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ORIGINAL PAPER

Mechanical and surface properties of semifinished potato tuber exposed to UV-C radiation at varied operational parameters

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Abstract
The current study aimed at investigating the effect of certain operational parameters of UV-C radiator on the selected mechanical properties of semifinished potato tuber. Innovator potato variety was selected for the preparation of semifinished potato strips. The prepared potato strips were stored for 24 h following exposure at the desired storage condition. The irradiation experiment was carried out using a UV-C chamber at varied UV-C doses, Mode of exposure, and distance from the radiator. UV-C dose has a pronounced effect over the other tested parameters. Samples subjected at 60 mJ/cm^2 resulted in higher resistance to compression and bending force while the resistance to cutting force was enhanced at a lower UV-C dose (15 mJ/cm^2). Mechanical properties were not significantly impacted by the mode of exposure and distance from the light. Furthermore, the Morphological and microstructural properties of the sample were examined using SEM and AFM resulting in alteration in granule size, spacing, and roughness of the irradiated samples.

Keywords UV-C · Mechanical properties · Potato tuber · Semifinished

Introduction

Mechanical properties of postharvest products are the most decisive factors in determining the quality of the products and have a direct influence on the acceptability of the consumers [1, 2]. However, without the intervention of surface treatment, the stability of texture could be maintained for a very short period of storage and the qualities usually degraded quickly after harvest [3]. The texture of postharvest products is defined as a measure of the force required to shred a bulk sample [4]. Ultraviolet-C (UV-C) is considered as a safe, effective, and economical treatment that can be used to maintain the postharvest quality of fruit and vegetables during storage [5, 6]. UV-C surface treatment is currently approved technology and is extensively used to extend the shelf life of fresh products. The result obtained from the effect of UV-C on the textural properties of fruit indicates that UV-C radiation, at an appropriate dose, combined with low storage temperature (10 °C) is an effective method to preserve the postharvest life of tomato, without adversely affecting the quality parameters [7]. This alternative method has a germicidal effect by inducting a resistance against microbial and improving the overall properties of products such as delaying softening, control of fruit decay, accumulation of antioxidants, phytoalexins, and phenolic compounds [8–10]. In addition to the commercial benefits of treating fruit with UV-C, it promotes a beneficial effect on human health that is vital for chronic health conditions [11]. UV radiation is responsible for the production the generation of defensive enzymes like phenylalanine ammonia lyases (PAL), [12], chitinases, and β-1,3-glucanases [13, 14]. In addition to this, UV-C is indicated to be involved in modifications in fruit surface cell walls [15]. A study highlights the penetrating effect of UV radiation on the external and inner tissue of the cell wall in relation to the textural properties of fruit [16]. The involvement of UV-C in the ripening process and the role of the cell wall degrading enzyme were studied. Consequently, it was found that UV-C has an impact in retarding the cell wall degrading enzyme and maintaining firmness. There is a research gap regarding the mechanical aspects of UV-C exposed semi-processed or fully processed products, creating an unexplored area for research. The ongoing research will serve as a significant

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contribution to enhancing UV-C surface treatment technology by investigating its potential influence on the mechanical properties of potato tuber.

Potato tubers, known for their widespread popularity and as a top product in the frozen food market, are among the most commonly consumed vegetable crops worldwide [17]. They are produced for end-users in various forms, often processed into semifinished products. The application of UV-C in maintaining potatoes and their derivative product has been inevitable. Intermediate products of potatoes nowadays are substantially utilized by different industries to convert them into diversified finished products. Studying the mechanical characteristics of semifinished products is critical because of its direct influence on thermally processed potatoes including blanching, drying up, and frying [18].

Different methods were employed to study the mechanical characteristics of vegetable fruits. Dynamic mechanical analysis (DMA), and other various techniques have been used to study the mechanical properties of food and vegetable crops including stress testing machines and dynamic mechanical analysis [19, 20]. Textural parameters are crucial sensory attributes measured by Textural Profile Analyser (TPA) used to determine properties such as hardness, consistency, viscosity, elasticity, adhesiveness, gumminess, and chewiness [18]. Surface mechanical properties such as hardness, distance to failure, and resistance to compression of strawberries exposed to UV-C were studied in relation to cell wall degradation [21]. Some related works on the effect of UV-C on different properties of intermediate potato tuber were reported and the need to correlate with findings is important, as mechanical properties are the result of physiological and chemical modification and transformations. An investigation on the fry fat content of the intermediate product as a result of UV-C exposure led to a significant amount of fry fat [22]. In a similar sample type, the author studied the effect of UV-C, storage time, and the mode of stimulation on the density of the intermediate strips [23]. The acrylamide content of Semifinished potato tuber exposed to UV-C irradiation brought a considerable increment as reported by the latest related articles [24]. Nonetheless, the examination of UV-C's impact on partially processed foods is quite limited in the existing literature. Specifically, there is a notable absence of research on semi-processed potato strips elsewhere. This is a matter of concern for the authors, given the high demand for semifinished products in the frozen food market, and studying the potential effect on the semifinished products will ensure the quality of finished products. Therefore, this study explores the key process parameters of UV-C treatment and their relationship with mechanical properties, while also examining any associated morphological changes. The current research work aims to study the effect of operational parameters (UV-C dose, mode of exposure, and distance from the light) on the selected mechanical properties of the semifinished potato tuber and to further study the morphological and microstructural changes.

The purpose of this study is to give a way forward in the technological improvement of UV-C irradiation treatment through the application of appropriate doses and related operational parameters. The study also provided a hypothetical correlation between cellular change and the selected mechanical properties by understanding the abundant literature on biochemical synthesis at the cellular level. It is therefore reasonable to investigate this phenomenon and its possible impact on mechanical properties, as it is crucial in the whole supply chain.

Materials and methods

Sample preparation and characterization

Potato tubers of the Innovator variety were used as raw material for the preparation of potato strips due to better mechanical properties over some other Polish potato varieties [25]. The Innovator variety belongs to the most commonly used varieties for French fries production by European, including Polish, companies. It is an early variety of culinary type B with regular round-oblong tubers, shallow eyes, and a medium content of starch (14.6%) [23]. Before experiments, Tuber was directly stored in a cold environment in a single layer on the mesh surface with a storage temperature of 10 °C, in the dark, and air relative humidity of 90%–95%. Before preparation, the tubers within the required dimension were thoroughly washed with water. The mass of the tubers was weighed using the AS310.R2 analytical scale ($d = 0.1$ mg) before and after the removal of the periderm as presented in Table 1. Potato tubers were peeled manually and cut out into strips using a manual adjustable French fry cutter. The dimensions of potato tuber strips and other characteristics are presented in Table 1. The strips cut out along the longitudinal tuber axis between the proximal and distal tuber ends.

Table 1 Characteristics of potato tuber and semifinished sample

Characteristics	Value
Raw tuber	
Raw tuber mass (g)	212 ± 44.5
Peeled tuber mass (g)	191.9 ± 42
Diameter (cm)	5.4–7.3
Semifinished product	
Mass (g)	12.23 ± 1.08
Length (cm)	6
Cross-sectional area (cm^2)	1

UV-C station

A UV-C NBV15 radiator was used with a light wavelength of 253.7 nm, power of 15 W, and power density of 100 μW·cm^{-2}. The lifetime of the NBV15 radiator assuring operational parameters is 8000 h. The radiator is equipped with a reflector made of high-quality aluminum with a high reflection coefficient. The 2D pictorial representation is shown in Fig. 1. The irradiation setup and procedures were performed according to Jakubowski 2019 [26]. Potato strips were exposed to varied UV-C doses (15 to 105 mJ/cm^2) which is measured in terms of intensity and exposure time as per Eq. (1), and the height of the UV-C radiator above the surface was varied from 10 to 40 cm. The semifinished potato strips were irradiated at different modes of exposure as one side, two sides, three sides, and four sides designated as Mode 1, Mode 2, Mode 3, and Mode 4. The exposed and control samples were directly immersed in water [27] for 24 h and kept in a cold environment at 4 °C until a mechanical test was performed.

$$\text{Dose}\left(\text{mJ/cm}^2\right) = \text{Intensity}\left(\mu\text{W}\cdot\text{cm}^{-2}\right) \times \text{exposure time (sec.)} \tag{1}$$

