



Preserving Nutritional Quality Attributes of Potatoes (*Solanum tuberosum* L.) Through Pre- plus Post-harvest Application of Various Plant Extracts

Siphokuhle Mbuyisa¹ · Isa Bertling¹ · Bonga Lewis Ngcobo²

Received: 31 March 2025 / Accepted: 22 August 2025 / Published online: 26 September 2025
© The Author(s) 2025



Abstract

Potato is an economically important non-grain, semi-perishable agricultural commodity. However, potato tubers become highly prone to moisture loss and quality deterioration after harvest, contributing to post-harvest losses. The present study, therefore, investigated the efficacy of various plant extracts on the retention of post-harvest quality of potato tubers. Freshly harvested ‘Sifra’ potato tubers were dipped into plant extracts (10 g/L level) and allowed to air-dry for 1 h on the benchtops before storage at ambient conditions (day: 22 ± 2 °C and $45 \pm 5\%$ RH). The treatments were as follows: *Ascophyllum nodosum* extract (ANE), aloe vera leaf extract (AVE), garlic bulb extract (GBE) and moringa leaf extract (MLE), as well as the control (water only). Plant extract applications, as post-harvest treatments, significantly ($p \leq 0.05$) influenced post-harvest quality of potato tubers. During storage, AVE application reduced physiological mass loss during storage by 60% compared with the control. Moreover, ANE and MLE treatment application considerably increased potato mineral concentrations and the presence of total soluble solids. These treatments also gave the most promising results as they showed the highest retention potential of tuber vitamin C, total carbohydrate, protein, phenolic and flavonoid concentrations, as well as antioxidant activity during storage. Based on these results, the use of natural plant extract, as an alternative to current chemical applications, is highly advisable and recommended to preserve post-harvest quality of potato tubers, without compromising consumers’ health.

Keywords Agrochemicals · Antioxidant activity · Nutritive value · Solanaceae · Storage

✉ Siphokuhle Mbuyisa
mbuyisas03@gmail.com

¹ School of Agriculture, Earth and Environmental Sciences, University of KwaZulu-Natal, P Bag X01 Scottsville, Pietermaritzburg 3209, South Africa

² Department of Horticulture, Durban University of Technology, P.O Box 1334, Durban 4000, South Africa

Introduction

The world's population is increasing exponentially and expected to reach 9.7 billion people by 2050 (Searchinger et al. 2013). Consequently, the global food demand is also projected to increase by 35–56% between years 2010 and 2050 (Van Dijk et al. 2021). To achieve sustainable development goals 1 and 2, no poverty and zero hunger respectively, potato (*Solanum tuberosum* L.), has a high potential to counteract this rising worldwide food demand (Devaux et al. 2014), as it is a versatile staple food crop, consumed in many parts of the world (Birch et al. 2012; Hussain 2016). In terms of human consumption, potato is ranked the fourth-most economically important food crop, after rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) (Zhang et al. 2017), with an annual global production exceeding 376 million tons (FAO 2022). Apart from being an excellent source of carbohydrates, Mahmud et al. (2015) noted that potatoes contain significant amounts of vitamins, minerals, crude protein, crude fats and fibre. In addition, Lovat et al. (2016) found a variety of antioxidant compounds present in potatoes, such as vitamin C, flavonoids, carotenoids and polyphenols; all these phytochemicals exhibit antioxidant properties, hence, are vital to human health.

Unlike cereal crops, potatoes are semi-perishable; hence, they become highly susceptible to moisture loss immediately after harvest, resulting in structural, nutritional and biochemical changes (Chen et al. 2024). These post-harvest changes are induced predominantly by the biological processes of sprouting, greening, respiration and transpiration, all contributing to post-harvest disease occurrences such as *Phytophthora infestans*, *Phytophthora erythroseptica* and *Pectobacterium carotovorum*, thus, causing significant post-harvest losses (Paul et al. 2016; Sinha et al. 2018). Worldwide, post-harvest losses are amongst the most-devastating challenges to the potato industry, accounting for 20–25% of annual produce losses. In developing countries, potato post-harvest losses range from 15 to 50% (FAO 2022). There is, however, very limited information available on post-harvest losses of potatoes in South Africa (Beretta et al. 2013).

Several strategies have been tested and found effective in reducing post-harvest losses of potatoes. Use of certain synthetic chemicals, such as sprout suppressants (e.g., chlorpropham and maleic hydrazide), fungicides or bactericides (e.g., Mancozeb®, Ridomil Gold® MZ and Metalaxyl®, chlorothalonil, copper oxychloride and copper sulfate), is amongst the most effective strategy employed to reduce potato post-harvest losses (Daniels-Lake 2013; Majeed et al. 2017). Despite their efficacy, a reduction in their application is required due to the possible detrimental effects they pose to human health and the surrounding environment. Given these adversities, new, innovative and eco-friendly alternative approaches that could be employed to reduce post-harvest losses without jeopardising consumers' health and the environment need to be explored.

The use of natural products, especially of plant-derived extracts, is emerging as a new technology to maintain potato quality, as these products have gained attention as alternative treatments due to their potential in improving food safety and

appearance by protecting produce from external factors; thus, they can improve post-harvest quality (Ogbuehi et al. 2016). These compounds have been tested by various authors using many horticultural commodities, including ‘Tommy Atkins’ mango (*Mangifera indica* L.) (Melo et al. 2018a, b; Shrestha et al. 2018), guava (*Psidium guajava*) (Malik et al. 2015), and blueberry (*Vaccinium corymbosum*) (Jaime-Guerrero et al. 2022). Interestingly, natural extract application has also been tested on vegetables, such as eggplant (*Solanum melongena* L.) (Ogbuehi et al. 2016), kale (*Brassica oleracea* var. *sabellica* L.) (Melo et al. 2018a, b), and tomatoes (*Solanum lycopersicum* L.) (Tunwari et al. 2019). Little information is available on the natural extract application on potatoes post-harvest; therefore, the current study aimed to evaluate the efficacy of pre- and post-harvest plant extract applications on post-harvest quality of potatoes.

Materials and Methods

Site, Plant Material, and Growing Conditions

The study was conducted in the post-harvest laboratory of the University of Kwa-Zulu-Natal, Pietermaritzburg Campus, South Africa ($-29^{\circ}62'57.3''$ S $30^{\circ}40'45.3''$ E). ‘Sifra’ potato tubers used in this experiment were harvested from plants grown in a glasshouse at the Controlled Environment Facility (CEF). Those potato plants, where tubers were harvested, were treated pre-harvest using various plant extracts, viz. aloe vera (*Aloe barbadensis*) leaf extract (AVE), *Ascophyllum nodosum* extract (ANE), garlic (*Allium sativum*) bulb extract (GBE) and moringa (*Moringa oleifera*) leaf extract (MLE), as well as the control (untreated). At pre-harvest, these treatments were applied bi-weekly starting from 4 weeks after emergence until tuber harvesting. After harvest, same extracts were used as post-harvest treatments in the post-harvest experiment. The environmental conditions in the laboratory were maintained at ambient temperature (22 ± 2 °C) and relative humidity ($45 \pm 5\%$) throughout the storage period.

Collection of Plant Material and Extract Preparation

To prepare the plant extracts, various plant materials were purchased from different suppliers. Brown algae powder was bought from a local market (Dis-Chem, Woodburn Mall, Pietermaritzburg, South Africa), while fresh Egyptian white garlic bulbs were obtained from a local supermarket. Fresh moringa leaf powder (MLP) was supplied by a commercial supplier (runKZN, Pietermaritzburg, South Africa), whereas healthy aloe vera plants were purchased locally from Woodland Nursery (Pietermaritzburg, South Africa). The plant extracts were prepared following the method described by Ngcobo and Bertling (2021) (ANE and MLE), Noor et al. (2008) (AVE) and Ting-Ting et al. (2012) (GBE), with slight modifications. Exactly 10 g of each plant material was weighed and homogenised in a glass beaker with 450 mL distilled water. The homogenates were then placed on

a hot plate, continuously agitated with a magnetic stirrer and boiled for 30 min at 100 °C. After boiling, the solutions were left to cool down for 2 h; then the supernatants were collected by filtering three times through muslin cloth. The filtrate was then diluted with distilled water to a final volume of 1 L.

