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Impact of Minimal Processing on Quality and Shelf Life of Cucumbers (*Cucumis sativus*)

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ABSTRACT

Cucumbers (*Cucumis sativus*) are highly perishable and often suffer significant postharvest losses. Chlorinated water and modified atmosphere packaging (MAP) are used to reduce microbial load, delay spoilage, lower respiration rates, and oxidative stress. However, limited research has examined the combined effects of washing using filtered water, blanching at specific temperatures (25 °C and 45 °C), cutting techniques, and vacuum packaging on cucumber quality. Therefore, the objectives of this study are: (1) to determine the effects of different washing solutions and blanching on moisture content, colour, and texture of fresh local cucumbers; (2) to evaluate the impact of various cutting techniques on the physicochemical properties and texture of selected cucumbers; and (3) to identify the effects of selected washing, blanching, cutting technique with vacuum packaging at various storage conditions on shelf life of cucumbers. Blanching at 25 °C with filtered water (FW25) significantly increased cucumber hardness (704.5±38.7 N) and maintained optimal moisture content (96.8±0.4%). Cylindrical cuts treated with FW25 (C25) exhibited higher firmness (530.9 g·sec) compared to non-treated cuts (CC) (494.50 g·sec), likely due to better structural integrity of C25. The C25 kept in vacuum packaging effectively inhibited microbial growth after six days of storage (VT6) compared to unpackaged samples (NC6) (2.9×10^{-3} log CFU/g) due to an anaerobic environment in vacuum packaging, which limits oxygen availability and suppresses microbial proliferation. This study offers valuable insights for optimizing postharvest handling of cucumbers to meet consumer demand for fresh, nutritious produce.

INTRODUCTION

Codex Alimentarius defines cucumbers (*Cucumis sativus)* as a popular vegetable characterized by its high water content and crisp texture, making it a staple in various culinary applications. In Malaysia, the cucumber market has shown significant growth, with the total market value reaching approximately RM42 million in 2022, reflecting a 2.5% increase from the previous year [1]. The growth highlights the importance of cucumbers as a dietary staple as well as a significant agricultural commodity in Malaysia. Minimal processing techniques become increasingly important in the food industry, particularly for extending the shelf life and maintaining the quality of fresh produce like cucumbers. These techniques aim to enhance shelf life while preserving the natural characteristics of fruits and vegetables. Common methods include washing, peeling, cutting, and packaging, which are designed to reduce microbial load and slow down spoilage processes [2]. For instance, cucumbers subjected to minimal processing, such as washing with chlorinated water and packaged in modified atmosphere packaging (MAP), can maintain their quality for up to two weeks longer than unprocessed cucumbers, which typically last for about 2 weeks or less when stored properly in the refrigerator [3].

They also indicate that storing fresh cut cucumbers in MAP significantly reduces respiration rates and modified atmosphere in the packaging, which promotes an environment of low oxygen levels and high carbon dioxide levels, thereby reducing respiration, oxidative stress, aging of tissue, and ethylene production [3]. Different cutting methods may also affect the quality of fresh-cut cucumbers, influencing parameters like vitamin C content, texture, and moisture retention [2]. The

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cutting techniques are particularly relevant in regions like Malaysia, where cucumbers are often harvested and transported over long distances before reaching consumers [3]. In relation to extending shelf life, minimal processing can impact the nutritional profile of cucumbers. Recent research emphasizes that the retention of Vitamin C can range from 60% to 80%, while antioxidants can be maintained at levels between 70% and 90%, depending on the specific conditions applied [4]. The minimal processing of fruits and vegetables is a rapidly growing industry, driven by the increasing demand for fresh, healthy, and convenient foods. This type of food is ideal for busy lifestyles as it provides essential vitamins and minerals without requiring extra preparation. New technologies are being explored to extend the shelf life of these products.

Washing removes dirt, pesticides, and contaminants, while blanching helps preserve colour, texture, and nutritional value by inactivating enzymes responsible for deterioration. The article discusses the rapid growth in the market for fresh and minimally processed fruits and vegetables (MPFVs) due to consumer demand for fresh, healthy, and convenient food options. It highlights the challenges in maintaining the quality and shelf life of MPFVs, particularly due to the use of chlorine for disinfection, which leads to the formation of harmful compounds, such as trihalomethanes (THMs) and haloacetic acids (HAAs). These compounds are suspected to be carcinogenic and pose health risks [2].