Mechanical characteristics

The universal testing machine MTS insight 2 was used in compliance with ASTM D695-15 for the determination of rupture force under stress (compression, cutting, and bending) of the UV-C exposed samples and control samples [28]. Semifinished potato strips were placed between the compression plates (Fig. 2A) at their center position and the testing was performed by applying the tension from the moving head until it reached the fracture points. The testing was equipped with a 2000N compression load cell for compression test. The crosshead was set at a constant speed of 30 mm/min. Then the crosshead moved at the test speed until it reached a strain corresponding to the strain endpoint input. The cutting test was performed with a similar setup except for the probe/fixtures used and the distance of penetration. The blade (Fig. 2C) is set with a knife comprising a Warner Bratzler blade (a reversible blade with knife-edge) inserted in an adjustable blade holder and fixed in a Universal testing machine. The slotted blade insert was located directly into the heavy-duty platform and acted as a guide for the blade whilst providing support for the product. The distance setting was set according to the tuber size so that it cut fully. The testing was equipped with a 25N cutting load cell. The bending test for this experiment was used to analyze the behavior of semifinished potato strips subjected to simple beam loading. The potato strip specimen was placed on two support anvils and bent through applied force on a single loading anvil directed at the center of the sample along the longitudinal direction as shown in Fig. 2B. The test speed was maintained at 30 mm/min with a bending load cell similar to the cutting test. The force deformation curve of three replicate samples was obtained for UV-C-treated semifinished potato strips and control samples. Each test was reported in terms of the average ultimate yield (For uniaxial

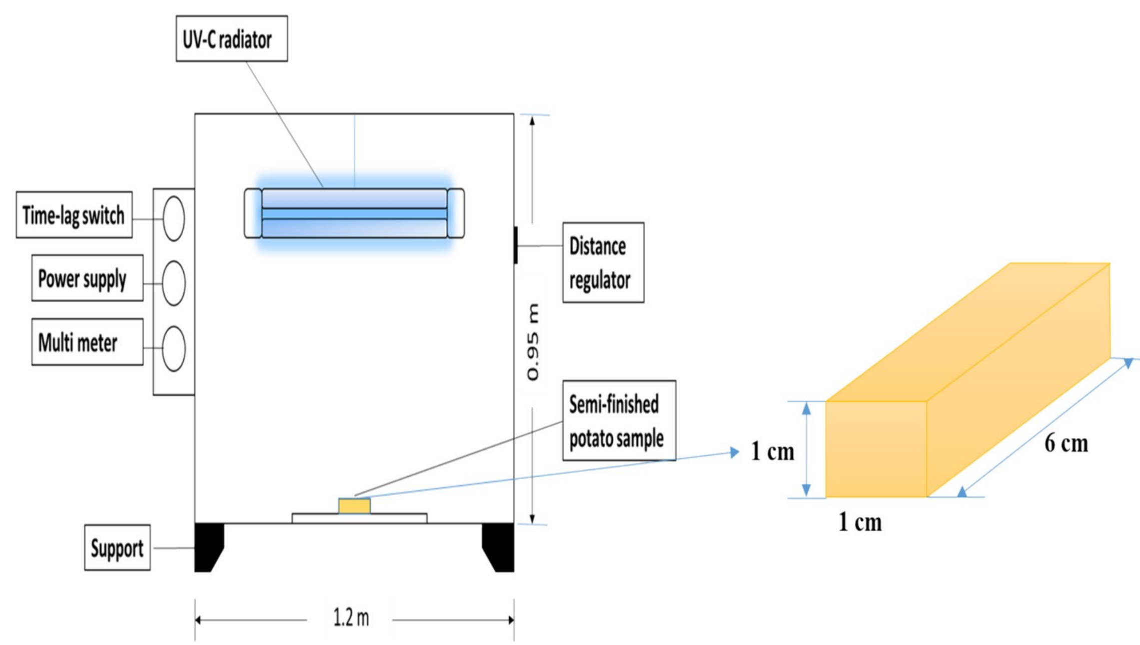

Fig. 1 Experimental set-up for UV-C station

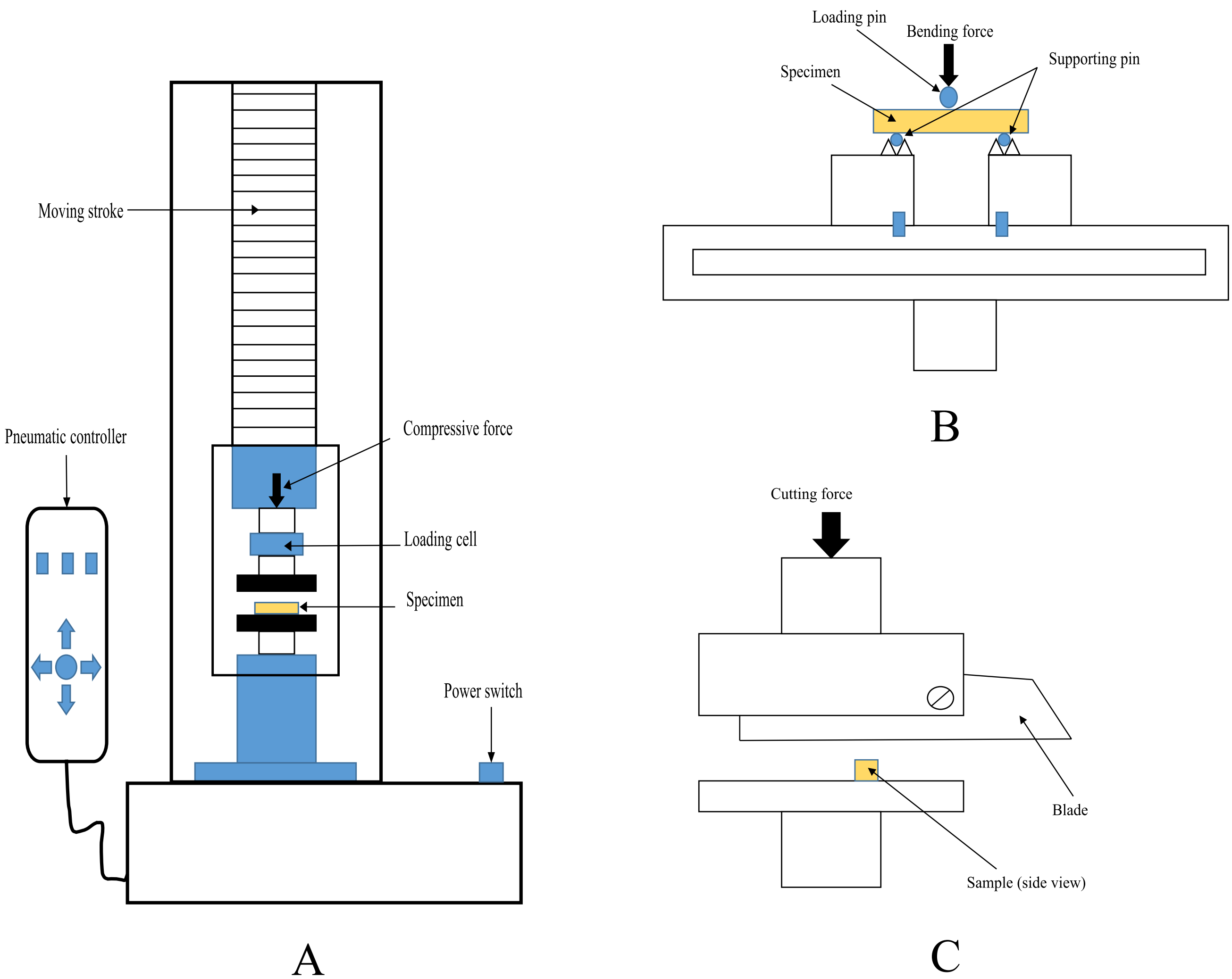

Fig. 2 Mechanical tests set up for **A** compressive force with full setup, **B** bending force, and **C** cutting force

compression tests, the data from the load-extension curve were peak stress) for three replicates and standard deviation. Stress–strain analysis was also generated for the selected test data.