Experimental Design

A completely randomised design (CRD) with two factors: treatments and storage period, was used in this experiment, with treatments as the first factor and storage period as the second. The treatments applied were AVE, ANE, GBE, MLE and a control, each replicated five times. The storage period was divided into five different levels: 0, 7, 14, 21 and 28 days. In this experiment, ‘Sifra’ potato tubers were selected and assigned randomly to each storage period level. Immediately after harvest (day 0), tubers were immersed in the respective treatments for 30 s, then placed on the laboratory bench and allowed to air-dry before storage under ambient conditions (25 ± 2 °C and 45% RH). Data on mass loss percentage were collected before immersion and recorded weekly until day 28, the last day of the storage period. In addition to mass loss percentage, nutritional quality parameters, including total carbohydrate, total protein, vitamin C, total phenolic, total flavonoid concentration and total antioxidant activity, were measured at each storage interval. Before these measurements, the periderm of tubers was peeled off and the samples were freeze-dried using a VirTis Benchtop Pro freeze dryer (VirTis BTP-9EGE0X, New York, USA).

Determination of Nutritional Quality Parameters

Mass Loss (%)

Tuber mass was recorded immediately after harvest (initial mass, M_i), then weekly until day 28 of storage using a fine analytical balance (AS220.R2. PLUS, Rawdweg Wagi Elektroniczne, Poland). Mass loss (%) was determined using the following equation:

$$ML(\%) = \frac{M_i - M_f}{M_i} \times 100 \quad (1)$$

where M_i is the initial tuber mass and M_f is the tuber mass on day 28 of storage.

Determination of Total Soluble Solids (TSS)

Total soluble solid percentage (TSS) was determined using a refractometer (RFM340+, Bellingham + Stanley Ltd, Tunbridge Wells, UK) and expressed in °Brix, where 1°Brix = 1 g sucrose/100 g extract solution.

Determination of Total Carbohydrate Concentration

The total carbohydrate concentration was determined using a slightly modified version of the traditional phenol–sulfuric acid method (DuBois et al. 1956). Freeze-dried potato flour (0.5 g) was weighed and transferred into test tubes, followed by addition of 80% ethanol. The solutions were then vortexed and incubated in a water bath at 85 °C for 15 min. After incubation, the samples were placed on ice for 5 min before 10 mL filtrate was obtained using Whatman filter paper No. 1. An aliquot (1 mL) of the clear filtrate was mixed with 1 mL distilled water and transferred into thoroughly rinsed test tubes. Subsequently, 1 mL 5% phenol solution (Sigma-Aldrich, Burlington, MA, USA) and 2.5 mL 75% H₂SO₄ were added for colour development. The samples were incubated at 85 °C for 10 min and then cooled on ice. The absorbance was measured at 490 nm on a UV-1800 spectrophotometer (Shimadzu, Kyoto, Japan). The carbohydrate concentration of each sample was calculated using a standard curve prepared with a glucose solution (20 mg/mL) and the resulting equation ($y=0.0974x-0.0467$; $R^2=0.9917$). The results were expressed in mg glucose equivalent per g dry mass (DM).

Determination of Total Protein Concentration

The protein concentration was determined using the procedure developed by Bradford (1976). Freeze-dried, ground potato material (0.5 g) was weighed using a Ohaus Scout® portable analytical balance (SPX2022, Parsippany, NJ, USA) and transferred into centrifuge tubes. Then, 30 mL 100 mM TRIS buffer (pH 8.0) was added and the mixture was vortexed. The samples were subsequently centrifuged using an Avanti J-26S XP centrifuge (Beckman Coulter, Brea, CA, USA) at 12,096 G for 15 min at 5 °C. After centrifugation, 0.1 mL of the supernatant was transferred to test tubes, followed by the addition of 5 mL Bradford reagent. The absorbance of each sample was measured spectrophotometrically using a UV-1800 spectrophotometer (Shimadzu, Kyoto, Japan) at 590 nm. Protein concentration was calculated from a standard curve prepared using bovine serum albumin (BSA) (Sigma-Aldrich, Burlington, MA, USA) with the equation ($y=0.0056x+0.1201$; $R^2=0.9842$) and expressed in mg BSA per g DM.

Determination of Tuber Vitamin C Concentration

Vitamin C was quantitatively determined using the 2,6-dichlorophenolindophenol (DCPIP) method developed by Boonkasem et al. (2015), with slight modifications. Freeze-dried potato powder (0.05 g) was weighed using Ohaus Scout® portable analytical balance (SPX2022, Parsippany, NJ, USA) and transferred into centrifuge tubes. Then, 20 mL of 3% metaphosphoric acid was added to each tube and the samples were centrifuged at 12,098 G for 10 min. The supernatant was collected and 1 mL of the supernatant was mixed with 3 mL of 0.2 mM DCPIP and agitated for 15 s. The absorbance of the samples was measured using a UV-1800 spectrophotometer (Shimadzu, Kyoto, Japan) at 515 nm. The vitamin C concentration was calculated using the equation $y=-0.0368x+0.8879$ ($R^2=0.9942$). Results were

expressed in mg vitamin C equivalent (AAE) per 100 g dry mass (mg AAE/100 g DM).

Determination of Total Phenolic Concentration (TPC)

The total phenolic concentration of potato tubers was determined using a slightly modified Folin-Ciocalteu assay, as described by Wang et al. (2009). Freeze-dried potato flour (0.5 g) was weighed using Ohaus Scout® portable analytical balance (SPX2022, Parsippany, NJ, USA) and transferred into centrifuge tubes. After adding 25 mL of 80% acetone and vortexing, the samples were centrifuged at 12,298 G for 30 min at 5 °C. Then, 1 mL of the supernatant was mixed with 2.5 mL 0.2 N Folin-Ciocalteu reagent and left to stand for 5 min. Thereafter, 4 mL Na₂CO₃ was added, followed by incubation at 80 °C for 30 min. After incubation, the tubes were cooled on ice for 5 min and the absorbance was measured using a UV-1800 spectrophotometer (Shimadzu, Kyoto, Japan) at 736 nm. The total phenolic concentration was calculated using a gallic acid standard curve ($y=0.0229x+0.1907$; $R^2=0.9886$) and expressed as mg gallic acid equivalent (GAE) per g sample mass (mg GAE/g DM).

Determination of Total Flavonoid Concentration (TFC)

The total flavonoid concentration (TFC) was quantitatively determined using the aluminium chloride (AlCl₃) assay described by Gu et al. (2019), with slight modifications. Freeze-dried potato flour (0.5 g) was weighed using Ohaus Scout® portable analytical balance (SPX2022, Parsippany, NJ, USA) and transferred into centrifuge tubes. To extract flavonoids, 10 mL of 95% ethanol was added as the extraction solvent and the samples were mixed using a vortex (Vortex-Genie 2, New York, NY, USA). The tubes were then incubated at 25 °C for 30 min before being filtered through Whatman No. 1 filter paper to remove residues and obtain clear supernatants. After filtration, 100 µL of the supernatant and 100 µL AlCl₃ were simultaneously added to test tubes. Before further incubation at 25 °C for 30 min, 200 µL sodium acetate solution was added to the mixture. The absorbance of the prepared samples was measured using a UV-1800 spectrophotometer (Shimadzu, Kyoto, Japan) at 440 nm. A quercetin standard curve ($y=0.027x+0.102$; $R^2=0.989$) was used to determine TFC, expressed as quercetin equivalents (QE) per gram dry mass (mg QE/g DM).

Determination of Antioxidant Activity [DPPH (2, 2-Diphenyl-1-Picrylhydrazyl)]

The free radical scavenging ability was using the 2,2-diphenyl-1-picrylhydrazyl antioxidant (DPPH) assay described by Rocchetti et al. (2019), with slight modifications. Freeze-dried potato flour (0.5 g) was weighed using Ohaus Scout® portable analytical balance (SPX2022, Parsippany, NJ, USA) and transferred into test tubes. Then, 10 mL of 95% ethanol was added and the samples were vortexed. The test tubes were incubated at 25 °C for 10 min before the supernatant was filtered through Whatman No. 1 filter paper to remove sample residues. After obtaining clear supernatant, 100 µL sample and 300 mL 0.1 mM DPPH (0.1 mM in 95%

methanol) reagent were added to the test tubes, which were then incubated in the dark for 30 min. The absorbance was measured using a UV-1800 spectrophotometer (Shimadzu, Kyoto, Japan) at 517 nm. The DPPH scavenging ability was calculated using a linear equation ($y = -0.0368x + 0.8879$; $R^2 = 0.994$) and was expressed as vitamin C equivalent per gram sample dry mass (mg AAE/g DM).

