with acetic acid	<ul style="list-style-type: none"> Reduction in growth of various foodborne pathogenic microbes like <i>Listeria monocytogenes</i> & <i>Salmonella</i> Typhimurium Improving microbial safety of fresh produce 	0.16J/cm ² with acetic acid (0.5%)	Jeong and Ha (2019)

and 1.5 kG y) strawberries. The study further concluded that doses of 1 and 1.5 kG y have an efficacy to increase the shelf-life and to reduce the weight and postharvest losses without much affecting the fruit TSS, pH and TA. Moreover, Vanamala et al. (2007) also revealed the positive effects of gamma irradiation on the grapefruit's quality. It was investigated that low dose of irradiation (0.3 kG y) maintained or increased the flavonoid content in the fruit pulp at the time of storage without adversely affecting its quality.

In addition, Wani et al. (2008) also demonstrated the influence of gamma radiation on the shelf-life of pears. In the study it was revealed that after the treatment (1.5–1.7 kG y) the decay of the fruit was delayed up to 16 days. Similarly, Niemira and Fan (2006) studied the effect of gamma radiation on different vegetables and revealed that exposure to gamma rays can effectively kills *Escherichia coli* thus extending shelf life of fresh produce. Feng et al. (2011) also recorded that gamma radiation at a dose of 2.8 kG y induces resistance of MuNoV in strawberries

resulting in 1.3-log reduction. The effect of gamma irradiation on different fruits and vegetables are mentioned in [Table 2](#).

5.2. X-rays

X-rays can be used as a more effective method for food preservation and to inactivate contamination causing microorganisms as it can pass through the thick materials (about 30–40 cm) and does not produce radioactive waste. Moreover, it has been stated that X-ray irradiation up to a dose rate of 10 kG y can be applied safely for lowering the population of pathogenic and spoilage micro-organisms ([Bisht et al., 2021](#)).

Specifically, [Jeong et al. \(2010\)](#) studied the effect of X-rays of lower energy (70 kV) on lettuce for inactivating *E. coli* 0157:H7. The study revealed that D_{10} -value at 0.04 kG y of X-ray was about 3.4 times less than that of the 0.136 kG y gamma-rays. Moreover, [Mahmoud et al. \(2010\)](#) also demonstrated that X-rays with a dosage of 2.0 kG y lowered the *E. coli* 0157:H7, *Shigella flexneri*, *Salmonella enterica* and *Listeria monocytogenes* by 5log CFU/spinach leaf.

Furthermore, [Mahmoud \(2012a\)](#) also concluded that X-ray can be applied for increasing shelf-life of parsley leaves without adversely affecting its quality parameters. The study revealed that the population of *Salmonella enterica*, *E. Coli* 0157:H7, *Shigella flexneri* and *Listeria monocytogenes* significantly reduced by 5.7, 5.8, 5.2 and 3.1 log CFU when exposed to X-rays at 1 kG y. In addition, this reduction was up to undetectable limits at 1.5 kG y. The effect of X-rays on different fruits and vegetables are mentioned in [Table 3](#).

6. Exposure of fruits and vegetables to different radiation doses

Food irradiation being a phytosanitary method for preservation of different fruits and vegetables is greatly influenced by various dose rate exposures. Furthermore, it is dependent on type of radiation used, storage period and temperature, composition of fruit or vegetable to be treated etc. Exposure of any food commodity to permissible limit prescribed for different ionizing and non-ionizing radiations is considered as the prior requirement for ensuring product safety and quality. Several existing studies have revealed a possible range of doses that can be applied to different fruits and vegetables for attaining a desired purpose without adversely affecting their physicochemical and nutritional parameters. Treatment of certain fresh produce with distinctive radiations and dose range followed by purpose of irradiation are listed below in [Table 4](#).

7. Consumer acceptance and commercial importance of irradiated fruits and vegetables

Currently, consumer demand for a tastier, fresher yet nutritious food and has led to a speedy growth in advancement of different food processing and production technologies. The advantages of various innovative techniques are very well known in providing a product with enhanced quality and shelf-life also followed by reduction in waste and occurrence of several foodborne pathogens. Moreover, these technologies also increase environment feasibility and acceptance of food products ([Castell-Perez and Moreira, 2021](#)). Even so, several limitations of emerging technologies like high pressure processing and pulsed electric field over food irradiation are well stated above, making it a more promising approach to attain the purpose of preservation.

However, consumer acceptance of irradiated products has always been a huge challenge. The major reason behind this fact is implication of word “radiation” in “food irradiation” thus turning into a major obstacle towards adoption of irradiated foods by consumers ([Prakash and de Jesús Ornelas-Paz, 2019](#)). Furthermore, consumers recognize probability of innovative techniques in a different manner as compared to the other experts, processors and producers. It has been observed that decision making attitude of consumer regarding food products is dependent on

feelings instead of facts. Thus, apart from lack of awareness, this comparative response of consumers towards irradiated products is a continuous challenge for food technologists. Nonetheless, the nutritional and safety acceptability of food irradiation cannot be questioned ([Castell-Perez and Moreira, 2021](#)).

Moreover, according to the reports of Coherent Market Insights (2021), global market of food irradiation will account for US\$ 298.1 Mn by end of year 2027 observing a CAGR of 4.9%. In addition, as per an estimate, the successful distribution of irradiated fruits and vegetables is about 20,000 tons every year, clearly signifying that further there can be a high-demand market for irradiated products ([Barkai-Golan and Follett, 2017](#)). Also, it has been mentioned that from the last few years, irradiated fruits and vegetables like mangoes, lychees, potatoes, citrus fruits, guavas, dragon fruits have been available in US supermarkets and received a positive response of consumers ([Prakash and de Jesús Ornelas-Paz, 2019](#)).

Consequently, food irradiation is still considered as a best technology for decontamination purposes of fresh fruits and vegetables but facing many obstacles due to poor consumer acceptance. Hence, there is a requirement of further studies in order to enhance the appeal and consumer acceptability of this promising technology. Food retailers and processors must continue to convey the accurate knowledge in favourable and positive manner so that perceived risks can be minimized leading to an enhanced and stable commercialization of irradiated fruits and vegetables ([Castell-Perez and Moreira, 2021](#)).

8. Conclusion

Despite the positive effects of conventional thermal (roasting, boiling, blanching) and certain non-thermal processing techniques like HPP, PEF, CPT in shelf-life extension and enzyme inactivation, their usage is frequently associated with a variety of vulnerabilities that have been already addressed in this review. Implementation of food irradiation as an emerging technology has recently sparked interest as a more effective and appropriate method, when compared to other thermal and non-thermal methods of food preservation, for minimizing postharvest losses in fresh produce and ensuring food safety in order to overcome quarantine and trade-related barriers in the international arena. It has been considered as one of the most dependable and safest strategies for preserving the physico-chemical, sensory, and nutritional aspects of many fresh horticultural products. It has demonstrated excellent efficacy in sterilization, inactivation of pathogenic and spore-forming microorganisms, delaying maturation and senescence process, leaving no chemical residue in the food, removing anti-nutritional components, and inhibiting food allergies without significant increase in temperature and coming into direct contact with the food material. This technology is applied to wide range of fruits and vegetables with excellent penetration and minimal quality loss in less time. However, such sophisticated technology continues to confront acceptance challenges owing to high capital costs, customer reluctance to accept irradiated food, localized radiation dangers, and unwanted flavour alterations caused by lipid oxidation. As a result, scientific evidence is still needed to increase commercialization.

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