Statistical analysis

The results of mechanical properties obtained from the different experimental runs were statistically analyzed by means of analysis of variance (ANOVA). The experimental design consists of three factors (Dose, Distance from the light, and mode of exposure) and three dependent variables (compressive, cutting, and bending force). The normality of data was checked by the Shapiro–Wilk test. The evaluation of the difference of means was carried out by the one-way ANOVA. The data were expressed as means ± SD (standard deviation) of a triplicate run in each experiment and presented using an error bar plot. The test results were considered significant only after reaching $P < 0.05$. The compression, cutting, and bending tests of the irradiated sample were compared with the control sample, and multiple comparisons were performed using the Tukey test. The statistical analysis and graphical plot were performed using RStudio version 2022.07.2 + 576 and OriginPro 2019b version 9.6.5.169.

Microscopic analysis

Scanning electron microscopy (SEM)

The surface morphology of the semifinished potato tuber of selected samples was subjected to SEM analysis. SEM images for the control sample (0 mJ/cm^2) were also analyzed for comparison. Sample morphologies were analyzed using the SEM/FIB Quanta 3D 200i (FEI) microscope. Samples were coated with a 15 nm thick carbon layer at an acceleration voltage of 10 kV or 20 kV Resulting in currents from 4.7 nA down to 0.2 nA and 10 mm working distance. An image with several magnifications was registered for the longitudinal (surface) and cross-sectional side of the strip. The particle size and distributions was calculated using the ImageJ (version 1.54d) software [29].

Atomic force microscope (AFM)

The surface microstructural analysis of semifinished potato tuber treated at different doses and control samples was characterized using an AFM technique. AFM topography images were obtained with Dimension Icon XR microscope (Bruker, Santa Barbara, CA, USA) working in the air in the Peak Force Tapping (PFT) mode, using standard silicon cantilevers with a nominal spring constant of 0.4 N/m, triangular geometry tip and nominal tip radius of 2 nm. Roughness measurements were generated in several areas of 1 × 1 µm. Surface topography and profiles were also measured. Image visualization and roughness parameter was determined and analyzed by using Gwyddion 2.63 [30].

Result and discussion

UV-C dose

The effect of UV-C dose on the mean compressive force, cutting force, and bending force were studied as shown in Fig. 3A–C. As can be depicted from Fig. 3A compressive force tends to be higher at moderate doses. Samples treated at 15, 30, 45, and 105 mJ/cm^2 are not different from the control sample. Samples irradiated at 60 mJ/cm^2 followed by 75 mJ/cm^2, and 90 mJ/cm^2 showed a superior compressive force resulting in 770.60 ± 14.35N, 752.14 ± 46.53N, and 742.62 ± 31.09N, respectively and are different from the control sample and samples treated from 15 to 45 mJ/cm^2 and 105 mJ/cm^2. The most notable result is that the sample treated at 60 mJ/cm^2 measured the highest resistance to compressive load and was statistically different from the whole treatment and the control sample.

Figure 3B shows the effect of UV-C dose on the mean cutting force. Potato strips treated at lower doses of 15 mJ/

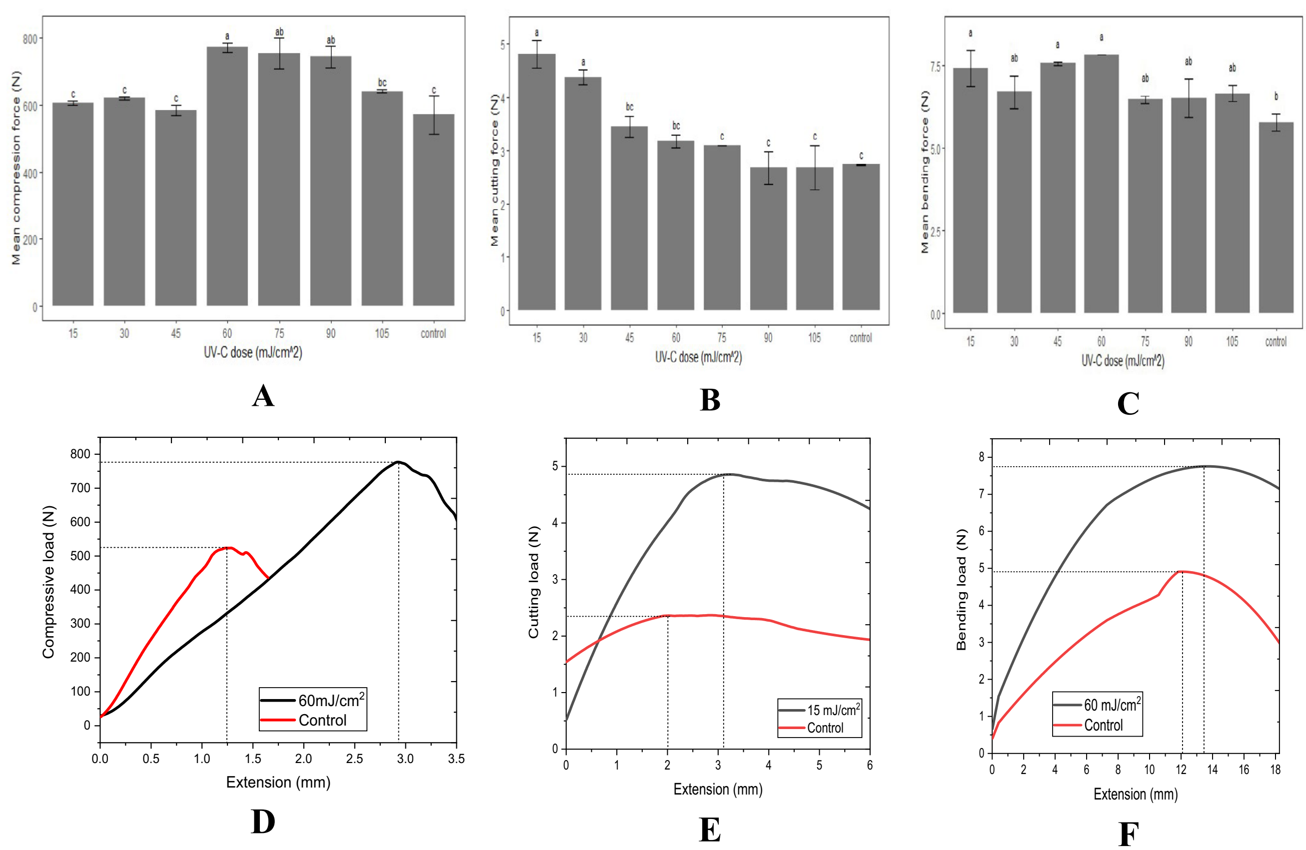

Fig. 3 Effect of UV-C dose on **A** mean compressive force **B** mean cutting force and **C** bending force at two sides exposure and 20 cm distance from the light. Different letters indicate significant differences based on a Tukey test at a significance level of $\alpha = 0.05$. Load-extension graphical plot for **D** compressive load treated at 60 mJ/cm^2 **E** cutting load treated at 15 mJ/cm^2 and **F** bending load treated at 60 mJ/cm^2

cm^2 and 30 mJ/cm^2 resulted in superior cutting resistance and are different from all other treatments including the control sample. The corresponding value of the cutting force is 4.8 ± 0.25N and 4.37 ± 0.14N at 15 mJ/cm^2 and 30 mJ/cm^2, respectively. The remaining samples treated from 45 to 105 mJ/cm^2 are not statistically different from the control sample. preliminary research on the effect of UV-C dose on different potato varieties indicated a similar trend of resistance to cutting load and enhancement of cutting load at a lower value (7.5 mJ/cm^2) [25].

Bending characteristics are one of the most important characteristics that the potato strips experience during storage as it has a longer longitudinal dimension as compared to the lateral dimension. The influence of dose on the mean bending force is depicted in Fig. 3C. Samples treated at 15, 45, and 60 mJ/cm^2 resulted in higher bending force measured at 7.41 ± 0.54N, 7.55 ± 0.04N, and 7.817 ± 0N, respectively. Statistical analysis provided that samples treated at 15, 45, and 60 mJ/cm^2 are different from the control sample.