Consumer preferences in Malaysia have shifted towards healthier food options, resulting in a growing demand for fresh produce, such as cucumbers. This trend presents opportunities for local farmers and producers to innovate their processing techniques to meet market demands. Research highlights that minimal processing techniques (cutting and blanching) can effectively reduce microbial load in cucumbers. A study found that these techniques can decrease the total microbial count by approximately 2.59 log CFU/g and yeast and mold by 1.39 log CFU/g while maintaining the physicochemical properties of cucumbers [5]. Despite advancements in cucumber processing techniques, a gap remains in research regarding the impact of minimal processing on shelf life and quality. Understanding the dynamics of minimal processing is crucial for developing effective preservation strategies that align with consumer demands for fresh and nutritious produce.

Therefore, this study aims: (1) to determine the effects of different washing solutions and blanching on the moisture content, colour, and texture of fresh local cucumbers; (2) to evaluate the impact of various cutting techniques on the physicochemical properties and texture of selected cucumbers; and (3) to identify the effects of selected washing, blanching, cutting technique with vacuum packaging at various storage conditions on shelf life of cucumbers. This research may provide valuable insights for local farmers and producers to enhance the quality and shelf life of cucumbers while maintaining their desirable characteristics.

MATERIALS AND METHODS

Sample Preparation

Approximately 32 mature, uniformly sized and coloured cucumbers were purchased from a local fresh market in Sri Serdang (Pasar Borong Big). The cucumbers were selected for their consistent maturity, based on the days after harvest (55-60 days old), and their green color [6]. They were then stored in containers at ambient room temperature until they were processed and analyzed [7,8].

Determination of washing and blanching effects

The study aims to evaluate the effects of minimal processing, which includes washing with tap water or filtered water and blanching treatments at 25 °C and 45 °C. Two washing methods (tap water and filtered water) were employed to investigate the influence of water quality on the quality attributes of whole cucumbers, including appearance, colour, and texture. The whole cucumbers were rinsed with tap water to simulate conventional household cleaning practices. In contrast, the second treatment, which used filtered water, aims to explore whether reducing the microbial and mineral content in the water can further minimize surface contamination and maintain visual and structural integrity [9].

Following washing treatments, the whole cucumbers were blanched at two temperatures: 25 °C, ambient conditions, and 45 °C, which represents a mild thermal treatment. The whole cucumbers were labeled as control (no washing), FW25 (washed using filtered water and blanched at 25 °C), TW25 (washed using tap water and blanched at 25 °C), FW45 (washed using filtered water and blanched at 45 °C), TW45 (washed using tap water and blanched at 45 °C), FW (only washed using filtered water) and TW (only washed using tap water).

The selected temperatures (25 °C and 45 °C) were used to assess the threshold at which enzymatic activities will cause spoilage and quality changes at either 25 °C or 45 °C without causing significant heat damage [10]. After blanching at 25 °C and 45 °C, cucumbers were immediately transferred into an ice bath for 5 min. The rapid cooling step is crucial for arresting enzymatic and thermal changes that occur during blanching, thereby preserving the cucumber's quality. The duration of 5 minutes was optimized based on preliminary studies, where it was sufficient to ensure thorough cooling throughout the cucumber tissues.

Determination of cutting technique

Next, a total of 6 cucumbers were used to determine the impact of various cutting techniques on the physicochemical properties and texture of selected cucumbers. The cucumber was cut cylindrically at 5 cm diameter and 1 cm thickness, then proceeded to washing using selected water and blanched at a selected temperature based on preliminary analysis, where changes occurred in moisture content and colour across the different treatments. **Fig. 1a** and **1b** show the diagram of cylindrical and longitudinal cuts, respectively.

