UV-C Irradiation

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Amongst the surface treatment technologies to emerge in the last few decades, UV-C radiation surface treatment is widely used in food process industries for the purpose of shelf life elongation, bacterial inactivation, and stimulation.

Keywords: UV-C radiation ; stress response ; mechanical properties ; stimulation ; potato tuber

1. Introduction

The non-thermal technique is relatively fruitful for elongating fresh foods' shelf life. Nevertheless, its potentiality of adversely influencing sensory attributes has been highlighted [1][2][3][4][5][6][7]. Several non-thermal technologies for the treatment of food crops have come to emerge over the last few decades. This technology included irradiations (pulsed ultraviolet, gamma, and X-ray) pulsed electric field, pulsed electromagnetic field, cold plasma, ultra-sonication, microwave, supercritical technology, high-pressure processing, etc. [8][9][10][11]. In the classification of surface treatment, microwave surface treatment can be considered as either a thermal or non-thermal surface treatment depending on the intensity used [12][13]. It is reported that the irradiation technology is of high energy. Therefore, alongside its desirable effects, it is expected to induce undesirable alterations by interacting with different structures as well as chemical constituents of the potato tubers [14]. Among other different crop treatment techniques, such as gamma irradiation and fumigation [15], the UV-C radiation technique is one of the non-thermal technologies that is dominantly used for the surface disinfection and decontamination of crops and fruits and is by far regarded as effective [16]. UV-C radiation, emitted at wavelengths of 200–280 nm along with UV-A (320–400 nm) and UV-B (280–320 nm), is reported to be retained by the ozone layer. The different regions of UV radiation are shown in **Figure 1** [17][18][19]. UV-C radiation, because of its high absorption level by the ozone layer, does not penetrate the earth in any appreciable amount. The shorter the wavelength, the higher the energy of the photon as depicted from the Planck relation. This short wavelength carries a higher pocket of energy which is capable of destroying microorganisms by damaging the microbial DNA, causing cross-linking between neighboring thiamine and cytosine in the same DNA strand [20][21].

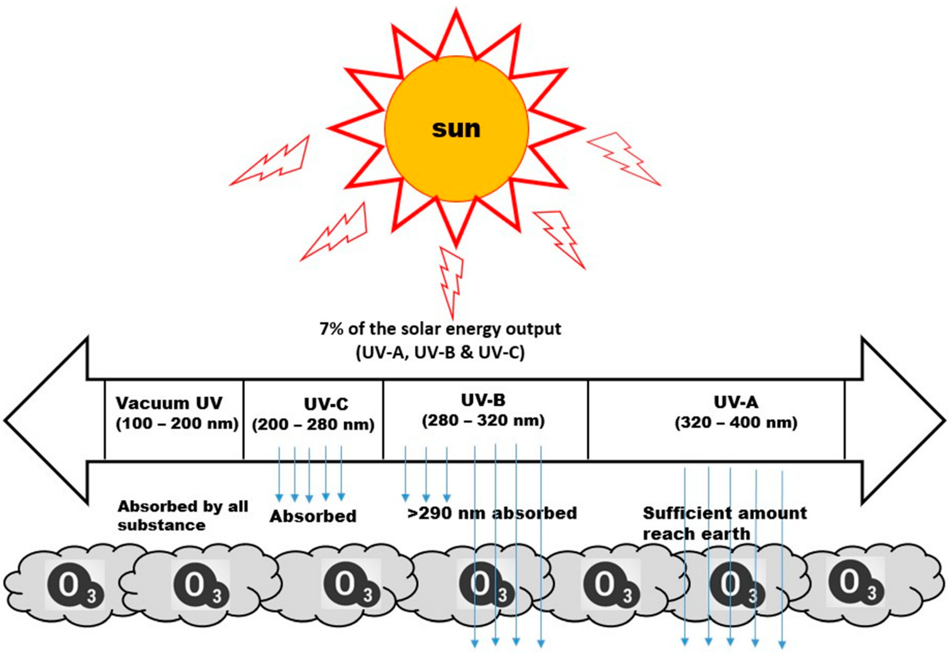

Figure 1. Different regions of UV radiation.