It is noted that the UV-C dose between 15 and 60 mJ/cm^2 could be considered as appropriate doses for resistance of the applied mechanical load. The higher compressive force at a lower dose is due to the induction of a defense response mechanism and increases resistance against foreign attacks by inducing the biosynthesis of large amounts of chemicals [31]. This action to resistance mechanism might give rise to the resistance to deformation and mechanical injuries. A similar result was noted in a previous study on potato tuber exposed to 69.4, 86.3, and 171.9 µW.cm^2 showing lower deformation (higher resistance to impact) as compared to the control sample [22]. It was reported a mechanical characteristics are the result of cellular change and rheology [32], which is discussed in Sect. "The role of biochemical synthesis in defense response mechanism". A previous study conducted the effect of soaking UV-C-exposed potato sticks and reported a decrease in acrylamide content. For this reason, water-soaking assisted UV-C exposure was applied in this study due to its lower sugar and lower acrylamide content [22].

Further analysis of the mechanical characteristics was extracted in load vs extension properties (Fig. 3D–F) for those samples that recorded the highest mechanical properties.

Young's modulus (Eq. 2) describes the relative stiffness of a material, which is measured by the slope of a stress and strain graph. It is calculated by the ratio of stress (N) value to its corresponding strain value (mm^2).

$$\text{Young's modulus} = \text{Stress}/\text{Strain} \quad (2)$$

The treatment method of UV-C at 60 mJ/cm^2 increased the resistance to compression by ~ 26% compared to the control sample (Fig. 3D). The control sample resulted in Young's modulus of 424.34 N/mm^2 is higher than the UV-C treated sample (249.96 N/mm^2) indicating the stiffness properties and deformation at lower extension. The UV-C exposed sample was able to resist the compressive load and deformed at a higher ultimate strength. Similar results indicated the lower modulus for the samples exposed to UV-A and UV-C irradiation, showing a viscoelastic characteristic [1].

Figure 3E shows the cutting stress against an extension for the sample irradiated at 15 mJ/cm^2. A considerable improvement in the resistance capability of cutting load was observed. A lower dose at 15 mJ/cm^2 brought the resistance to cutting load by ~ 43.14%. Cutting test is associated with the change in tissue structure by sheering /cutting at a specific point. A lower dose is reported by several researchers to have an advantage in key textural parameters such as delayed softening, maintained firmness, and most importantly higher hardness [33–36]. The bending load against the extension is shown in Fig. 3F. The ultimate yield is far higher than the control sample. Exposing the sample at 60 mJ/cm^2 increased the resistance to bending force by ~ 26%. The stiffness of the irradiated sample was higher for cutting and bending stress.

Mode of exposure

The mode of exposure determines the number of surfaces exposed by irradiation. Exposing the sample at different sides increases the irradiation area. The result obtained for the impact of the type of exposure on the mechanical properties is demonstrated in Fig. 4A–C. The value of mean compressive force (Fig. 4A) at a constant dose on the three lateral sides shows the highest result (871.25 ± 75.35 N), which is different from the control sample with a mean compressive force of 642.80 ± 23.32 N. This particular result is comparable to the previous study carried out on the investigation of acrylamide content on UV-C exposed semifinished samples depicting three side exposed samples was significantly different [24]. Figure 4B shows the effect of different modes of exposure in mean cutting force showing sample treated at three and four sides of the strip is different from the control sample; however, lower resistance was recorded by the treated sample. The mean bending force is not different between the control sample and treated samples as shown in Fig. 4C. The mode of exposure at a different side of the potato strips resulted in almost no significant change that might be related to the efficiency of the wall given a uniform reflection at any angle of the chamber. However, exposing the sample to three sides could increase the compressive strength.

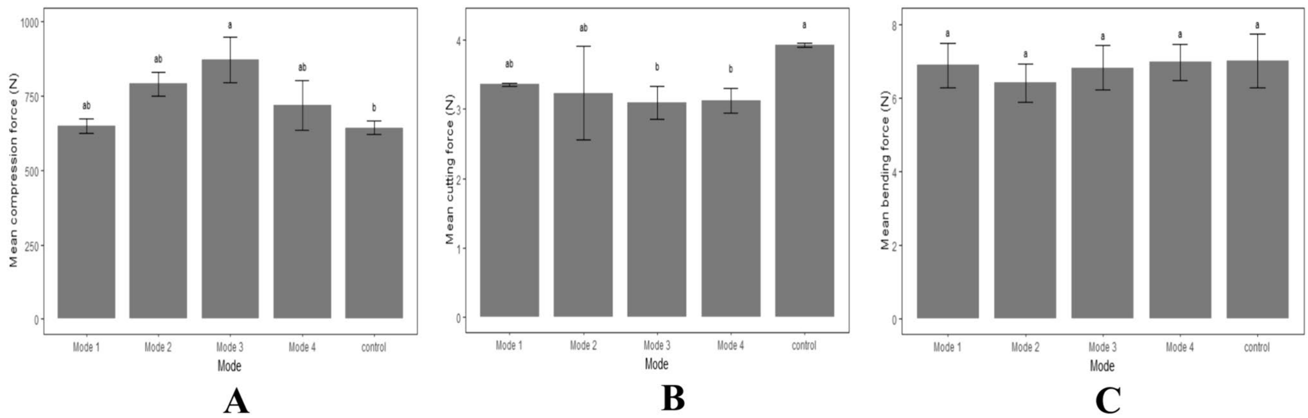

Fig. 4 Effect of mode of exposure on **A** mean compressive force **B** mean cutting force and **C** mean bending force at 60 mJ/cm^2 and 20 cm distance from the light. Different letters indicate significant differences based on a Tukey test at a significance level of $\alpha = 0.05$

Distance from the light

The geometric configuration of UV-C irradiation onto a given sample is one of the factors affecting the efficacy of UV-C treatment. Distance from the light is one of the key factors reported to affect the performance of the irradiator [2, 37, 38]. As the distance from a point source of radiation increases, the irradiance decreases. Statistically, the mechanical properties are not different for mean compressive and bending forces as the distance from the light source increased from 10 to 40 cm. Figure 5A–C show the effect of distance from light on the mean compression, cutting, and bending force. The bending force obtained at a distance of 20 (5.93 ± 0.03 N) and 30 cm (6.23 ± 0.35 N) is different from the control sample (7.42 ± 0.37N). In addition, the bending force obtained from the sample exposed at 10 cm is the highest and different from the sample exposed at 20 cm.

Surface morphology

The morphology of the semifinished potato tuber was observed using SEM on different sides of the tuber strips**.** Figure 6 shows SEM image of the potato strip on its longitudinal side. Figure 7 is the SEM image for the potato strip cut in its cross-sectional area. SEM showed that UV-C surface irradiation changed the structure of the potato tuber. The sample treated at 0 mJ/cm^2 showed larger cellular tissue encapsulating the granules, a regular elliptical shape with slightly amorphous surfaces. Potato strips treated at 15 mJ/cm^2 exhibited a smoother surface but fine granules with slight dispersion out of the cluster. Further treatment of the sample at a higher dose (60 mJ/cm^2) induces certain cavities of tissues. Higher doses caused granule surfaces to appear rough and crimpy [39, 40]. A closer SEM image was analyzed at the higher magnification (1500x) in the same longitudinal surface as shown in Fig. 6D–F for samples treated at 0, 15, and 60 mJ/cm^2, respectively. A high level of granule integrity embedded in a matrix is observed in the

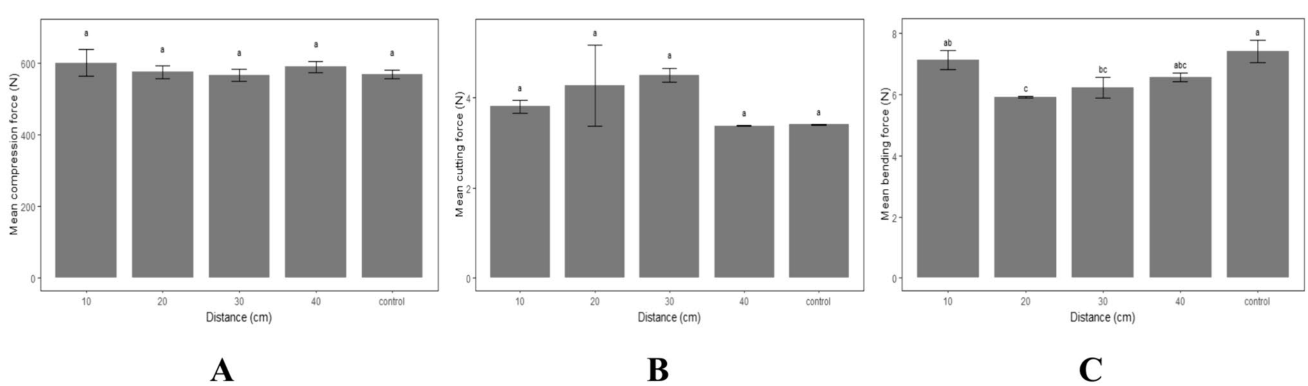

Fig. 5 Effect of distance from the light on **A** mean compressive force **B** mean cutting force and **C** means bending force at 60 mJ/cm^2 and two sides of exposure. Different letters indicate significant differences based on a Tukey test at a significance level of $\alpha = 0.05$