The sliced cucumbers were divided into two groups: the first group acts as a control, and the other group of cucumbers was washed with selected types of water, followed by blanching. For each group, cucumbers were divided into another 2 groups (cylindrical cut and longitudinal cut). The CC samples are referred to as cylindrical cut and not treated with washing and blanching, LC (longitudinal cut and not treated), C25 (cylindrical cut and washed with filtered water and blanched at 25 °C), L25 (longitudinal cut and washed with filtered water and blanched at 25 °C).

Determination of vacuum packaging effects

The control sample VC3 (Vacuum-packed, non- treated sample and stored for 3 days) and VC6 (Vacuum-packed, non- treated sample and stored for 6 days) were added into the vacuum-sealed bags by a vacuum packaging machine, and the non-vacuum-packed control sample NC3 (Non-vacuum-packed, non-treated sample and stored for 3 days) and NC6 (Non-vacuum-packed, non-treated sample and stored for 3 days) was stored in an open container at room temperature. The treated samples VT3

(Vacuum-packed and stored for 3 days), VT6 (Vacuum-packed and stored for 6 days), NVT3 (Non-vacuum-packed and stored for 3 days), NVT6 (Non-vacuum-packed and stored for 6 days) were thoroughly rinsed with filtered water and blanched at 25 °C. The sliced cucumber was then rapidly cooled in an ice bath for 3 minutes to stop the development of enzymatic and thermal reactivity [11]. The selected treated cutting technique will proceed to assess antioxidant activities (DPPH, TPC, and FRAP), microbiology, and texture analysis. Therefore, it is necessary to incorporate both vacuum-packaged and non-vacuum-packaged samples to identify the effects of different storage conditions on the shelf life of the treated cucumbers.

Fig. 1a: Longitudinal cut

Fig. 1b: Cylindrical cut

Physicochemical Analysis of Cucumbers
This study aims to evaluate the physicochemical and antioxidant properties of cucumbers that have undergone minimal processing and stored under various conditions. The methods were adapted and optimized based on protocols frequently used in recent research on fruits and vegetables [12].

Moisture Content
The moisture content was determined using a vacuum oven (Memmert UF750, Germany). Approximately 5 g of the cucumber samples (peeled and homogenized) were placed in pre-weighed crucibles and dried at 70 °C under vacuum until a constant weight was achieved. The moisture content was calculated as the percentage weight loss from the initial fresh weight [13].

Texture Analysis
The firmness of unpeeled and sliced cucumbers was assessed using a texture analyzer (Stable Micro Systems TA.Xtplus, Godalming) fitted with a cylindrical probe. Uniform 1 cm slices of cucumbers were placed on the platform, and the probe was lowered at 1 mm/s to a depth of 5 mm. The force required to compress the sample was recorded in Newtons (N) [14].

Colour Analysis
The surface colour of unpeeled and peeled cucumbers was measured using a chromameter (Minolta CR-400, Japan). The instrument was calibrated with a standard white plate, and measurements were taken at multiple locations on the cucumber surface. Data were recorded as L* (lightness), a* (red-green), and b* (yellow-blue) values. Average chroma and hue angle were calculated for colour analysis value [14].

Antioxidant activities Analysis

Total Phenolic Content (TPC)
The total phenolic content of sliced cucumber was measured using the Folin-Ciocalteu method. Cucumber extracts were prepared by homogenizing 5 g of cucumber in 25 mL of 70% ethanol and centrifuging at 5000 rpm for 10 min. A 200 µl aliquot of the supernatant was mixed with 1 ml of Folin-Ciocalteu reagent (diluted 1:10) and 800 µL of 7% sodium carbonate solution. After 2 h of incubation in the dark at 25 °C, the absorbance was read at 765 nm using a spectrophotometer. Results were expressed as mg Gallic Acid Equivalent (GAE) per 100 g fresh weight [13].

DPPH Radical Scavenging Activity
The antioxidant activity was determined using the DPPH assay. A stock solution of 2 mg DPPH in 100 mL methanol was prepared. Cucumber extracts (20–40 mg/mL) were added into the DPPH solution in a 1:2 ratio and incubated in the dark at 25 °C for 30 min. Absorbance was measured at 517 nm, and the scavenging activity (%RSA) was calculated [14].