Statistical Analysis

GenStat statistical software (GenStat®, 21 st edition, VSN International, UK) was used for the analysis of variance (ANOVA) to determine significant differences. Duncan's multiple range test at a 5% level of significance ($p \leq 0.05$) was applied for mean separation and comparison.

Results

Mass Loss (%)

Mass loss of potato tubers increased with storage duration, as expected; however, all post-harvest treatments significantly reduced ($p \leq 0.05$) mass loss more so than the control (Figure 1). The mass lost over the 28-day storage by the AVE treatment was significantly less than that of other treatments; hence, AVE recorded the lowest mass loss percentage (17.84%), followed by ANE and MLE, which recorded 20.71 and 23.11% mass loss, respectively (Figure 1).

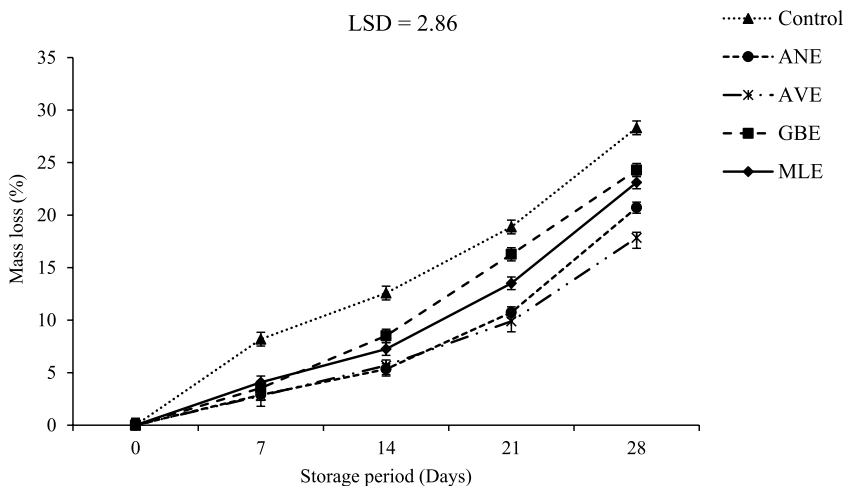


Fig. 1 Influence of pre- plus post-harvest treatments on the rate of mass loss of potatoes during storage. Control (no application), ANE (*Ascophyllum nodosum* extract), MLE (moringa leaf extract), GBE (garlic bulb extract) and AVE (aloe vera leaf extract). LSD at ($p \leq 0.05$) = 2.86. Points indicate means ($n = 5$) $\pm$ standard error

Total Soluble Solids (TSS)

Analysis of variance of the total soluble solids (TSS) indicated significant differences ($p \leq 0.05$) between treatments (Figure 2). As expected, the TSS of tubers increased with storage duration; hence, after 28 days of storage, TSS values of treated potato tubers were significantly higher than the control (Figure 2). Specifically, ANE and MLE applications increased TSS significantly, yielding the highest TSS values (5.58 & 5.38 °Brix, respectively) on day 28 of storage compared with other treatments.

Total Carbohydrate Concentration

Significant differences ($p \leq 0.05$) between treatments were observed over the storage period. The total carbohydrate concentration decreased with storage duration for all treatments (Figure 3). While total carbohydrates decreased, pre- and post-harvest application of all plant extracts sustained carbohydrates at a higher concentration than the control (Figure 3). On day 28 of storage, MLE and ANE recorded 6.27 and 5.45 mg/g DM, respectively; hence, these two treatments were not significantly different, although MLE had a tendency to outperform ANE. These two treatments

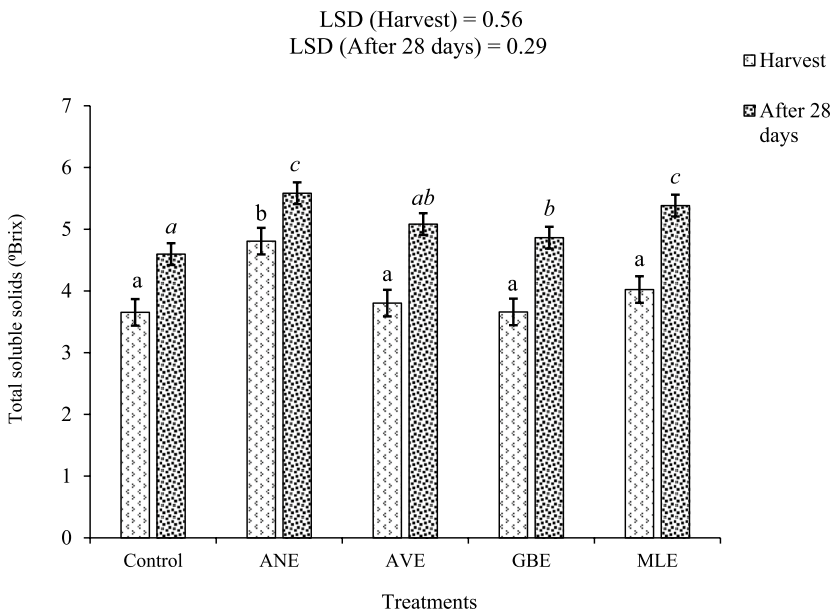


Fig. 2 Effect of pre- plus post-harvest treatments on the total soluble solids (TSS) of potatoes stored for 28 days. ANE (*Ascophyllum nodosum* extract), AVE (aloe vera leaf extract), GBE (garlic bulb extract), MLE (moringa leaf extract) and Control (no application). According to Duncan's multiple range test ($p \leq 0.05$), bars followed by different lowercase letters indicate significant differences between treatments. LSD ($p \leq 0.05$) (Harvest)=0.56 and (After 28 days)=0.29. Bars indicate means ($n=5$) $\pm$ standard error

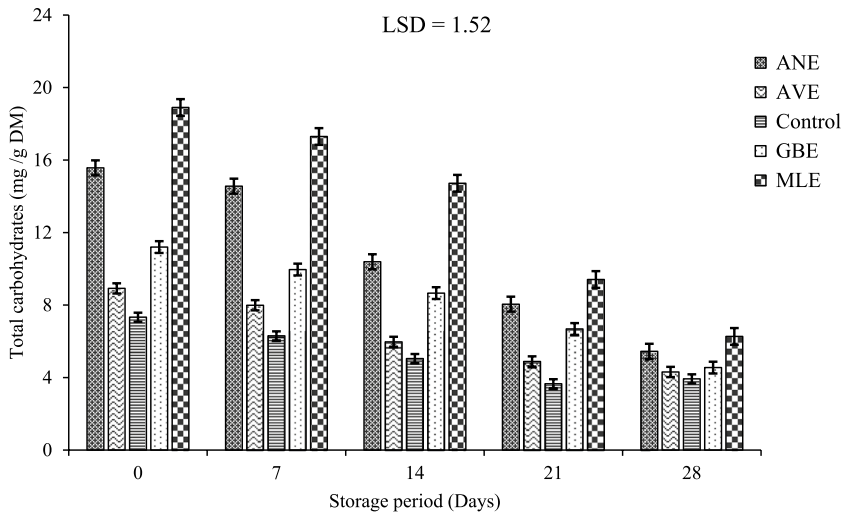


Fig. 3 Influence of pre- plus post-harvest treatments on total carbohydrate concentration of potatoes stored for 28 days. ANE (*Ascophyllum nodosum* extract), AVE (aloe vera leaf extract), GBE (garlic bulb extract), MLE (moringa leaf extract) and Control (no application). LSD at ($p \leq 0.05$) = 1.52. Bars indicate means ($n=5$) $\pm$ standard error

resulted in a significantly higher carbohydrate concentration compared to all other treatments.