Even if this surface treatment has consent from Food and Drug Administration and other institutes as recognized disinfectant technology [22][23], it is important to study its impact on the characteristics of the crop. Numerous studies have already been focused on the bactericidal and fungicidal capacity of UV-C treatment in plant products, but information on product quality attributes is scanty. Limited studies have been reporting that short wave UV-C has a pronounced effect on plants' physiology and structure. It was reported that there induces a significant structural damaging effect on the plant cell, most specifically on the chloroplasts, mitochondria, and membranes [24][25]. The change in cellular structure is directly related to the overall alteration of the mechanical properties of the plant. This correlation is well described by a previous study conducted on the potato tuber cell structural parameters having a significant effect on the overall mechanical characteristics such as strength and modulus of elasticity [26]. Moreover, in the other study on UV-C exposed strawberries, cellular structural changes in relation to the physical properties of the fruit were studied stating that delayed softening and higher firmness are caused by changes in the activity of enzymes and proteins responsible for cell wall disassembly [27]. It was clearly stated that the change in mechanical characteristics of food derived from plants arises from three structural factors at the cellular level are turgor, cell wall rigidity, and cell-cell adhesion [28][29].

The mechanical characteristics of crops play a prominent role in deciding the acceptability in the chains of target users, such as food processing industries and people. Since plants are biological materials with complex structures that have high exposure to mechanical change, these changes can lead to irreversible changes in structure and other crop characteristics where these changes are reported to be invisible, having inner deformations [26]. Potatoes are the fourth-ranking food crop in the world in terms of calories and are extensively produced throughout the world [30][31][32]. The mechanical properties of the potato or derived products following surface treatment by irradiation during either growth or storage represent an imperative factor for meeting consumers' needs, as they are required for determining other properties when characterizing food qualities. Most importantly, one of the most important features here is the texture that potentially undergoes change, since external factors are concerned [33][34][35][36][37].

Studies have shown the influence of different physical treatment methods inducing a change in potato mechanical characteristics. Microwave treatment methods have found extensive applications in various processing and operations [38][39][40][41]. Studies have demonstrated their influential effects on the texture, compression test, weight loss, morphological, and microstructural changes of potatoes [42][43][44]. In the process of extending the shelf life of potatoes, gamma radiation is also an important facility nowadays. Several studies on the effect of gamma irradiation on physicomechanical properties of potatoes have been carried out on different potato cultivars for the evaluation of sprout weight, appearance quality, texture, specific gravity, morphology, puncture test, shear test, and compressive tests at varied dosses ranging from 0.04 to 100 kGy under different storage conditions [14][45][46][47][48]. From the result, Gamma irradiated resulted in an intact, rigid cell wall, more cavities, and bigger lamellar structure. At lower dose, mechanical properties were maintained, and sprouting was inhibited, while increased specific gravity at higher dose was also indicated. Texture was reduced with increasing dose, and the appearance of potato tuber was firm and slightly shrivelled. One of the non-destructive evaluation techniques is an ultrasound that applies a low range of intensities (0.1–20 kHz), but higher intensities (20–100 kHz) are reported to alter the physical, mechanical, and structural characteristics of starch granules derived from potato [49][50]. The results indicated that the sonicated potato tubers showed a change in molecular order in the crystalline region. A transparent appearance of the potato starch was also found. The effect of pulsed magnetic field treatment on the firmness, energy for cutting, and smoothening of the surface of potato was investigated at lower pulses ranging from 1 to 2.5 kV. It was concluded that firmness and energy for cutting were reduced while smoothening of the surface increased [8][51].

2. Influence of UV-C on the Physical and Mechanical Properties of Different Crops

UV-C surface treatment technology is a set of techniques by which a specific wavelength of 254 nm is delivered from a source for the purpose of microbial inactivation, disinfection, and stimulation. The short wave carries a pocket of energy necessary to inhibit microorganisms from the surface of the product by developing defense mechanisms. However, the application is highly dose dependent and results a positive and negative impact on the mechanical properties of the given product. In the quest of the current state of the art, a number of findings were reported in different types of products and varieties as well. It is apparently clear that the UV-C effect on the plant products is highly dependent on UV-C dose.

2.1. Physical Properties

With a specific focus in food characterization, textural profile analysis (TPA) offers comprehensive properties important to the acceptability of a product by the end user. A wide set of parameters traced from TPA analysis includes hardness, cohesiveness, viscosity, elasticity (springiness), adhesiveness, resilience, brittleness (fracturability), chewiness, and gumminess. This is one of the most important parameters as far as the UV-C stimulation is concerned with the cell physiology. The properties of firmness, hardness, and change in mass are critically assessed as they are greatly influenced by the anatomy of the plant tissue, the strength of the cell wall, and ultimately other mechanical properties. It is one of the most important parameters when it comes to UV-C stimulation and cell physiology [52].