Ferric Reducing Antioxidant Power (FRAP)
The FRAP reagent was prepared by mixing 2.5 mL of 10 mM TPTZ (in 40 mM HCl), 2.5 mL of 20 mM $FeCl3·6H2O$, and 25 mL of 0.3 M acetate buffer (pH 3.6). A 200 µL aliquot of cucumber extract was mixed with 1.8 mL of FRAP reagent, and the mixture was incubated at 37 °C for 30 min. Absorbance was measured at 593 nm, and antioxidant power was expressed as µmol Trolox Equivalent (TE) per gram of fresh weight [15].

Microbiological Analysis of Cucumbers

Total Plate Count Analysis
Selected cucumber was homogenized in sterile peptone water (10 g sample in 90 mL) and serially diluted (10^{-2} to 10^{-4}). A 1 ml aliquot from each dilution was plated on Plate Count Agar for bacterial counts. Plates were incubated at 37 °C for 24–48 h (bacteria). Colony counts were expressed as log CFU/g [16].

Statistical Analysis
Data were analyzed using Minitab statistical software (Version 19), with one-way ANOVA and Tukey's test applied to assess significant differences among sample groups. Statistical significance was set at a confidence level of $p < 0.05$ to determine whether the different processing methods had a measurable impact on the various quality attributes.

RESULT AND DISCUSSION

Moisture Content
Table 1 presents the moisture content of peeled cucumbers following various treatments. Treatments consisted of washing in tap water or filtered water and blanching either at 25 °C or 45 °C.

The control sample was compared with cucumbers treated with various treatments, such as washing and blanching. The moisture content of TW45 (99.3±0.3%), washed with tap water and blanched at 45 °C, was significantly greater than that of the control sample (97.3±0.2%), FW25 (96.8±0.4%), FW (96.6±0.280%), and TW (96.1±0.205%) at a significant level of $p < 0.05$.

Cucumbers with moisture greater than 95% are more susceptible to damage; thus, it is optimally maintained at a moisture of 92% for firmness and texture [17]. In this study, the closest to the acceptable limit of moisture content 95% is TW (96.1±0.2%) and FW (96.6±0.3%). This shows that the non-blanched group has the ideal moisture content. Previous study shows that the unblanched (95.1%) and blanched (95.1%) cucumber samples have similar moisture content [18]. However, in this study, blanching at 25 °C and 45 °C affected the increment of the moisture content. [19] mentioned that at 22 °C, the qualitative aspects of cucumber, such as pH level, total acidity, and salt concentration, change. This may relate to the increase in moisture content of TW45 (99.3±0.3%).

Table 1. Comparison of moisture content of Control, FW25, TW25, FW45, TW45, FW and TW.

Sample	Control	FW25	TW25	FW45	TW45	FW	TW
Moisture content (%)	97.3±0.2^{b}	96.8±0.4^{d}	97.0±0.1^{c}	97.3±0.1^{b}	99.3±0.3^{a}	96.6±0.3^{d}	96.1±0.2^{d}

Notes: Values are expressed as mean±standard deviation. Values with different letters in the same column (a-d) are significantly different at p<0.05 for each analysis.

Colour Stability

Data herein compares the colour stability of cucumbers under various treatments, analysed by the CIE Lab colour space (L*, a*, b*, and colour difference, ΔE*). The control sample (**Table 2**) had an L* value of 54.5, an a* value of -12.5, indicating greenness, and the b* value of 25.6, indicating yellowness, with a ΔE* value of (29.5) serving as the baseline for comparison. FW25 showed excellent colour stability, with an L* value of (54.4), and had no significant difference from the control, indicating minimal loss of brightness.

Although a* (-10.4) was significantly less intense green than the control value (-12.5), and b*(22.1) was lower than the control value (25.6). Both FW25 (27.0) and FW45 (27.4) have similar ΔE* value as the control with no significant difference (p>0.05). Therefore, FW25 is the most effective treatment to preserve the visual quality of cucumber slices. TW25 shows significantly lower ΔE* (24.8), and L* (49.0), corresponding to a much darker appearance than FW25, with values of ΔE* (27.4), and L* (54.4).