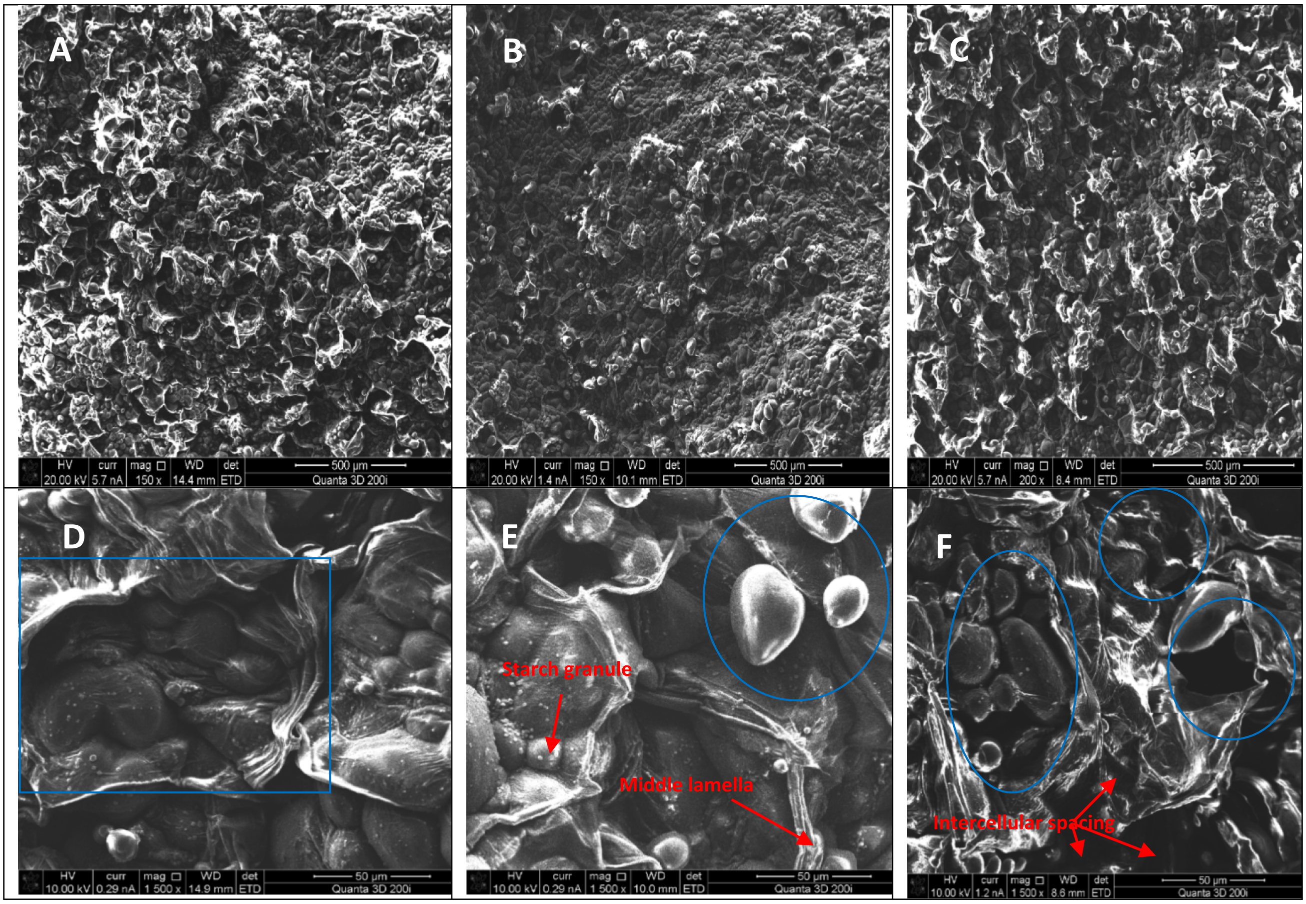

Fig. 6 SEM image in the longitudinal surface of the semifinished sample treated at 0 mJ/cm^2 at a magnification of **A** 150× and **D** 1500x; 15 mJ/cm^2 at a magnification of **B** 150× and **E** 1500x; and 60 mJ/cm^2 at a magnification of **C** 150× and **F** 1500x

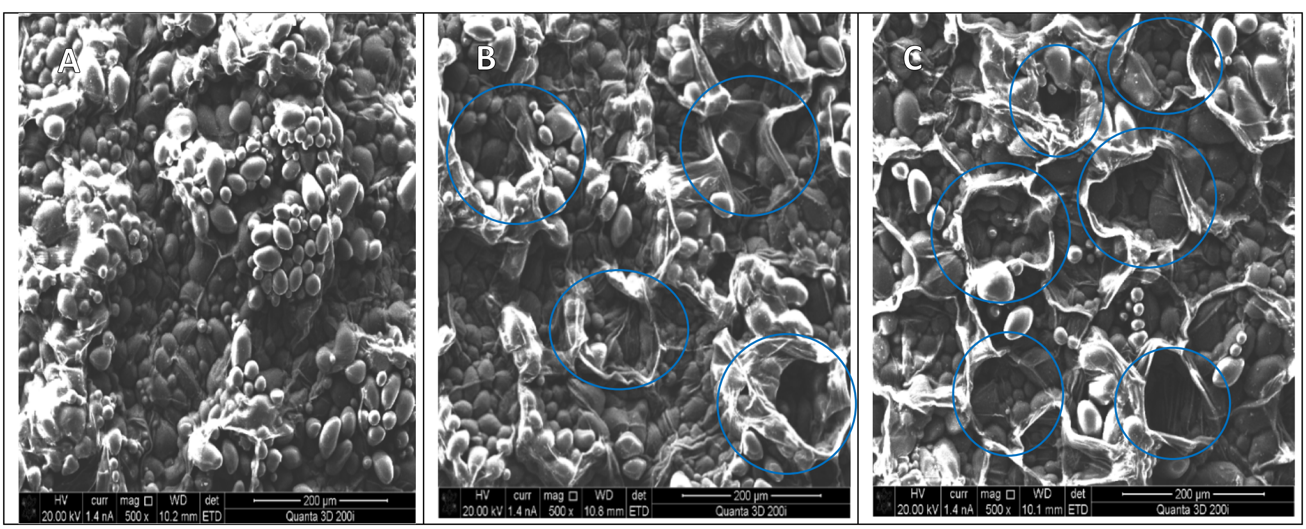

Fig. 7 SEM image taken at 500× for the cross-sectional area of semifinished samples treated at **A** 0 mJ/cm^2, **B** 15 mJ/cm^2, and **C** 60 mJ/cm^2