Total Protein Concentration

The pre- and post-harvest treatments of potato tubers significantly maintained ($p \leq 0.05$) protein concentrations at levels higher than the control over the storage period. Total protein decreased with storage in all treatments, as expected; however, ANE-treated potatoes maintained the highest total protein concentration over the entire storage period. On day 28 of storage, this treatment recorded the highest protein concentration (77.4 mg/g DM), followed by MLE with about half of that protein (38.2 mg/g DM) (Figure 4).

Vitamin C

Significant differences ($p \leq 0.05$) in vitamin C equivalents (AAE) were observed between potatoes treated pre- and post-harvest with the various plant extracts. The vitamin C concentration decreased with the storage period, particularly up to day 21 of storage (Figure 5). ‘Sifra’ potato tubers treated with plant extracts showed a considerable decrease in vitamin C concentration lower than a control. On day 28 of storage, MLE treatment had a pronounced effect in vitamin C concentration, unlike other treatments, maintained levels higher than other treatments, recording 8.19 mg

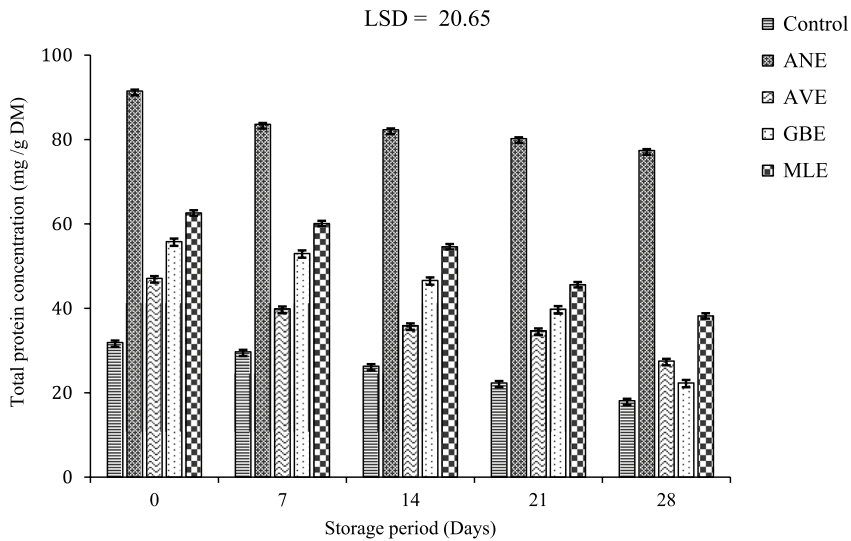


Fig. 4 Influence of pre- plus post-harvest treatments on total protein concentration of potatoes during storage. ANE (*Ascophyllum nodosum* extract), AVE (aloe vera leaf extract), GBE (garlic bulb extract), MLE (moringa leaf extract) and Control (no application). LSD at ($p \leq 0.05$) = 20.65. Bars indicate means ($n = 5$) $\pm$ standard error

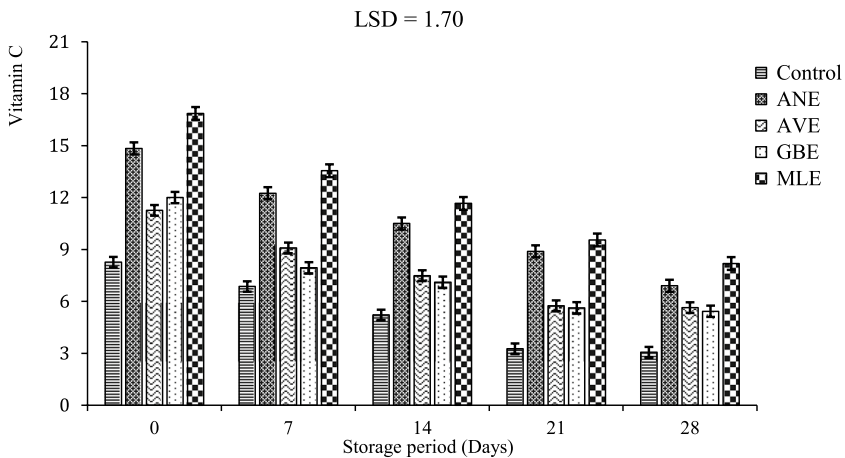


Fig. 5 Influence of pre- plus post-harvest treatments on vitamin C concentration of potatoes during storage. ANE (*Ascophyllum nodosum* extract), AVE (aloe vera leaf extract), GBE (garlic bulb extract), MLE (moringa leaf extract) and Control (no application). LSD at ($p \leq 0.05$) = 20.65. Bars indicate means ($n = 5$) $\pm$ standard error

AAE/g DM, with the second-highest concentration being ANE-treated tubers with 6.9 mg AAE/g DM.

Total Phenolic Concentration (TPC)

The total phenolic concentration (TPC) of potato tubers increased from harvest to day 7 of storage, then decreased gradually during further storage (Figure 6). The pre- and post-harvest treatment of potato tubers using all extracts positively affected total phenolic concentrations, maintaining TPC higher than the control until day 21 of storage. On day 28 of storage, the highest TPC was recorded in potato tubers treated with ANE (29.8 mg GAE/g DM), followed by MLE (22.47 mg GAE/g DM). The control recorded the lowest TPC (15.62 mg GAE/g DM).

Total Flavonoid Concentration (TFC)

Post-harvest treatment of potato tubers using all treatments significantly influenced ($p \leq 0.05$) TFC during the storage period. An increase in TFC was only observed from days 0 to 7, then decreased gradually with further storage (Figure 7). On day 28 of storage, ANE-treated tubers recorded the highest TFC (17.78 mg QE/g DM) compared with other treatments and the control. The second highest flavonoid concentration was found in MLE-treated tubers, which recorded 16.50 mg QE/g DM (Figure 7).

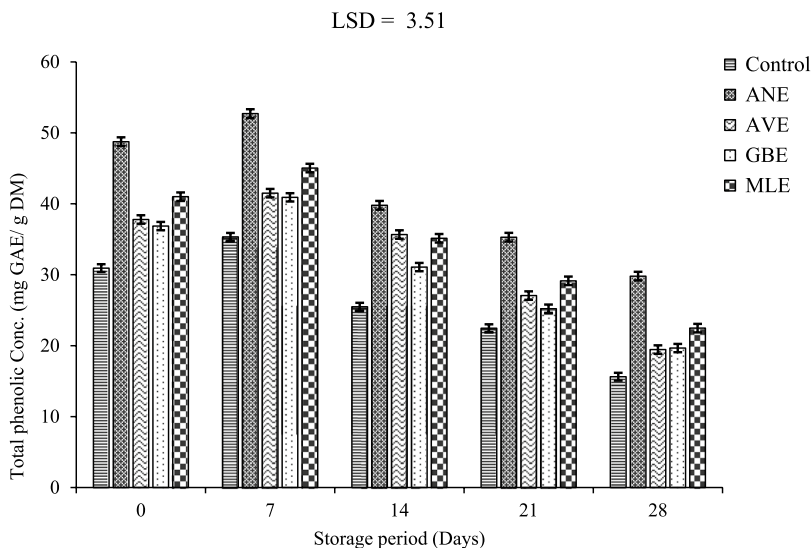


Fig. 6 Influence of pre- plus post-harvest treatments on total phenolic concentration of potatoes during storage. ANE (*Ascophyllum nodosum* extract), AVE (aloe vera leaf extract), GBE (garlic bulb extract), MLE (moringa leaf extract) and Control (no application). LSD at ($p \leq 0.05$) = 3.51. Bars indicate means ($n = 5$) $\pm$ standard error

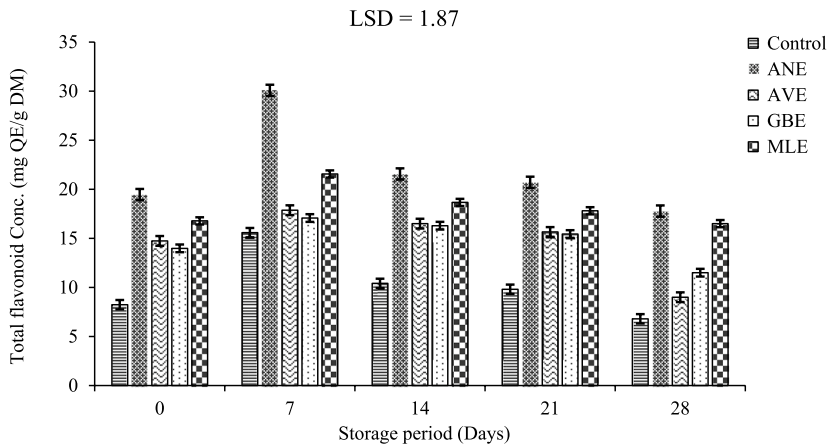


Fig. 7 Influence of pre- plus post-harvest treatments on total flavonoid concentration of potatoes during storage. ANE (*Ascopyllum nodosum* extract), ACE (aloe vera leaf extract), GBE (garlic bulb extract), MLE (moringa leaf extract) and Control (no application). LSD at ($p \leq 0.05$) = 1.87. Bars indicate means ($n=5$) $\pm$ standard error