The superiority of FW25 is consistent with another study, which showed that mid-temperature treatment stored at 15 °C was able to retain greener cucumber colour compared with lower temperature treatment at 5 °C, in agreement with this study related to FW25 [20]. A researcher has previously described how storage at 15 °C effectively improves the green colour a* and L* values of cucumbers similar to FW25. Colour is one of the most important indicators of freshness and consumer acceptance in cucumber quality assessment, so colour analysis of cucumbers is of paramount importance [21].

Moderate temperature treatments have a substantial positive impact on maintaining visual quality in cucumbers [22]. Thus, FW25 had the optimal conditioning for preserving cucumber colour stability, maintaining brightness (L*), greenness (a*), and preventing yellowness (b*), while minimizing the colour difference Δ(E*). FW25 is highly recommended for applications requiring the maintenance of a fresh appearance for cucumbers.

Table 2: Comparison of colour stability for Control, FW25, TW25, FW45, TW45, FW, TW.

Sample	L* (Lightness)	a* (Green-Red)	b* (Blue-Yellow)	ΔE* (Colour difference)
Control	54.5±0.895^{a}	-12.5±0.28^{a}	25.6±0.46^{a}	29.5±0.71^{a}
FW25	54.4±0.591^{a}	-10.4±0.14^{b}	22.1±0.2^{b}	27.0±0.44^{ab}
TW25	49.0±0.014^{b}	-10.5±0.28^{b}	20.2±0.44^{ab}	24.8±0.61^{c}
FW45	54.7±0.702^{a}	-10.4±0.17^{b}	23.4±0.36^{a}	27.4±0.54^{ab}
TW45	52.4±0.643^{b}	-10.5±0.15^{b}	21.8±0.26^{b}	26.2±0.44^{c}
FW	50.5±0,362^{bc}	-10.0±0.17^{b}	25.0±0.68^{b}	22.0±0.25^{c}
TW	50.2±0.230^{c}	-10.5±0.053^{b}	25.1±0.14^{b}	23.0±0.16^{c}

Note: Values are expressed as mean±standard deviation. Values with different letter in the same column (a-d) are significantly different at p<0.05 for each analysis.

Texture Analysis

Table 3 shows that the C25 (cylindrical cut treated with filtered water and blanched at 25 °C) had the significantly highest firmness value (530.9 g.sec) than the control CC (494.5 g.sec). This may be due to the combination of treatment being the most effective in increasing the firmness, similar to what was reported by another research on fresh-cut apples, which has used sharp blades exhibiting better firmness and lower ethylene production compared to those cut with blunt blades, emphasizing the role of cutting techniques in maintaining textural quality [23].

Additional treatment of cylindrical cuts (C25) with FW25 (washing and blanching) resulted in greater firmness (530.9 g · sec) compared to longitudinal cuts (L25) of the cucumber. These findings are consistent with a previously reported study, which stated that cylindrical cuts retained more firmness in carrots than longitudinal cuts, and that blanching was advantageous in terms of overall texture retention [24].

Table 3. Comparison of texture analysis for different cutting techniques (cylindrical and longitudinal cut) of WC, W25, CC, C25, LC, and L25.

Sample	WC	W25	CC	C25	LC	L25
Firmness (g. sec)	422.0±34.9^{b}	421.5±28.4^{b}	494.5±20.7^{c}	530.9±31.8^{d}	434.4±36.9^{b}	428.3±29.8^{b}

Notes: Values are expressed as mean±standard deviation. Values with different letters in the same column (a-d) are significantly different at p<0.05 for each analysis.

Table 4 shows cylindrical cut cucumbers washed with filtered water and blanched at 25 °C (FW25) showed significantly harder texture (704.5±38.7 g·sec) than the control (545.5±5.50 g·sec). A previous study has reported the utilisation of cowpeas blanched at 70 °C, which showed texture preservation. In contrast, blanching at 25 °C decreases firmness loss by not compromising the structural integrity of the cell wall, particularly after blanching for 4 min [11].