sample treated at 0 mJ/cm^2 (see blue rectangle in Fig. 6D) compared to the sample treated at 15 and 60 mJ/cm^2, which shows dispersed granules. For instance, the degree of dispersion can be seen from the sample treated at 15 mJ/cm^2 that some granules were displaced from the compacted arrangement (see blue circle in Fig. 6E). On the other hand, samples treated at 60 mJ/cm^2 caused slight deformation, fracturing, and collapse of structure (see blue circles in Fig. 6F). The cellular tissues of potatoes is a collection of fluid-filled parenchyma cells bound together by inter-cellular cohesion [41]. This inter-cellular part of the cell wall can be seen in Fig. 6D bounded together and shielding the granules. This tissue appeared to some extent in a sample irradiated at 15 mJ/cm^2 but some part of the tissue burst out as can be seen in Fig. 6E (blue circle) releasing some part of the granule from the bounding tissue. The sample treated at a higher dose (60 mJ/cm^2) exhibited a significant extent of disintegration of granules from the intercellular tissue, which can be revealed from Fig. 6F showing debonding from the intercellular tissue. Exposure to external energy followed by cold storage imparts the strength of the inter-cellular cohesion decreases and the cell wall strength increases. The process of cell separation, also known as debonding, plays a vital role in elucidating the behavior of fruits during treatment, and it significantly influences the overall quality of food products [42]. During debonding of starch granules as a result of treatment, leads to 'mealy' which occurs when the texture of the sample becomes dry and bitty as the cells separate into small clumps and little fluid is released [42, 43]. The middle lamella shown in the samples treated at 15 mJ/cm^2 has changed its structure in the sample treated at 60 mJ/cm^2 due to the dissolution. Higher radiation causes a broken middle lamella and increases intercellular spacing. Tissue behavior is governed by cell properties, and as deformation advances, the cell responses undergo alterations due to the influence of applied external forces [44, 45]. The morphology of the potato strip at its cross-sectional area also exhibited a noticeable change. The morphology of the sample treated at 0 mJ/cm^2 was smooth with few or no pores or cracks. From Fig. 7A, the potato strip granules are not similar in their shape and size, most of the small granules appear spherical, medium sizes tend more like ellipsoid shape and the large granules are elongated ellipsoid shape. Samples treated at 15 mJ/cm^2 resulted in the formation of surface pores showing fractured regions and opening up thin tissue (blue circles). Irradiation of the sample at 60 mJ/cm^2 brought bigger cavities that might be formed from the rapture of granules leaving a distorted type of circular hole. However, the inner granules and structure were not disrupted. The middle lamella is noticeable as an octagonal shape, which might be a result of the eruption out/debonding of thin tissue.

In addition to the morphological qualitative analysis related to the shape and visual appearance, the size of starch granules was determined. Figure 8 shows the particle size distribution of starch granules calculated from SEM images. The behavior of the curve indicates how particle sizes are various in each sample. The mean size of the untreated sample has a higher particle size (diameter = 58.28 μm) than irradiated samples of 15 mJ/cm^2 (53.75 μm) and 60 mJ/cm^2 (52.40 μm). The size of granules ranges from 33.06–88.0 μm, 26.07–68.73 μm, and 20.1–85.70 μm for samples irradiated at 0, 15, and 60 mJ/cm^2, respectively. From Table 2, the highest particle size variability was shown by the sample treated at 60 mJ/cm^2 with a standard deviation

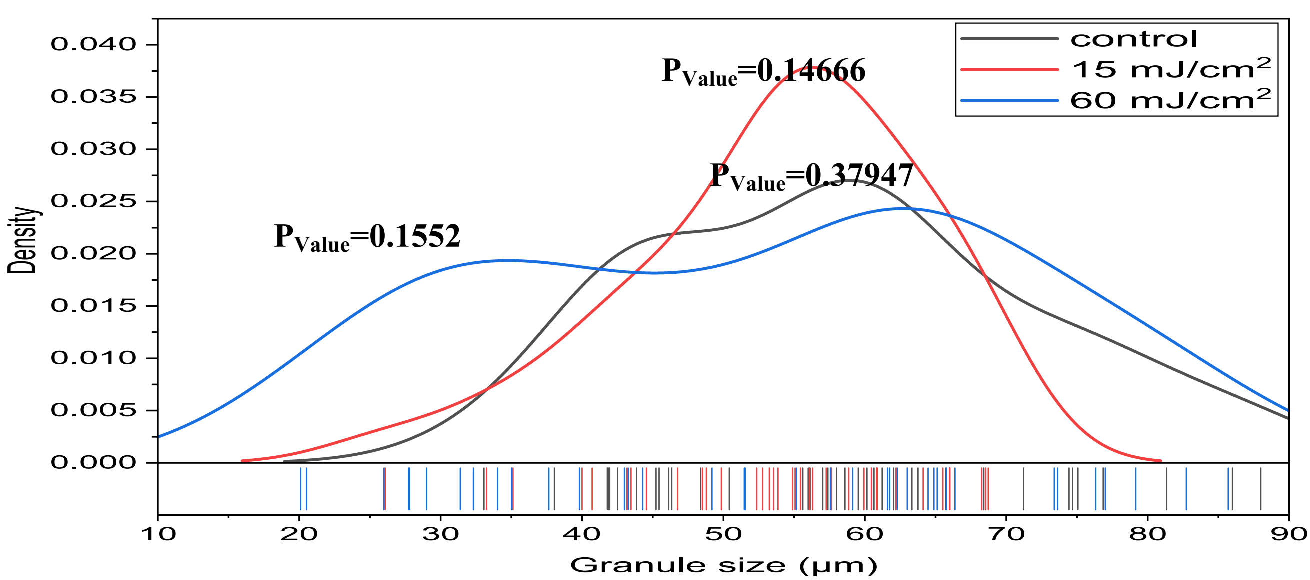

Fig. 8 Probability density curve for the particle size distribution of starch granules for samples treated at 0, 15, and 60 mJ/cm^2

Table 2 Descriptive statistics for particle size distribution

UV-C dose	Mean (µm)	Standard deviation	Sum	Minimum	Median	Maximum
0 mJ/cm^2	58.27543	13.81237	2156.191	33.061	58	88
15 mJ/cm^2	53.75868	10.32924	1989.071	26.077	55.073	68.731
60 mJ/cm^2	52.40973	18.81333	1939.16	20.1	55.145	85.703

of 18 µm. Both UV-C treated and untreated samples have a granule size in close agreement with the literature that reported the size of potato starch varies between 20 and 110 µm for larger granules [46].

Microstructural analysis

To verify the possible presence and essentiality of microscopic pore structures on the surface, the surficial nanostructure of UV-C irradiated and non-irradiated semifinished potato tuber was investigated using AFM. The 2D topographic images and 3D isometric topographic images are shown in Fig. 9. The surface of the non-irradiated tuber sample appeared to be relatively rougher and higher textural profile (Fig. 10) than the samples exposed to 15 and 60 mJ/cm^2 respectively. As shown in Fig. 9A, C, E, the 2D topographic images confirmed that the surface of the semi-finished potato in its original form presented pronounced fluctuating morphologies. From Table 3, the roughness value of the non-irradiated sample is 7.74010 nm. Skewness (Rsk) and Kurtosis (Rku) describe the surface under Gaussian distribution. A positive Rsk means the surface