Total Antioxidant Activity

Analysis of variance of the total antioxidant activity indicated a significant difference ($p \leq 0.05$) between the treatments (Figure 8). The total antioxidant activity of

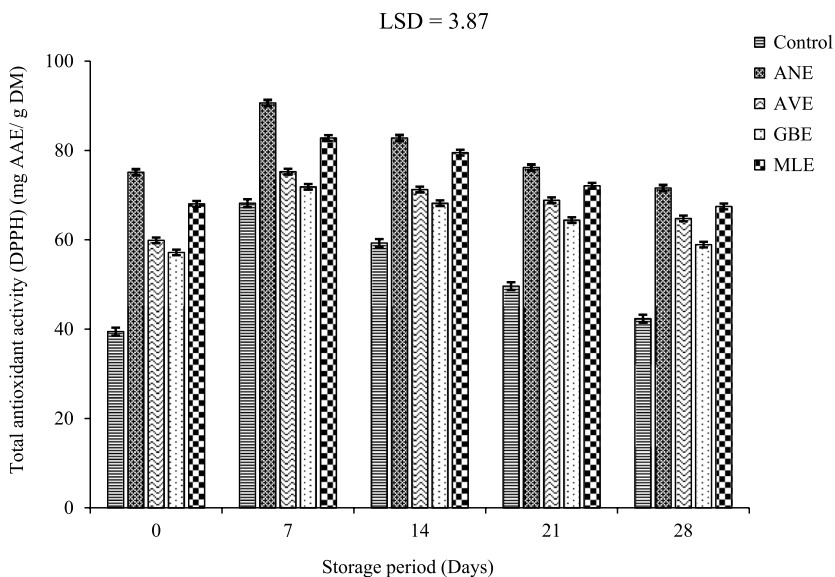


Fig. 8 Influence of pre- plus post-harvest treatments on total antioxidant activity of potatoes during storage. ANE (*Ascopyllum nodosum* extract), AVE (aloe vera leaf extract), GBE (garlic bulb extract), MLE (moringa leaf extract) and Control (no application). LSD at ($p \leq 0.05$) = 3.78. Bars indicate means ($n=5$) $\pm$ standard error

potato tubers increased from days 0 to 7 of storage, then decreased gradually with further storage period. On day 28 of storage, the total antioxidant activity of all treated potato tubers was considerably higher than the control (Figure 8). ANE treatment yielded the highest antioxidant activity, thus, recorded (71.59 mg AAE/g DM), followed by MLE (67.47 mg AAE/g DM) and AVE (64.78 mg AAE/g DM) at day 28 of storage.

Discussion

Due to the perishable nature of fruit and vegetables, protection and quality preservation of such food commodities have become vital components in achieving sustainable development goals 1 and 2, thereby achieving global food security (Ogunnubi et al. 2020). Plant extract application, as pre- and post-harvest treatments, has received large attention due to their positive effect on reduced post-harvest spoilage, extended shelf-life and preserved post-harvest quality, without posing negative effects on consumers' health and the ecosystem (Ogbuehi et al. 2016). Plant extracts have an immense potential to interfere with physiological processes that are part of post-harvest quality deterioration without causing adverse effects (Zulfikar et al. 2020). The present study, therefore, intended to evaluate the effects of various plant extracts on preserving the post-harvest quality of 'Sifra' potato tubers. The pre- and post-harvest application of natural plant extracts prepared from aloe vera leaves (AVE), *Ascophyllum nodosum* algae (ANE), moringa leaves (MLE) and garlic bulbs (GBE) had a positive influence on post-harvest quality of potato (Figs. 1, 2, 3, 4, 5, 6, 7 and 8).

Mass loss causes deterioration of structural and visual quality characteristics; thus, rendering tubers unmarketable, resulting in significant economic losses. In the present study, it was observed that mass loss increased with a longer storage period; however, dipping tubers into various plant extracts considerably reduced this mass loss over time (Fig. 1). These findings correspond with Liamngee et al. (2019), who found that dipping 'Roma' tomato fruit into MLE solutions of different concentrations substantially decreased mass loss during storage. Similarly, Fan et al. (2014) reported that an ANE concentration of 1.0 g/L significantly reduced the percentage mass loss of 'Unipack 12' spinach during a 35-day storage period. Abidi et al. (2023) also demonstrated a positive effect of olive leaf extract (5%), reducing mass loss of 'Blanvio 10' and 'Plagold 15' peaches (*Prunus persica*) during storage; these results are in line with the present study. Reduction in mass loss could be explained by plant extracts forming a layer around the tuber surface that is difficult to permeate (coating); hence, this treatment reduced the respiration rate by inhibiting gaseous exchange (Mahajan et al. 2018). Such a coating ultimately resulted in reduced moisture loss, thereby suppressing sprout development (Sogvar et al. 2016). In addition, plant extracts contain a wide range of compounds, such as vitamin C, phenolics and flavonoids, which exhibit antimicrobial and antioxidant properties (Tesfay et al. 2016). Application of such extracts, therefore, inhibits microbial or pathological attacks, thereby reducing tuber decay.

Generally, total soluble solids (TSS) are chemical components used to predict fruit maturity and shelf-life (Reboredo-Rodriguez et al. 2014); hence, this parameter helps to determine whether the nutritional status of the produce is acceptable, thereby alluding to its economic value. The present study reveals that potato tuber TSS increases with an increase in the storage period, although application of various plant extracts as post-harvest treatments, especially ANE and MLE, had a profound effect on maintaining tuber TSS levels during storage (Fig. 2). These findings are similar to Shrestha et al. (2018), who observed a significant increase in TSS levels of ‘Calcuttia Maldah’ mango fruit during storage, following the application of various plant extracts. An increase in TSS in fruit tissues over time could be attributed to the accumulation of sugars caused by the breaking down of complex starch molecules into simple sugars, such as glucose, fructose and sucrose (Brishti et al. 2013). Azene et al. (2014) reported that, as the fruit approaches senescence, stored carbohydrates are converted into simple soluble sugars, thereby increasing TSS; a similar trend was seen in our study (Fig. 3). The increase in TSS level could also be explained by the fact that ANE and MLE are polysaccharide-rich natural products (Abdalla 2014; Chater et al. 2016). Application of such extracts, therefore, could have increased the activity of certain enzymes, including sucrose synthase, invertase and amylase, resulting in the hydrolysing of starch molecules and converting them into simple, soluble sugar molecules (Kumar et al. 2009), thereby increasing tuber TSS.

Carbohydrates are the most abundant and widely distributed primary metabolites in horticultural commodities, especially in root vegetables and tubers, which comprise 15–25% carbohydrates (Yahia and Carillo-Lopez 2018). In most agricultural crops, carbohydrates contribute significantly to texture, colour, flavour and nutritive value (Yu et al. 2021). Carbohydrates also fuel and regulate the accumulation of specialised ‘sensory’ compounds that are crucial post-harvest quality of agricultural commodities (Trouvelot et al. 2014). In the present study, it was observed that carbohydrates decrease with an extended storage period (Fig. 5). Although carbohydrates overall declined, treatment application, especially MLE, had a pronounced effect, maintaining carbohydrates of tubers during storage at levels higher than the control (Fig. 3). These findings coincide with Idah and Aderibigbe (2007), who noted a significant decline in carbohydrate concentration in dried tomatoes as the storage period continues. Idah et al. (2010) also demonstrated a considerable decrease in carbohydrate concentration as the storage period of tomato and orange (*Citrus sinensis*) was extended, similar to the results found in the present study. Similarly, Famuyin et al. (2020) demonstrated a significant decrease in carbohydrate concentration in cherry tomatoes (*Solanum lycopersicum* var. *cerasiforme*) during 18-day refrigerated storage. These carbohydrates decline during storage could be due to the breaking down of complex, insoluble starch molecules into simple, soluble sugar, ultimately increasing TSS (Fig. 2). The decrease in carbohydrate concentration could also be due to plant extract applications, which might have increased sucrose synthase, invertase and amylase activity; hence, resulting in the hydrolysis and faster conversion of complex starch molecules into simple sugars (Kumar et al. 2009), thereby decreasing tuber carbohydrates. Additionally, a decrease in carbohydrate concentration could

be closely linked to oxidation processes due to the available O₂ triggering the conversion of starch into simple sugars (Azene et al. 2014).