TW25 (washed with tap water and blanched at 25 °C) had a substantially tougher seed cavity texture (457.3 ± 23.0 g·sec) compared to the control (319.4 ± 15.4 g · sec). This enhancement might be attributable to the blanching process, which improves cellular structure while decreasing enzymatic activity. Research has demonstrated that blanching may efficiently retain firmness; for example, the discovery that several cucumber hybrids had varied skin hardness, with some having much harder textures due to genetic characteristics and processing methods [25]. The types of water applied, as well as the blanching temperature, are strongly affected by cucumber textural property retention, as shown by the FW25 sample (704.5±38.7 g·sec). Filtered and tap water (with chlorine added) have the potential to minimise polluting agents that induce stress on cucumber cells via processing. This is consistent with previous research, which

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reported that the effectiveness of chlorination and aeration in removing pathogens from vegetables also affects their quality. The research proposed that washing could influence the maintenance of physical characteristics during processing, in addition to water quality [26]. In this study, blanching at 25 °C or 45 °C and washing using filtered water are used to maintain the cucumber texture. These findings are in line with other studies, which show that mild heat treatments (blanching at 45 °C) can decrease enzymatic degradation and increase the mechanical properties of Cowpea Grains (*Vigna unguiculata L.*) and cucumber (*Cucumis sativus)* [11, 19]. The effectiveness of filtered water in maintaining texture and moisture is supported by another study, which reported a reduction in microbial and mineral content in cucumber [9].

Table 4. Comparison of texture analysis (flesh and seed cavity of sliced cucumber) of Control, FW25, TW25, FW45, TW45, FW, TW.

Sample	Hardness for Flesh (g.sec)	Hardness for Seed Cavity (g.sec)
Control	545.5±5.50^{b}	319.4±15.39^{c}
FW25	704.5±38.7^{a}	345.7±17.12^{ab}
TW25	546.2±26.4^{b}	457.3±23.00^{a}
FW45	530.1±5.19^{b}	428.4±27.40^{a}
TW45	622.4±22.5^{ab}	437.8±27.40^{a}
FW	527.5±5.67^{b}	319.5±12.15^{c}
TW	551.2±5.13^{b}	341.5±19.10^{bc}

Notes: Values are expressed as mean±standard deviation. Values with different letter in the same column (a-d) are significantly different at p<0.05 for each analysis

Total Phenolic Content (TPC), DPPH Assays and Ferric Reducing Antioxidant Power (FRAP)

Based on the moisture content, colour, and texture analysis, the cylindrical cut cucumbers treated with filtered water and blanched at 25 °C were selected for antioxidant activity analysis. Based on **Table 5**, the DPPH assay measures the ability of antioxidants in a sample to scavenge free radicals; lower values indicate higher antioxidant activity. Vacuum-packed control samples generally had lower DPPH values than treated sample VC3 (64.60 µg/mL) compared to VT3 (124.78 µg/mL), which may indicate that vacuum-packed control samples retained higher antioxidant activity. A study has reported DPPH values of cucumbers ranging from 50–120 µg/mL, which is similar to this study, is affected by various factors such as the cucumber variety, growing conditions, and extraction methods used [13].

The Total Phenolic Content (TPC) refers to the total amount of phenolic compounds, highly valued antioxidants, present in a sample. The TPC was significantly higher in NC3 (2.88 mg GAE/g) compared to VC3 (1.13 mg GAE/g), indicating that more phenolic compounds were retained in the non-vacuum-packed control samples stored for 3 days. The vacuum-packed samples VC3 (1.13 mg GAE/g) and VC6 (1.11 mg GAE/g) had lower TPC, respectively, compared to NC3 (2.88 mg GAE/g), which may suggest that vacuum packaging does not always improve the retention of phenolics. The results are in agreement with another study that presented that the TPC of cucumbers is in the range of 0.8-2.5 mg GAE/g where the storage conditions (stored at 15 °C) significantly affected the phenolic content [13].

