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Degradation Kinetic Modelling of Colour, Texture, Polyphenols and Antioxidant Capacity of York Cabbage after Microwave Processing

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Short running head: Effect of microwaving on physio-chemical properties of York cabbage

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Abstract

Vegetables as an essential component of the human diet usually undergo some type of processing before being consumed. In the present study, impact of microwave (MW) processing on various physiochemical properties of York cabbage was studied. York cabbage was processed at 400, 560 and 800W for 0 to 14 min with an increment of 2 min followed by a kinetic study for the degradation of polyphenols, flavonoids, antioxidant capacity, colour and texture were carried out. Results showed that MW processing leads to significant reductions in the texture, colour, polyphenols and antioxidant capacity. For all the MW processing power studied total phenolic content reduced by up to 85-90% while total flavonoid content reduced by up to 60-73% after 14 min of MW processing. These results were further confirmed by HPLC-DAD analysis. Serious losses in the antioxidant capacity (83-98%) were also observed as a result of MW processing as compared to fresh counterparts and a similar trend was observed for firmness, which reduced by up to 58.8-61.6%, and colour up to 15.2-36.9%. First-order reaction model showed a good fit for the different studied parameters, with coefficients of determination (R^2) ranging from 0.90 to 0.99, except for texture (firmness) and colour (chroma), which followed zero-order (R^2= 0.88-0.98).

Keywords: Antioxidant activity, colour, kinetic models, microwave, polyphenols, texture, York cabbage

1. Introduction

Fruits and vegetables are an essential component of the human diet. Evidences from epidemiological studies suggest that diets rich in fruit and vegetables are associated with a lower risk of several diseases like atheroscelerosis, stroke, cancer, diabetes, arthritis and aging (Southon, 2000; Blasa *et al.*, 2010). *Brassica oleracea* species constitutes a number of common vegetables like cauliflower, broccoli, kohlrabi, kale, cabbage and Brussels sprouts. Among these vegetables, cabbage is an economically and nutritionally important vegetable and consumed widely around the globe. It is rich in a number of biologically active metabolites such as vitamins, phenolic acids, flavonoids and isothiocyanates, which are associated with antioxidant (AO), antibacterial and anticancer properties and contribute to health promotion.

Fruits are most commonly consumed raw; however, vegetables such as cabbage usually undergo some type of processing before being consumed. Among the various available processing methods such as boiling, microwave (MW) and steaming; MW processing has gained more interest both for domestic purposes in addition to industrial applications. MW heating has many advantages over conventional heating including precise timing, rapidity, and energy saving (El-Abassy *et al*., 2010). It is 3-5 times faster than conventional heating; therefore, it has the potential to improve product quality with reduced heating time.

Microwaving relies on the application of dielectric heating in order to heat food products. This is accomplished by using MW radiation to heat water and other polarized molecules within the food, which lead to heat generation in the entire volume due to internal thermal dissipation of the vibrations of the water molecules in the food (Decareau, 1985; Kamel

and Stauffer, 1993). In contrast, conventional heating generates heat at the contact surface first, and then the heat diffuses inwards.

Thermal processing techniques emphasize the achievement of commercial sterility while minimizing changes in nutritional value and sensory properties. However, no matter how minimal the heating source is, thermal processing can promote reactions that could affect the overall quality of foods. Quality loss involves both subjective factors like taste that cannot be readily quantified, and quantifiable factors such as nutrient degradation (Awuah *et al.*, 2007). In recent years, many studies have been undertaken to investigate nutrient properties of various vegetables processed by MW heating such as ready to eat vegetables (Murcia *et al.*, 2009), broccoli (Zhang and Hamauzu, 2004), potato, carrot, onion, broccoli, and white cabbage (Faller and Fialho, 2009), peas, carrot, spinach, cabbage, cauliflower, turnips (Sultana *et al.*, 2008), broccoli, green beans and asparagus (Brewer and Begum, 2003). However, both positive and negative effects have been reported depending upon differences in process conditions and morphological characteristics of vegetables.

Data on the effect of MW processing on kinetic modelling of physiochemical properties of vegetables are scarce (Ramesh *et al.*, 2002). For the design of an optimized process that can lead to a maximized preservation of phytochemicals, kinetic modelling is necessary to derive basic kinetic information for a system in order to describe the reaction rate as a function of experimental variables and hence, to predict changes in a particular food during processing (Van Boekel, 2008; Yu *et al.*, 2011). A number of kinetic models such as zero-order, first-order and fractional conversion (FC) first-order have been used for phytochemical content, AO capacity, texture and colour degradation for a range of fruit and vegetables (Gonçalves *et al.*, 2010). Therefore, the purpose of our study was to

find out effects of MW processing of York cabbage on the degradation kinetics of a number of physiochemical properties such as texture, colour, polyphenols, and AO activity. These objectives are justified having in mind that the literature lacks some information on kinetic evaluation of phytochemicals, antioxidant capacity, physical characteristics such as colour and texture together upon MW processing.

2. Materials and methods

2.1 Plant materials and their preparation

Fresh Irish York cabbage (*Brassica oleracea var. capitata alba subvar. conica*) was purchased from a local supermarket in Dublin in April 2010. Eighteen to twenty York cabbage heads (25-30 kg) were randomly selected and trimmed of their outer leaves and stem. The heads were then divided into four segments and the central core was removed. The segments were chopped into 0.5 × 5-6 cm pieces, using a vegetable cutting machine. A pooled batch of about 18 kg chopped cabbage was stored in a plastic bag under dark refrigerated conditions (4°C±0.5) and was utilized as the raw material for all subsequent treatments. A 50 g sample was taken from the pooled batch (in duplicate) as reference for fresh, unprocessed cabbage.