Generally, proteins are essential in plants and play important roles in many biological processes, such as fruit development, ripening and senescence (Pedreschi 2017). Most importantly, proteins play a pivotal role as enzymes (Rasheed et al. 2020) and take part in various metabolic pathways, producing compounds that induce resistance of fruit and vegetables to abiotic and biotic stimuli (Pedreschi 2017). Although potatoes are rich in protein, changes occurring in the protein concentration of potato tubers during storage have not been studied extensively. The present study demonstrates that the protein concentration decreases with an increase in the storage period (Fig. 4). This has been previously described by Idah et al. (2010), who observed a significant decrease in protein concentration with an increase in the storage period of tomato and orange fruit. Similarly, Lee and Cho (2012) reported a decline in protein concentration of black soybean (*Glycine max*) stored at room temperature. The application of various plant extracts, especially ANE, had, however, a preservative effect on protein concentrations during storage (Fig. 4). The decline in protein during storage could be due to Maillard reactions, which occur between free amino groups of protein and carbonyl groups of reducing sugars, forming complex intermediate compounds by interacting with each other during storage (Rehman 2006). These complex intermediate compounds, therefore, might have inhibited proteolytic and amylolytic enzyme activities, causing a distinct decrease in protein levels (Lee and Cho 2012). In addition, proteins also play a crucial role in secondary metabolite production, especially of solanine, a glycoalkaloid compound that could induce protection of tubers against post-harvest stress (Barceloux 2009). This solanine production could have caused the total tuber protein concentration to decrease with storage. This phenomenon suggests that potato proteins might have been broken down into simple peptides and amino acids during storage (Shewry et al. 1995). The protein concentration-preservative effect of ANE could be due to the amount of protein this plant extract contains (Nayak et al. 2020). Potatoes are an excellent source of protein compared to other staple food crops; thus, reducing the decline in protein content is highly beneficial in sustaining its nutritional status.

In recent years, the consumption of plant-based foods, particularly fruit and vegetables, has gained immense attention due to their potential positive role in human health (Külen et al. 2013). Intake of plant foods with high concentrations of the analysed phytochemicals has been associated with the reduced risk of chronic disease, including cancer, diabetes and atherosclerosis (Gundgaard et al. 2003), as these foods contain significant amounts of phytochemicals, possessing antioxidant properties (Krinsky 2001). Vitamin C is synthesised via the Smirnoff-Wheeler pathway, converting sugars into galactose and L-galactolactone and, finally, vitamin C (Smirnoff and Wheeler 2024). In addition, phenolic compounds and flavonoids are major antioxidant compounds present in potato tubers, exhibiting antioxidant activity (Campos et al. 2006). Independent of treatment application, vitamin C decreased greatly with an increasing storage duration (Fig. 5), as also observed by Abidi et al. (2023), who noted a remarkable decline in vitamin C during peach storage. On the contrary, Galani et al. (2017) demonstrated a significant increase in vitamin C in potato tubers stored at room temperature (25–32 °C). Shrestha et al. (2018) also

reported that vitamin C concentrations initially increase, then decline during storage. This loss of vitamin C might be attributed to the rapid conversion of L-ascorbic acid into dehydro-ascorbic acid with the aid of ascorbic acid oxidase (ascorbinnase) (Shrestha et al. 2018). Moringa leaf extract (MLE) treatment had the highest ascorbic acid retention among all treatments throughout the storage period. This phenomenon might be ascribable to the fact that MLE contains vitamin C (Abdalla 2014). The pre-harvest foliar application of MLE, therefore, improved the transportation of vitamin C from the source to the sink (tubers), which ultimately resulted in enhanced vitamin C concentration even at post-harvest storage. This higher vitamin C concentration in MLE-treated tubers could also be due to the MLE application, which created a semi-permeable barrier on the tuber surface, thus, retarding the flow of oxygen into the tuber, in turn lowering the respiration rate (Singh 2000).

Total phenolic and flavonoid concentrations, as well as antioxidant activity, initially increased postharvest, then decreased (Figs. 6, 7 and 8). Loss of antioxidant compounds, especially phenolics and flavonoids, during the storage might be ascribed to their oxidative breakdown (Mditshwa et al. 2017). Galani et al. (2017) also reported that the decrease in antioxidant activity during storage could also be associated with the decreasing levels of antioxidant compounds (viz. ascorbic acid, phenolics, flavonoids, anthocyanins and carotenoids) (Figs. 5, 6 and 7). The best retention of total phenolics, flavonoids and antioxidant activity was observed following ANE application; this could be due to the fact that ANE is an excellent source of such compounds (Nayak et al. 2020). Exogenous application of ANE, therefore, also increased the internal concentration of antioxidant compounds in tubers; thus, tubers exhibited a high antioxidant activity following ANE treatment. These results are in line with Galani et al. (2017), who observed that total phenolic concentrations of potato tubers stored at room temperature (27 °C) initially increase, then decrease throughout the storage period. In contrast, Abidi et al. (2023) demonstrated a considerable decrease in total phenolic and flavonoid concentrations during peach storage.

Conclusion

Various plant-based extracts studied in this investigation had significant impacts on nutrient composition, post-harvest quality of potato tubers. The present study revealed that post-harvest dipping of potato tubers into plant extracts can improve post-harvest quality and prolong shelf-life. Application of plant extracts, especially of ANE and MLE, showed vast improvements in mineral concentrations, whereas AVE and ANE showed minimal physiological mass loss. In addition, total soluble solids, total carbohydrates, total proteins, vitamin C, total phenolics, total flavonoids and antioxidant activity were highest in ANE- and MLE-treated tubers. The performance of ANE and MLE was, hence, superior among all tested plant extracts, indicating that natural plant extract usage can be an excellent alternative for hazardous, synthetic pesticides. Plant extracts preserved post-harvest quality of potato tubers, while producing safer and healthier food for consumers.

Acknowledgements Technical support from Mr. Nkosi is gratefully acknowledged.

Author Contribution Conceptualisation: Isa Bertling and Siphokuhle Mbuyisa; methodology: Siphokuhle Mbuyisa; software: Siphokuhle Mbuyisa; validation: Siphokuhle Mbuyisa and Bonga Ngcobo; formal analysis: Siphokuhle Mbuyisa; investigation: Siphokuhle Mbuyisa; resources: Bonga Ngcobo; data curation: Bonga Ngcobo; original draft preparation: Siphokuhle Mbuyisa; review and editing: Isa Bertling and Bonga Ngcobo; visualisation: Bonga Ngcobo; supervision: Isa Bertling; project administration: Isa Bertling; funding acquisition: Siphokuhle Mbuyisa; supervision: Isa Bertling and Bonga Ngcobo.

Funding Open access funding provided by University of KwaZulu-Natal. This study was funded by the National Research Foundation (NRF), grant number (PMDS22061523208).