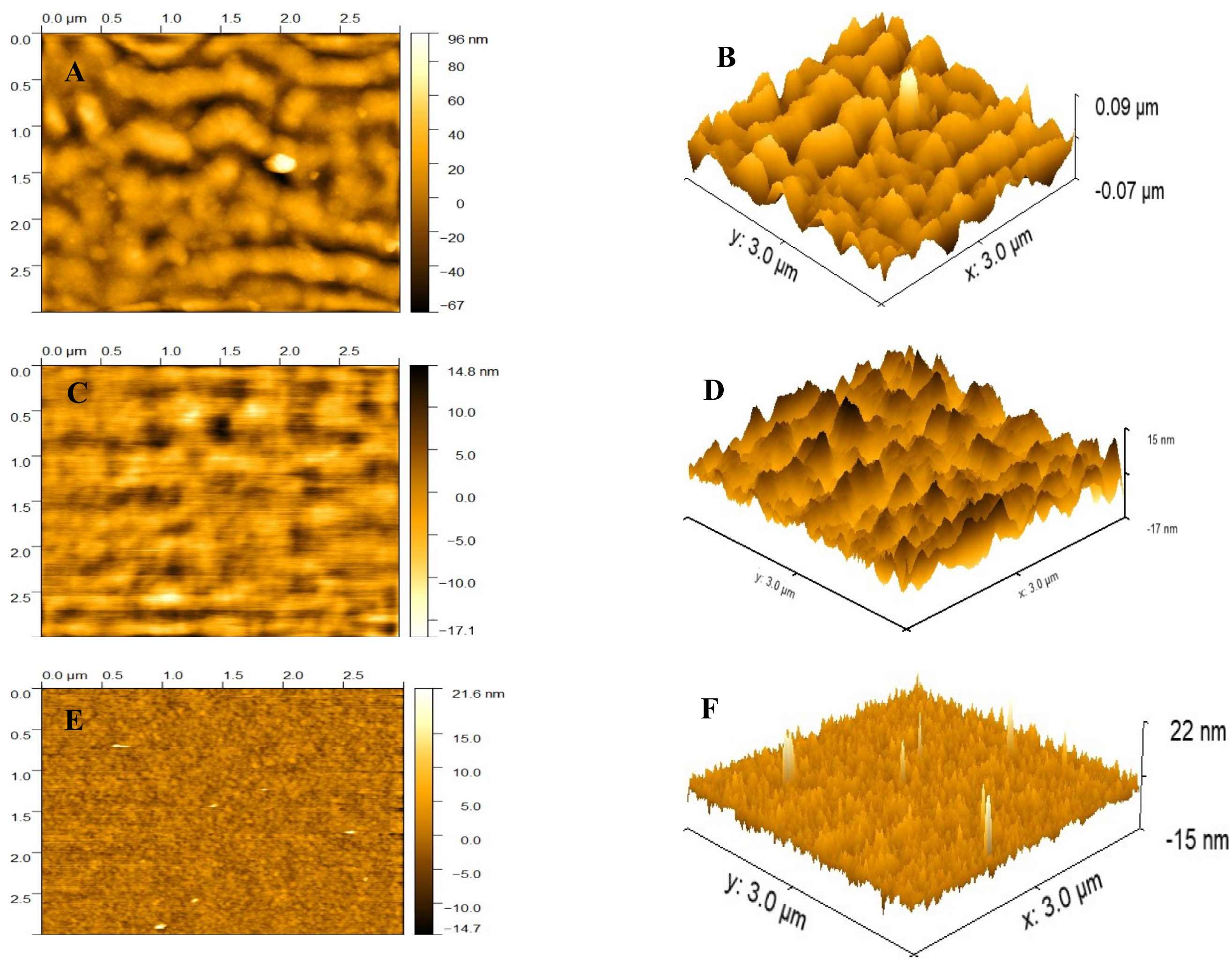

Fig. 9 AFM scanning of the surface of semifinished potato tuber; topographic image for sample exposed to **A** 0 mJ/cm^2 **C** 15 mJ/cm^2 and **E** 60 mJ/cm^2; 3D Phase images for **B** 0 mJ/cm^2, **D** 15 mJ/cm^2 and **F** 60 mJ/cm^2

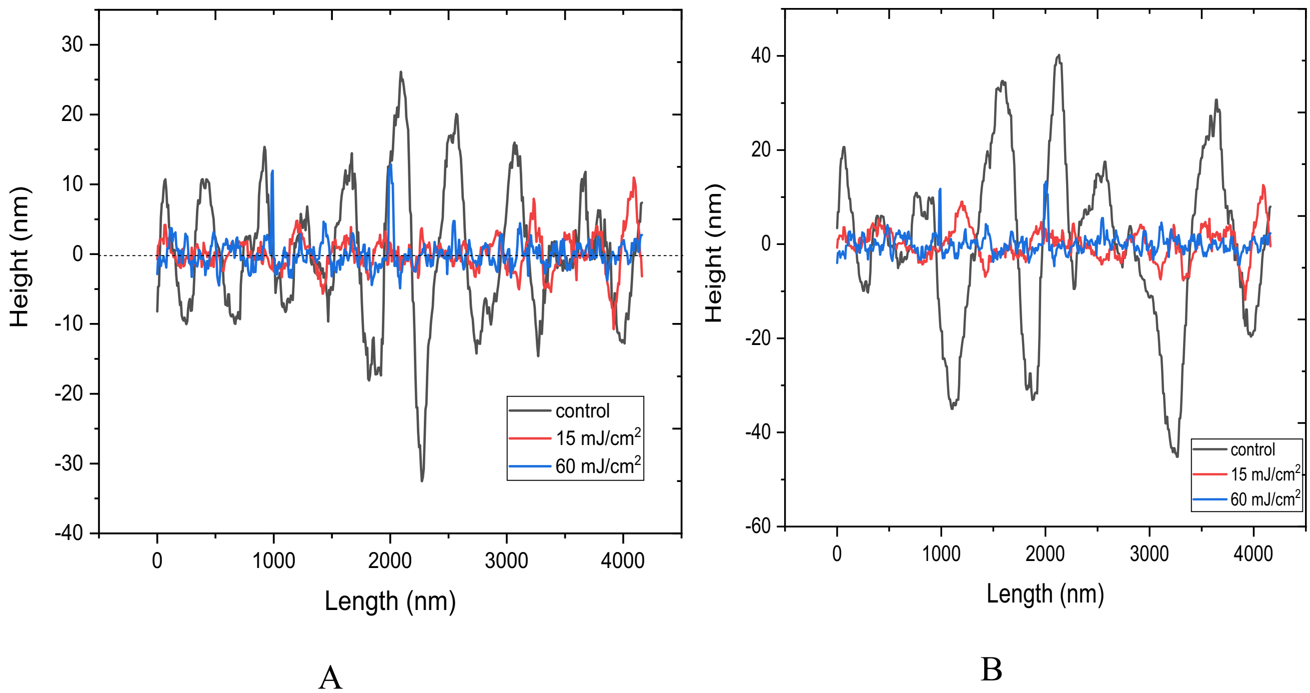

Fig. 10 Cross-section image of **A** surface roughness and **B** texture

Table 3 Roughness parameters

Parameters	Value (nm)		
	0 mJ/cm^2	15 mJ/cm^2	60 mJ/cm^2
Roughness average (Ra)	7.74010	1.99253	1.42643
Root mean square roughness (Rq)	9.89367	2.83366	2.11028
Maximum height of the roughness (Rt)	61.3000	27.1309	20.2874
Maximum roughness valley depth (Rv)	32.5275	16.1492	7.45243
Maximum roughness peak height (Rp)	28.7724	10.9816	12.8350
Average maximum height of the roughness (Rtm)	36.1423	12.9250	11.9219
Average maximum roughness valley depth (Rvm)	15.9230	6.59629	4.71479
Average maximum roughness peak height (Rpm)	20.2193	6.32869	7.20715
Average maximum height of the profile (Rz)	39.7163	15.5986	12.7343
Average maximum height of the roughness (Rz ISO)	36.1423	12.9250	11.9219
Maximum height of the profile (Pt)	85.4015	25.7419	21.3604
Mean spacing of profile irregularities (Sm)	209.761	107.712	81.3146
Skewness (Rsk)	-0.0349783	-0.443920	2.07149
Kurtosis (Rku)	3.36518	7.69392	13.4906

has high picks and filled valleys, while a negative means deep scratch (grooves) and lack of peaks. A Rku larger than 3 indicates the surface has high peaks and/or low valleys, while a smaller than 3 implies low peaks and/or valleys. The values of Rsk from Table 3 are −0.0349783 (0 mJ/cm^2), −0.443920 (15 mJ/cm^2), and 2.07149 (60 mJ/cm^2). From the result, negative skewness was recorded for non-irradiated samples and samples treated at 15 mJ/cm^2 implying the lack of peaks and the presence of deep scratches. The sample treated at 60 mJ/cm^2 however resulted in a positive skewness showing the presence of sharp peaks. These are visually observed from the 3D isometric view shown in Fig. 9F. The Rku values for all samples are greater than 3, implying there all exists high peaks with thin 'bell' structures and are characterized as Mesokurtic. Comparatively, the non-irradiated sample has the lowest Rku value (3.36518), indicating lower peaks that correspond to the broadening of peaks and thickening of the tails. Samples treated at 15 mJ/cm^2 and 60 mJ/

cm^2 with Rku values of 7.69392 and 13.4906 respectively experience high peaks.

The role of biochemical synthesis in defense response mechanism

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. In addition to its primary purpose as microbial inactivation from the surface, it indirectly elicits defense mechanisms on harvested crops when it is applied at appropriate doses (hormetic doses) [47]. It has been reported by several researchers that this technology is highly dose-dependent and could result in positive or negative impacts on the mechanical properties of the given product. Nevertheless, their findings about the impact of UV-C exposure on the mechanical properties of potato tuber and derivative products are scanty and the available works of literature are explored mainly on weight loss [48–51], sprouting [52–54], firmness [55] and deformation[26]. Somehow, the available studies could be linked to understanding intercellular phenomena during irradiation and possibly correlate with the current study. The application of varied doses in the semifinished sample resulted in a meaningful result in the mechanical properties. The notable result was obtained at lower doses or moderate doses ranging from 15 to 60 mJ/cm^2. This could support the idea of the favorable dose for the favorable stress response. However, different findings use different doses and it makes it difficult to set a clear margin for a lower dose. The enhancement of mechanical properties at a lower dose can be justified from the cellular point and its possible relation with the mechanical characteristics as detailed below.