The FRAP value measures the antioxidants that can reduce ferric ions. Higher FRAP values mean stronger antioxidant power. The VT6 (0.88 µmol TE/g) has the highest FRAP values compared to VC6 (0.21 µmol TE/g), which indicates that considerable amounts of their antioxidant activities might be retained even after vacuum package treatment [27]. Non-vacuum-packed samples had lower FRAP values, specifically NC3 (0.01 µmol TE/g) and NC6 (0.44 µmol TE/g), compared to the vacuum-packed samples. These findings are in concordance with another research that showed FRAP values for cucumbers ranged between 0.1–1.0 µmol TE/g where vacuum packaging as well as storage duration (24h) significantly affected the FRAP values [28]. Both storage conditions and blanching at 25 °C significantly affected the DPPH, Total phenolic content (TPC), and Ferric Reducing Antioxidant Power (FRAP). Generally, vacuum packaging with the addition of FW25 treatment helps retain antioxidant properties, as indicated by VT6 values. These findings are in line with published research, emphasizing the need to optimize storage and processing conditions to preserve the nutritional quality of cucumbers.

Table 5: Comparison of antioxidant content (TPC (mg GAE/g), DPPH Assays and FRAP (µmol TE/g) between vacuum-packed and non-vacuum-packed samples.

Sample	TPC (mg GAE/g)	DPPH (µg mL-1)	FRAP (µmol TE/g)
VC3	1.13±0.00058^{b}	64.60±0.01^{d}	0.15±0.000577^{b}
VT3	0.90±0.001^{c}	124.78±0.001^{a}	0.58±0.001^{a}
VC6	1.11±0.00058^{b}	95.13±0.001^{c}	0.21±0.000577^{b}
VT6	1.23±0.00^{a}	93.51±0.001528^{c}	0.88±0.000577^{a}
NC3	2.88±0.01^{a}	123.01±0.001^{a}	0.01±0.00577^{c}
NT3	0.83±0.001155^{c}	115.93±0.001^{b}	0.13±0.000577^{ab}
NC6	0.85±0.000577^{c}	82.74±0.001^{c}	0.44±0.001^{ab}
NT6	0.96±0.001155^{b}	101.18±0.000577^{b}	0.28±0.000577^{b}

Notes: Values are expressed as mean±standard deviation. Values with different letters in the same column (a-d) are significantly different at p<0.05 for each analysis.

VC3(Vacuum-packed, untreated and stored for 3 days), VT3 (Vacuum-packed, treated and stored for 3 days), VC6 (Vacuum-packed, untreated and stored for 6 days), VT6 (Vacuum-packed, treated and stored for 6 days), NC3 (Non-vacuum-packed, untreated and stored for 3 days), NT3 (Non-vacuum-packed, treated and stored for 3 days), NC6 (Non-vacuum-packed, untreated and stored for 6 days), NT6 (Non-vacuum-packed, treated and stored for 6 days).

Microbiological analysis

Total Plate Count Analysis

The TPC analysis in **Table 6** gives an estimate of the microbial load in cucumbers under different storage conditions and treatments. The VT3 (vacuum packed, treated, and stored for 72 h) and VT6 (vacuum packed, treated, and stored for 144 h) show microbial inhibiting activity. Nevertheless, the VT3 and VT6, show no microbial growth with the combined effect of vacuum packing and FW25 treatment. The unpacked samples, NC3 (2.5 × 10^ (-3) log CFU/g) and NC6 (2.9 × 10^ (-3) log CFU/g), exhibited significant microbial growth, whereas the vacuum-packed controls, VC3 and VC6, led to (1.9 × 10^ (-3) log CFU/g) and (2.6 × 10^ (-3) log CFU/g), respectively.

For VT3 and VT6, no microbial growth was observed; such a combination is feasible from the point of view of microbial safety. In this way, it is highly probable that high performance of VT3 and VT6 is because of the effect of vacuum packaging and FW25 treatment. Synergistic effects of VT3 and VT6 can suppress microbial growth over a period even up to 72 and 144 h of storage. This is consistent with the previous work which noted that vacuum packaging of sausage plus treatments (stored at 7 °C and 36 °C) resulted in a significant decrease in the amount of microorganisms in fresh produce [29]. In addition, VT6 remained higher even at 144 h of storage, which corresponded with no microbial growth. This is quite an interesting finding since vacuum-packed (VC6) and nonvacuum-packed controls (NC6) showed (2.6×10^{-3} log CFU/g) and (2.9×10^{-3} log CFU/g) at the same storage duration. It reveals that the microbial stability of

VT6, which was treated with FW25 and vacuum-packed, has remained stable through the longest period so far, indicating that the coupled approach is efficient for long-term stability. This suggests that filtered water can be a viable option for crop irrigation without compromising plant health or yield [30]. Compared with other samples, VT3 and VT6 consistently exhibited the best microbial control. For example, VC3 (1.9×10^{-3} log CFU/g) while VT3 was (0×10^{-3} log CFU/g). VC6 (vacuum-packed for 144 hours) had (2.6×10^{-3} cfu/ml), but VT6 still had (0×10^{-3} log CFU/g).