Data Availability The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Abdalla MM (2014) Boosting the growth of rocket plants in response to the application of *Moringa oleifera* extracts as a biostimulant. *J Life Sci* 11:1113–1121
- Abidi W, Akrimi R, Gouiaa M (2023) Impact of moringa leaf extract, olive leaf extract, and calcium chloride on quality attributes of peach cultivars during cold storage. *J Agric Sci Techn* 5:609–621
- Aulakh J, Regmi A (2013) Post-harvest food losses estimation: development of consistent methodology. Food and Agriculture Organization of the United Nations, Rome, Italy
- Azene M, Workneh TS, Woldetsadik K (2014) Effect of packaging materials and storage environment on post-harvest quality of papaya fruit. *J Food Sci Technol* 51:1041–1055. <https://doi.org/10.1007/s13197-011-0607-6>
- Barceloux DG (2009) Potatoes, tomatoes, and solanine toxicity (*Solanum tuberosum* L., *Solanum lycopersicum* L.). *Dis-a-Mon* 55:391–402. <https://doi.org/10.1016/j.disamonth.2009.03.009>
- Beretta C, Stoessel F, Baier U, Hellweg S (2013) Quantifying food losses and the potential for reduction in Switzerland. *Waste Manag* 33:764–773. <https://doi.org/10.1016/j.wasman.2012.11.007>
- Birch PR, Bryan G, Fenton B, Gilroy EM, Hein I, Jones JT, Prashar A, Taylor MA, Torrance L, Toth IK (2012) Crops that feed the world 8: potato are the trends of increased global production sustainable? *Food Secur* 4:477–508. <https://doi.org/10.1007/s12571-012-0220-1>
- Brishti FH, Misir J, Sarker A (2013) Effect of biopreservatives on storage life of papaya (*Carica papaya* L.). *Int J Food Sci* 2:126–136. <https://doi.org/10.7455/ijfs/2.1.2013.a10>
- Boonkasem P, Sricharen P, Techawongstein S, Chanthai S (2015) Determination of ascorbic acid and total phenolics related to the antioxidant activity of some local tomato (*Solanum lycopersicum*) varieties. *Der Pharma Chem* 7:66–70
- Bradford MM (1976) A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. *Anal Biochem* 72:248–254. <https://doi.org/10.1006/abio.1976.9999>
- Campos D, Noratto G, Chirinos R, Arbizu C, Roca W, Cisneros-Zevallos L (2006) Antioxidant capacity and secondary metabolites in four species of Andean tuber crops: native potato (*Solanum* spp.),

- mashua (*Tropaeolum tuberosum* Ruiz & Pavón), oca (*Oxalis tuberosa* Molina) and ulluco (*Ullucus tuberosus* Caldas). J Sci Food Agric 86:1481–1488. <https://doi.org/10.1002/jsfa.2529>
- Chater PI, Wilcox M, Cherry P, Herford A, Mustar S, Wheeler H, Brownlee I, Seal C, Pearson J (2016) Inhibitory activity of extracts of Hebridean brown seaweeds on lipase activity. J Appl Phycol 28:1303–1313. <https://doi.org/10.1007/s10811-015-0619-0>
- Chen Q, Yuan L, Guan Z (2024) Screening of plant essential oils as potato sprout suppressants at low storage temperature. Potato Res 67:325–338. <https://doi.org/10.1007/s11540-023-09637-5>
- Daniels-Lake BJ (2013) The combined effect of CO₂ and ethylene sprout inhibitor on the fry colour of stored potatoes (*Solanum tuberosum* L.). Potato Res 56:115–126. <https://doi.org/10.1007/s11540-013-9234-0>
- Devaux A, Kromann P, Ortiz O (2014) Potatoes for sustainable global food security. Potato Res 57:185–199. <https://doi.org/10.1007/s11540-014-9265-1>
- DuBois M, Gilles KA, Hamilton JK, Rebers P, Smith F (1956) Colorimetric method for determination of sugars and related substances. Anal Chem 28:350–356. <https://doi.org/10.1021/ac60111a017>
- Famuyin J, Patrick OA, Sedara A (2020) Effect of maturity stage on quality and shelf life of tomato (*Lycopersicon esculentum* Mill) using refrigerator storage system. Eurasian J Agric Res 4:23–44
- Fan D, Kandasamy S, Hodges DM, Critchley AT, Prithiviraj B (2014) Pre-harvest treatment of spinach with *Ascophyllum nodosum* extract improves post-harvest storage and quality. Sci Hortic 170:70–74. <https://doi.org/10.1016/j.scienta.2014.02.038>
- FAO (Food and Agriculture Organization of the United Nations). FAOSTAT Data (2022). Rome: FAO. <http://www.fao.org/faostat/en/?#data/QC>. Accessed 15 Jul 2023
- Galani JHY, Mankad PM, Shah AK, Patel NJ, Acharya RR, Talati JG (2017) Effect of storage temperature on vitamin C, total phenolics, UPLC phenolic acid profile and antioxidant capacity of eleven potato (*Solanum tuberosum*) varieties. Hortic Plant J 3:73–89
- Gopalakrishnan L, Doriya K, Kumar DS (2016) *Moringa oleifera*: a review on nutritive importance and its medicinal application. Food Sci Hum Wellness 5:49–56. <https://doi.org/10.1016/j.fshw.2016.04.001>
- Gu C, Howell K, Dunshea FR, Suleria HA (2019) LC-ESI-QTOF/MS characterisation of phenolic acids and flavonoids in polyphenol-rich fruits and vegetables and their potential antioxidant activities. Antioxidants 8:405. <https://doi.org/10.3390/antiox8090405>
- Gundgaard J, Nielsen JN, Olsen J, Sørensen J (2003) Increased intake of fruit and vegetables: estimation of impact in terms of life expectancy and healthcare costs. Public Health Nutr 6:25–30. <https://doi.org/10.1079/PHN2002355>
- Hussain T (2016) Potatoes: ensuring food for the future. Advances in Plants & Agriculture Research 3:178–182. <https://doi.org/10.15406/apar.2016.03.00117>
- Idah PA, Aderibigbe BA (2007) Quality changes in dried tomatoes stored in sealed polythene and open storage systems. Leonardo Electron J Pract Technol 10:123–136
- Idah PA, Musa JJ, Abdullahi M (2010) Effects of storage period on some nutritional properties of orange and tomato. AU J Technol 13:181–185
- Jaime-Guerrero M, Álvarez-Herrera JG, Ruiz-Berrío HD (2022) Postharvest application of acibenzolar-S-methyl and plant extracts affect physicochemical properties of blueberry (*Vaccinium corymbosum* L.) fruits. Agron Colomb 40:58–68. <https://doi.org/10.15446/agron.colomb.v40n1.100044>
- Krinsky NI (2001) Carotenoids as antioxidants. Nutrition 17:815–817. [https://doi.org/10.1016/S0899-9007\(01\)00651-7](https://doi.org/10.1016/S0899-9007(01)00651-7)
- Külen O, Stushnoff C, Holm DG (2013) Effect of cold storage on total phenolics content, antioxidant activity and vitamin C level of selected potato clones. J Sci Food Agric 93:2437–2444. <https://doi.org/10.1002/jsfa.6053>
- Kumar R, Singh S, Singh OV (2009) Bioconversion of lignocellulosic biomass: biochemical and molecular perspectives. J Microbiol Biotechnol 3(5):377–391. <https://doi.org/10.1002/chin.200928268>
- Lee JH, Cho KM (2012) Changes occurring in compositional components of black soybeans maintained at room temperature for different storage periods. Food Chem 131:161–169. <https://doi.org/10.1016/j.foodchem.2011.08.052>
- Liamngee K, Terna AC, Ussuh MW (2019) Effect of *Moringa oleifera* leaf extract on the postharvest quality of tomato fruits during storage. J Postharvest Technol 7:45–55
- Lovat C, Nassar AM, Kubow S, Li XQ, Donnelly DJ (2016) Metabolic biosynthesis of potato (*Solanum tuberosum* L.) antioxidants and implications for human health. Crit Rev Food Sci Nutr 56:2278–2303. <https://doi.org/10.1080/10408398.2013.830208>