The firmness of bell pepper fruit treated at 0.25 kJ·m^{-2} and its control sample significantly dropped at the initial storage period, but after seven days of storage the UV-C treated sample was found to be firmer than the control. A weight loss experiment in the same fruit resulted in lower weight loss in the treated sample [53]. An experiment on the UV-C treated in green asparagus confirmed an appreciable increment in tissue toughness and a significant increase in cutting energy (sheer force) even at a lower UV-C dose of 1 kJ·m^{-2} and 8 min exposure time [54]. Conversely, a low UV-C dose up to 3.8 kJ·m^{-2} is indicated to have an insignificant change in textural properties [55]. Observations on the fresh-cut melon after UV-C exposure confirms no significant difference in the firmness as a result of UV-C application at 1.2 kJ·m^{-2} followed by storage at 6 °C [56]. No significant difference was observed among treated and control samples in delaying softening at a lower UV-C dose. The research work on the firmness and weight loss characteristics of UV-C exposed fresh-cut apples were analyzed by different authors and resulted in no significant change in the firmness [57][58], while a decrease in weight loss by 6% was noted at an exposure time of 1 min and intensity of 1.2 kJ·m^{-2} UV-C [57]. For fruit crops, weight loss is an important parameter as it is associated with dehydration, which significantly determines the commercial value of the fruit. The weight loss of amaranth vegetables treated at a moderate UV-C dose of 1.7 kJ·m^{-2} reduced the weight loss significantly better than the control [59]. The weight loss experiment on different UV-C exposed tomato cultivars, namely "cherry tomato" and *Elpida*, showed no effect and reduced weight loss when treated at 3.7 kJ·m^{-2} and 4 kJ·m^{-2}, respectively [60][61]. It was depicted that a lower UV-C dose of up to 4 kJ·m^{-2} has a minor effect on the firmness of tomato [62] and blueberry fruits [63]. The firmness value of different tomato cultivars was enhanced when exposed to UV-C treated in the range of 3 kJ·m^{-2} to 4.2 kJ·m^{-2} [60][61][64][65][66][67]. An experiment conducted on the quality parameters of UV-C exposed pineapple at the dose of 4.5 kJ·m^{-2} over the range of 0–90 s and followed by a 10 °C storage condition was able to retain the firmness properties better than the control samples [68]. Exposure to 7.11 kJ·m^{2} induced higher tissue softening in lettuce and caused the development of abnormal color in cauliflower [69][70].

Research work on a comparative study of the effect of UV-A and UV-C over the temperature range of 25–100 °C on oyster mushrooms reported UV-C exposed mushroom samples had a higher increase in loss modulus and loss factor than that of UV-A exposed ones. From the outcome, it was concluded UV-C light had a greater impact on the mechanical properties of oyster mushrooms compared to UV-A light [71]. Storage modulus was lower for the samples exposed to both UV-A and UV-C, indicating the samples had a viscoelastic characteristic.

In the quest for the previous state of the art, the most decisive factor was found to be firmness, which was studied dominantly following the UV-C irradiation and storage. It was also noted from recent research that firmness is an important sensory characteristic for consumers and is the factor that is highly affected by mechanical processes that potentially induce the ejection of intracellular fluid due to tissue rupture [72].

The textural aspect of mechanical property is dominantly used in the processing, as well as with raw vegetables and fruits, which is connected with the rheological characteristics of biological materials called firmness or hardness. It expresses the maximum force required to attain a specific strain in compression, puncture, and cut tests [52][73].

2.2. Mechanical Properties

Mechanical properties of harvested vegetables and fruits are important characterization throughout processing, storage, and consumption. Mechanical properties may be defined by cell structure and are dependent on the physical state, flow properties, and porosity. In the light of measurements, force-deformation methods are commonly used in textural or mechanical properties of solid foods, fresh vegetable/fruit, and their derivatives in their solid state. The basic mechanical properties that are determined from the force-deformation includes rupture force, toughness, cutting force, shear force, and strength [74], which are effective for different purposes, such as product standardization, transportation, handling, and design purposes as well. If researchers take account of the dimension of a product in the mechanical testing, stress–strain characterization, for example, can be used and some important properties can be obtained from the result of this test, such as yield strength, Young's modulus, ultimate strength, and modulus of elasticity.

Recent research conducted intensive work on mechanical changes of UV-C irradiated strawberries at a varied irradiation dose of 0.8, 2, and 4 kJ·m^{-2} by changing the storage duration from 0 to eight days at 0 °C. Resistance to compression, crush resistance, and distance to tissue failure attributes dropped significantly during storage. According to the author, the resistance to compression was higher at a lower UV-C dose. At 2 kJ·m^{-2} and 4 kJ·m^{-2}, tissue deformation reported a higher value [75]. In the latest work on the effect of UV-C irradiation on some of the mechanical characteristics of blueberries *'O'Neal'* a puncture test was performed at UV-C intensities of 5.3, 8.3, and 11.4 kJ·m^{-2}, exposure time of 7, 11, and 15 min, and storage time from 0 to 15 days. According to the report, mechanical parameters were not affected by