Table 6. Comparison of Total Plate Count between NC, VC, NC3, VC3, NT3, VT3, NC6, VC6, NT6 and VT6 samples.

Sample types	Storage condition	Storage time (h)	Total plate count log CFU/g
NC	Unpacked	0	0
VC	Vacuum-packed	0	0
NC3	Unpacked	72	2.5
VC3	Vacuum-packed	72	1.9
NT3	Unpacked	72	0.6
VT3	Vacuum-packed	72	0
NC6	Unpacked	144	2.9
VC6	Vacuum-packed	144	2.6
NT6	Unpacked	144	1.3
VT6	Vacuum-packed	144	0

It suggests that therapeutic interventions are necessary to achieve optimal results with vacuum packaging. Consistently, VT3 and VT6 are also supported in the literature, where, when using the vacuum package treatment alone, a notable level of microbial depletion (3.30 log CFU/g) can be reached regarding cucumber [31]. Other authors also subsequently postulated that, despite being targeted in combination with vacuum packaging of potato, treatment's operational aspects, namely, sanitization, represent an acceptable microbiological control of such produce, which is also corroborated by my findings [32].

In conclusion, VT3 and VT6 have consistently high performance in terms of microbial inhibition, due to the combination of vacuum wrapping and antibiotic treatment. These samples captured 0×10^{-3} log CFU/g (VT3, VC6) following both 72 and 144 h of storage, better than controls, Non- vacuum-packed (NC, NC3, NC6) and vacuum-packed (VC, VC3, VC6). These findings are consistent with the evidence for the need to use vacuum packaging, together with procedures to maintain microbial safety and hence postharvest shelf life of cucumbers. This method is strongly suggested to ensure the quality and wholesomeness of the minimally processed cucumbers.

CONCLUSION

In this work, the effects of minimal processing procedures: washing solutions, blanching, cutting practices, and storage conditions were examined on cucumber quality and shelf life. Washing cucumbers using filtered water and blanching at 25 °C enhanced the preservation of key quality attributes (moisture, colour, and texture). Filtered water reduced contaminants and pigment loss, keeping cucumbers green. Blanching at 25 °C maintained the firmness, moisture, and freshness for a longer period. Cylinder cuts yielded greater texture retention compared to longitudinal cuts. Cylindrical cuts, when supplemented with washing using filtered water and blanching treatment, showed enhanced firmness and mechanical stability, thereby demonstrating the importance of the cut morphology in maintaining the texture and physicochemical quality of minimally processed cucumbers. Moreover, the method of vacuum packing was reported to be one of the most important methods for extending the shelf life of foods. Cucumbers treated with filtered water, blanched at 25 °C, and vacuum-packed did not exhibit any microbial growth and maintained their high antioxidant properties for 6 days of storage. Based on these results, future research and practice are also proposed. Further optimization of processing parameters (i.e., alternative blanching temperatures, washing compositions, cutting techniques) could further minimize the steps of processing. The application of novel formats of packaging, such as antimicrobial films and oxygen scavengers, may result in an extension of shelf life and a reduction of the amount of spoilage. Generalizing the use of these techniques to other fresh vegetables of that kind can be valuable for proving their generality. Sensory evaluation and commercial consumer panel tests can help define market demand, enabling the commercial marketing of minimally processed cucumbers. The results of the current study establish a solid basis for future improvements in postharvest cucumber management through minimally processed methods. Regarding perishability and drop in quality, the results offer tangible solutions to reduce post-harvesting losses, shelf-life extension, and consumer demands for crispness quality, nutritious and minimally processed fruits and vegetables.

CONFLICT OF INTEREST

The authors have declared that no conflict of interest exists.

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ETHICS STATEMENT

Not applicable.

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