- Mahajan BVC, Tandon R, Kapoor S, Sidhu MK (2018) Natural coatings for shelf-life enhancement and quality maintenance of fresh fruits and vegetables: a review. *J Postharvest Technol* 6:12–26
- Mahmud AA, Hossain M, Kadian MS, Hoque MA (2015) Physiological and biochemical changes in potato under water stress condition. *Indian J Plant Physiol* 20:297–303. <https://doi.org/10.1007/s40502-015-0173-4>
- Majeed A, Muhammad Z, Ullah Z, Ullah R, Ahmad H (2017) Late blight of potato (*Phytophthora infestans*): fungicides application and associated challenges. *Turk J Agric Food Sci Technol* 5:261–266. <https://doi.org/10.24925/turjaf.v5i3.261-266.1038>
- Malik AA, Bhat A, Ahmed N, Kaul R (2015) Effect of post-harvest application of plant extracts on physical parameters and shelf life of guava. *Asian Agri-Hist* 19:185–193
- Mbuyisa S, Bertling I, Ngcobo BL (2023) Impact of foliar-applied plant extracts on growth, physiological and yield attributes of the potato (*Solanum tuberosum* L.). *Agronomy* 14(1):38. <https://doi.org/10.3390/agronomy14010038>
- Mditshwa A, Magwaza LS, Tesfay SZ, Opara UL (2017) Post-harvest factors affecting vitamin C content of citrus fruits: a review. *Sci Hortic* 218:95–104. <https://doi.org/10.1016/j.scienta.2017.02.024>
- Melo MD, Sganzerla WG, Duarte GC, Ferrareze JP, de Lima Veeck AP, Ferreira PI (2018) Effect of rosemary, garlic, pepper and lemongrass extracts in post-harvest of organic Brassica oleracea L. leaves. *Communications in Plant Sciences* 8:75–81. <https://doi.org/10.26814/cps2018011>
- Melo TAD, Serra IMRDS, Sousa AA, Sousa TYO, Pascholati SF (2018) Effect of *Ascophyllum nodosum* seaweed extract on post-harvest ‘Tommy Atkins’ mangoes. *Rev Bras Frutic* 40:1–12. <https://doi.org/10.1590/0100-29452018621>
- Nayak P, Biswas S, Dutta D (2020) Effect of seaweed extracts on growth, yield and economics of ‘Kharif rice’ (*Oryza sativa* L.). *J Pharmacogn Phytochem* 9(3):247–253. <https://doi.org/10.22271/phyto.2020.v9.i3d.11269>
- Ngcobo BL, Bertling I (2019) Influence of foliar Moringa oleifera leaf extract (MLE) application on growth, fruit yield and nutritional quality of cherry tomato. *Acta Hort* 1306:249–254. <https://doi.org/10.17660/actahortic.2021.1306.31>
- Noor A, Gunasekaran S, Manickam AS, Vijayalakshmi MA (2008) Antidiabetic activity of Aloe vera and histology of organs instreptozotocin-induced diabetic rats. *Curr Sci* 94:1070–1076
- Ogbuehi HC, Emeribe EO, Asagwara JO (2016) Potential of ginger (*Zingiber officinale*) extracts on shelf-life of eggplant (*Solanum melongena* L.). *Int J Appl Pure Sci Agric* 2:171–178
- Ogunnupebi TA, Oluyori AP, Dada AO, Oladeji OS, Inyinbor AA, Egharevba GO (2020) Promising natural products in crop protection and food preservation: basis, advances, and prospects. *International Journal of Agronomy* 2020:8840046. <https://doi.org/10.1155/2020/8840046>
- Paul V, Ezekiel R, Pandey R (2016) Sprout suppression on potato: need to look beyond CIPC for more effective and safer alternatives. *J Food Sci Technol* 53:1–18. <https://doi.org/10.1007/s13197-015-1980-3>
- Pedreschi R (2017) Post-harvest proteomics of perishables. In *Proteomics in Food Science* (pp 3–16). Academic Press. <https://doi.org/10.1016/B978-0-12-804007-2.00001-1>
- Rasheed, F, Markgren J, Hedenqvist M, Johansson E (2020) Modeling to understand plant protein structure-function relationships-implications for seed storage proteins. *Molecules* 25:873. <https://doi.org/10.3390/molecules25040873>
- Reboredo-Rodríguez P, González-Barreiro C, Cancho-Grande B, Simal-Gándara J (2014) Quality of extra virgin olive oils produced in an emerging olive growing area in north-western Spain. *Food Chem* 164:418–426. <https://doi.org/10.1016/j.foodchem.2014.05.043>
- Rehman ZU (2006) Storage effects on nutritional quality of commonly consumed cereals. *Food Chem* 95:53–57. <https://doi.org/10.1016/j.foodchem.2004.12.017>
- Rocchetti G, Castiglioni S, Maldarizzi G, Carloni P, Lucini L (2019) UHPLC-ESI-QTOF-MS phenolic profiling and antioxidant capacity of bee pollen from different botanical origin. *Int J Food Sci Technol* 54:335–346
- Shewry PR, Napier JA, Tatham AS (1995) Seed storage proteins: structures and biosynthesis. *Plant Cell* 7:945. <https://doi.org/10.2307/3870049>
- Shrestha S, Pandey B, Mishra BP (2018) Effects of different plant leaf extracts on post-harvest life and quality of mango. *International Journal of Environment, Agriculture and Biotechnology* 3:239082. <https://doi.org/10.22161/ijeab/3.2.14>
- Sinha R, Khot LR, Schroeder BK, Sankaran S (2018) FAIMS-based volatile fingerprinting for real-time post-harvest storage infections detection in stored potatoes and onions. *Postharvest Biol Technol* 135:83–92. <https://doi.org/10.1016/j.postharvbio.2017.09.003>

- Smirnoff N, Wheeler GL (2024) The ascorbate biosynthesis pathway in plants is known, but there is a way to go with understanding control and functions. *J Exp Bot* 75:2604–2630. <https://doi.org/10.1093/jxb/erad505>
- Sogvar OB, Saba MK, Emamifar A (2016) *Aloe vera* and ascorbic acid coatings maintain post-harvest quality and reduce microbial load of strawberry fruit. *Postharvest Biol Technol* 114:29–35. <https://doi.org/10.1016/j.postharvbio.2015.11.019>
- Tesfay SZ, Modi AT, Mohammed F (2016) The effect of temperature in moringa seed phytochemical compounds and carbohydrate mobilization. *South Afr J Bot* 102:190–196. <https://doi.org/10.1016/j.sajb.2015.07.003>
- Ting-Ting W, Zhi-Hui C, Khan MA, Qing N, Ling H (2012). The inhibitive effects of garlic bulb crude extract on *Fulvia fulva* of tomato. *Acta Horticulturae* 43(5):2575–2580. <https://doi.org/10.17660/actahortic.2012.933.52>
- Trouvelot S, Héloir MC, Poinssot B, Gauthier A, Paris F, Guillier C, Combier M, Trad L, Daire X, Adrian M (2014) Carbohydrates in plant immunity and plant protection: roles and potential application as foliar sprays. *Front Plant Sci* 5:592. <https://doi.org/10.3389/fpls.2014.00592>
- Tunwari BA, Labaran AG, Aji PO, Kyugah JT, Williams WS (2019) Effect of plant extracts on post-harvest shelf-life and quality of tomato fruits in storage at Wukari, Taraba state. *International Journal of Agriculture, Environment and BioResearch* 4:0.35410/IJAEB.2019.4492
- Van Dijk M, Morley T, Rau ML, Saghai Y (2021) A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nat Food* 2:494–501. <https://doi.org/10.1038/s43016-021-00322-9>
- Wang T, Jonsdottir R, Ólafsdóttir G (2009) Total phenolic compounds, radical scavenging and metal chelation of extracts from Icelandic seaweeds. *Food Chem* 116:240–248. <https://doi.org/10.1016/j.foodchem.2009.02.041>
- Yahia EM, Carrillo-Lopez A (2018) Post-harvest physiology and biochemistry of fruits and vegetables: carbohydrates. Woodhead Publishing. 175–205:175. <https://doi.org/10.1016/B978-0-12-813278-4.00009-9>
- Yu J, Wang K, Beckles DM (2021) Starch branching enzymes as putative determinants of post-harvest quality in horticultural crops. *BMC Plant Biol* 21:1–16. <https://doi.org/10.1186/s12870-021-03253-6>
- Zhang H, Xu F, Wu Y, Hu HH, Dai XF (2017) Progress of potato staple food research and industry development in China. *J Integr Agric* 16:2924–2932. [https://doi.org/10.1016/S2095-3119\(17\)61736-2](https://doi.org/10.1016/S2095-3119(17)61736-2)
- Zulfiqar F, Casadesús A, Brockman H, Munné-Bosch S (2020) An overview of plant-based natural biostimulants for sustainable horticulture with a particular focus on moringa leaf extracts. *Plant Sci* 295:110194. <https://doi.org/10.1016/j.plantsci.2019.110194>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.