UV-C treatments until 15 days of storage time when irradiated samples showed higher values of rupture force, deformation, and weight loss [76]. In a related study, a compression test (stress –strain) was performed on UV-C exposed fresh-cut apples at an exposure time of 10, 15, and 25 min and UV-C intensity at 5.6, 8.4, and 14.1 kJ·m^{-2}. True stress and deformability modulus were noticeably reduced at lower exposure time and UV-C dose [58]. The effect of UV-C on the mechanical characterization as well as the dimensions (length, width, and height) of *Faba* bean during storage was studied by considering various UV-C exposure times (0, 30, 60, and 90 min) and during storage periods of 0, three, six, and nine months. The result indicated that main dimensions, mass and bulk volume, and true volume were decreased by increasing the storage period and decreasing ultraviolet irradiation time. UV-C irradiation time increased with reducing the storage time, although, length and thickness decreased slightly. From this research, very important mechanical tests, such as shear force and shear penetration, were also investigated on the UV exposed *Faba* bean. The authors described the decrement of both the sheer force and penetration force of seed as UV-C exposure time increased during the given storage time [77]. The mechanical properties of different UV-C irradiated plant commodities are briefly presented in **Table 1**.

Table 1. Mechanical and related characteristics of UV-C exposed plant products.

Commodity	Operational Condition	Key Finding	Reference
Sweet corn kernels	**UV-C dose at 0. 1.94, and 4.01 kJ·m^{-2}, controlled atmosphere of with %oxygen: %carbondioxide: %nitrogen ratios of 21:0.03:78, 3:10:87, and 3:15:82 at 6 °C for 20 h.**	**Hardness remains unchanged**	[78]
Fresh-cut green onion	**UV-C exposure time at 3, 5, 10, and 15 min and storage days of 5, 10, 15 days and storage temperature of 5 °C.**	**Higher UV-C exposure results in higher weight loss (%).**	[79]
Tomato (*Lycopersicon esculentum* L.)	**UV-C dose 3.7 kJ·m^{-2} from 0 to 25 days of storage duration time at 16 °C and relative humidity of 95%.**	**Firmness (Newton) decreased with storage duration. Higher resistance penetration compared to the control sample.**	[80]
Cucumber (*Cucumis sativus* L.)	**UV-C dose of 4.5 kJ·m^{-2} stored for 15 days at 4 °C, a combination of UV-C with Nano-coating Nanocapsules.**	**The UV-C control sample brought better firmness, as the loss was delayed to day 9 of storage.**	[81]
Peeled garlic (*Allium sativum* L.)	**UV-C dose of 2 kJ·m^{-2} stored for 15 days at room temperature.**	**High firmness value with the UV-C treated sample.**	[82]
Cherry tomato	**UV-C dose of 3.7 kJ·m^{-2}**	**UV-C treated and control sample both mass loss and firmness were unaffected.**	[60]
Tomato *(Lycopersicon esculentum* L.)	**UV-C dose of 4.2 kJ·m^{-2} for 8 min**	**The firmness decreased gradually during storage in both the control and UV-C treated tomatoes.**	[67]
Common dandelion and purple coneflower	**UV-C dose of 3.8 J·m^{-2}, 1 m of distance from light source, 10 to 120 exposure time, and 21 days of storage period.**	**Fresh and dry weight loss recorded for both dandelion and purple coneflower is higher than the control sample.**	[83]
Strawberry	**UV-C dose of 1.70 kJ·m^{-2} for 4.8 min and Storage duration of 0, 2, and 4 days at 21 °C.**	**No difference in firmness between fruit from control and UV-C-treated samples.**	[84]
Mango (*Kensington Pride*)	**UV-C dose at 4.0, 8.3, and 11.7 kJ·m^{-2}), room temperature (20 ± 1 °C), relative humidity at 80%, and ethylene storage duration from 3 to 12 days.**	**At a higher UV-C dose, the firmness is significantly higher than untreated fruits after 6 days of storage. No significant difference in weight loss with the control sample.**	[85]
Tahitian lime (*Citrus latifolia*)	**The doses were 3.4, 7.2, and 10.5 kJ·m^{-2}. Fruits were located 20 cm from the UV-C light source.**	**Higher dose (10.5 kJ·m^{-2}) reduced weight loss.**	[86]
Mango (*Tommy Atkins*)	**UV-C dose of 8220 mW·m^{-2} and exposure time of 10 and 20 min. and storage temperature 5 and 20 °C**	**Lower weight loss and high firmness for Samples exposed to 10 min and 5 °C.**	[87]

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