Several studies demonstrated lower doses could induce the production of antimicrobial compounds, which indirectly play a role in slowing down ripening and senescence processes, and activate the accumulation of secondary metabolites, mainly phenolic compounds [56, 57]. These chemicals are formed as a result of the production of phenylalanine ammonia-lyase (PAL) which induces the formation of a phenolic compound referred to as phytoalexins. Minimally processed potato slices at different doses (2.28, 6.84, 11.41, and 13.68 kJ/m^2) and varied storage time experience a better level of total phenolic content at 6.84 kJ/m^2. It was indicated phenols are considered secondary metabolic chemicals that exhibit various chemical structures and biological characteristics, which are responsible for outcomes in texture, appearance, flavor, and safety of processed products [58]. In overall comparison, the untreated sample and UV-C irradiated vegetables are quite different, specifically the effect of UV-C treatment on the synthesis of such antioxidant compounds and enzymes can vary depending on the hormetic doses, time of exposure, and treated fruit [59]. UV-C treated sample has higher Phytochmicals due to the induction of phenolic biosynthesis, which occurs under stress conditions such as excessive UV light, wounding, or pathogen infection [60].

The application of hormetic dose absorbed by biological material, which interacts with atoms and molecules, mainly water, produces ROS (Reactive oxygen species) by the univalent reduction of O_2 in a rapid and controlled manner [61]. The primary ROS formed in the cell is O_2^-, which triggers a cascade of reactions that result in the formation of a variety of ROS and induction of antioxidant enzymes such as superoxide dismutase, Catalase, peroxidase, monodehydroascorbate reductase, glutathione and oxidized glutathione maintaining redox homeostasis. A key ROS is H_2O_2 produced by superoxide dismutase, which is involved in cross-tolerance (resistance to a particular stress that also confers resistance to another form of stress), hormonal activity, and gene expression [62]. This suggests that H_2O_2 may be responsible for the improvement of the antioxidant status of fruits activating gene expression of enzymes (such as PAL) related to the synthesis and accumulation of secondary metabolites with antioxidant capacity (phenolic acids and flavonoids) [62]. The compound produced by PAL can also balance the synthesis of ROS at a hormetic dose. One of the factors that contribute to the high production of ROS is high UV-C dose application. This will lead to excessive ROS production, resulting in cellular damage and cell death. A study reported on the wound healing process in UV-C exposed potato tuber through ROS and its role in maintaining cell membrane integrity [63]. The study depicted enzymes' role during UV-C irradiation such as protein kinase (CDPK), NADPH oxidase (NOX), and superoxide dismutase (SOD), in the activation of promoted superoxide anion (O2.-) and hydrogen peroxide (H_2O_2) that is produced at tuber wounds. The hypothetical cellular response to hormetic dose is depicted as shown in Fig. 11 (created with Biorender [62]).

In this study, the dose treatment levels are not severe dose and can be taken at a lower dose compared to the several doses applied in the previous research works [2]. Nevertheless, it is possible to observe the change in the mechanical resistance within this limit. The resistance to mechanical impact depends on the type of load applied to the sample. This is evidenced by the result of compression, cutting, and bending force, having a wide range of favorability. The compression force was improved by the sample exposed at 60 mJ/cm^2 while a much lower dose favors improved cutting and bending force. The mechanical behavior of fruit depends on the structural features of the cellular conglomerate that compose the tissues [64]. The stimulation process enhances the resistance capacity of the tissue but the response to a single cut and a uniform compact force in all directions is quite different. The compression force at a moderate dose was able to resist an extended load due to the presence of intercellular spaces within potato tubers could favor compressive and bending force by exerting additional tuber volume

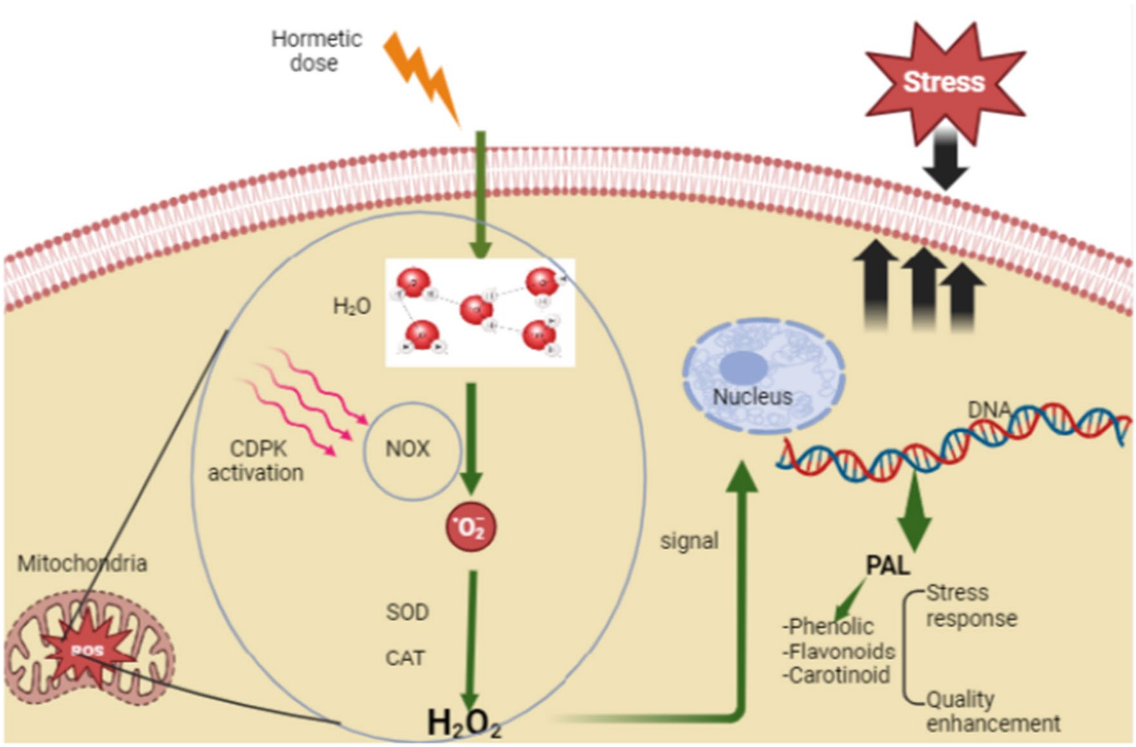

Fig. 11 Hypothetical biochemical process during UV-C irradiation at hormetic dose

and increasing the elasticity. However, may not necessarily enhance the cutting force applied as a single blade is exerted potentially bursting the air voids.

Conclusion

From the result, the UV-C dose has a pronounced effect on the mechanical properties of the semifinished product. Compressive load and bending load were greatly influenced at 60 mJ/cm^2 resulting in resistance of load at 770.60 ± 14.35N and 7.817 ± 0N, respectively as compared to the control sample 569.79 ± 56.28N and 5.78 ± 0.25N for compressive and cutting load recordings respectively. However, the cutting load was influenced at a lower dose (15 mJ/cm^2) 4.8 ± 0.25N higher than the control sample with a value of 2.73 ± 0.01N. The effect of the mode of exposure and distance from the light was not able to bring a significant influence on the mechanical properties of the semifinished product. However, irradiation of the sample at three sides brought enhanced resistance to compressive load. Further insight into the mechanical analysis was studied on the stress–strain properties confirming higher stiffness of the control sample for the compressive load. SEM image confirmed certain morphological changes between the treated sample at different doses and the control sample. More pores, cracks, intercellular spacing, and dispersion were noted for a sample treated at a 60 mJ/cm^2 dose. However, there is no considerable granular size difference between irradiated and control samples. Further insight characterization using AFM resulted in more smothering and sharp picks for irradiated samples.

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Data availability Data collected during the study will be provided by the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Compliance with ethics requirements This article does not contain any studies with human or animal subjects.

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