2.2 MW processing

MW processing was carried out using a domestic oven (Sharp, Model R 244; Sharp Electronics (UK) Ltd, Manchester, Lancashire, M40 5BE) with a maximum output power of 800W. Microwave heating was carried out at 400, 560 and 800W which are 30, 50 and 100% of power output. The main reason behind specifying these power levels is to represent MW power typically applied in food processing applications. The procedure consisted of adding 50 g of chopped cabbage in 500 ml beaker filled with 100 ml deionize water and then was placed inside the MW oven. The microwaving time was noted as soon

as the vegetables were placed inside the MW at the studied power. For all the power levels studied, samples were withdrawn every 2 min up to 14 min. The processed material was drained, cooled in ice water (1-4ºC) for 1 min and then allowed to drain for 30 sec. The processed samples were kept in a plastic bag (20×25 cm) and colour and texture analysis were carried out on the same day. In order to eliminate bias, treatments were completely randomized and were performed in duplicate. The processed samples were submerged in liquid nitrogen and ground to a coarse powder using mortar and pestle and stored in plastic bags at –20°C until further analysis (10-15 days).

2.3 Preparation of extracts

A 5 g of crushed cabbage sample was extracted using 50 ml of 60% methanol. In order to prevent sample oxidation during the extraction process, a reduced environment was created using nitrogen flushing. Flasks were kept in a shaking incubator (Innova 42, Mason Technology, Dublin, Ireland) at 100 rpm and 40°C for 2 h. The infusions were filtered with Whatman #1 until a clear extract was obtained. The extracts were evaporated to dryness in a multi evaporator (Syncore Polyvap, Mason Technology, Dublin, Ireland) at 60°C at their respective pressure and stored at –20°C until used.

2.4 Phytochemical analysis

2.4.1 Determination of total phenolic and flavonoid content

Total phenolic content (TPC) and total flavonoid content (TFC) of samples were estimated according to our earlier report (Jaiswal *et al.*, 2012a). Fresh and MW processed cabbage extracts were dissolved in deionized water (1 mg/ml) as samples were soluble in water. In brief, for the TPC estimation, 100 µl aliquot of sample in deionized water were mixed with 2 ml of 2% Na_2CO_3 and were allowed to stand for 2 min at room temperature. After incubation, 100 µl of 1N Folin-Ciocalteau's phenol reagent was added. Reaction

mixture was allowed to stand for 30 min at room temperature in the dark. Absorbance of all the sample solutions was measured at 720 nm. Results were expressed as mg gallic acid (Sigma-Aldrich, Steinheim, Germany) equivalents per 100 g (mg GAE/100 g) fresh weight (fw) of cabbage.

For the TFC estimation, 250 µl of sample was mixed with 1.25 ml of deionized water and 75 µl of 5% $NaNO_2$ solution. After 6 min, 150 µl of 10% $AlCl_3 \cdot H_2O$ solution was added. Finally, 0.5 ml of NaOH (1M) solution was added and the total volume was made up to 2.5 ml with deionized water. Absorbance against blank was taken at 510 nm. Results were expressed as mg quercetin (Sigma-Aldrich, Steinheim, Germany) equivalents per 100 g (mg QE/100 g) fresh weight of cabbage.

2.4.2 HPLC-DAD analysis of polyphenolic compounds

HPLC-DAD analysis of fresh and MW processed cabbage polyphenols was carried out according to Jaiswal *et al.* (2011). In brief, the HPLC system consisted of a reversed-phase HPLC column on an Alliance HPLC (Waters, e2695 Separations modules) equipped with an auto sampler and controller with dual pump, a 2998 photodiode array detector (PDA) and the Empower software. An Atlantis C18 column (250 mm × 4.6 mm, 5µm particle size) from Waters (Waters, Milford, MA) was used for polyphenolic separation at 25ºC. All the solvents used were similar to our earlier report (Jaiswal *et al.*, 2011). The chromatogram was monitored at 280 nm and complete spectral data were recorded in the range of 220-600 nm.

2.5 Antioxidant capacity analysis

In the present study, four different methods namely 2,2-Diphenyl-1-picrylhydrazyl (DPPH) radical scavenging capacity, Ferric reducing AO potential (FRAP) assay, Lipid peroxidation in a hemoglobin-induced linoleic acid system (LPO) and Hydrogen peroxide

(H_2O_2) scavenging assay were used for the estimation of total AO capacity of the fresh and processed York cabbage. All the methods were carried out according to the existing protocols in our laboratory (Rajauria *et al.*, 2012). For the DPPH radical scavenging capacity and LPO inhibitory ability, ascorbic acid was used as a reference compound and the results were expressed as mg ascorbic acid equivalents per 100 gram (mg AscE/100g) (fw) of cabbage. Trolox was used as a standard for FRAP assay and the results were expressed as mg trolox equivalents per 100 gram (mg TE/100g) (fw) of cabbage; whereas BHT was used as a reference compound for H_2O_2 scavenging capacity and the results were expressed as mg BHT equivalents per 100 gram (mg BHTE/100g) (fw) of cabbage.

2.6 Instrumental texture analysis

The texture of the raw and MW processed samples was analyzed using an Instron texture analyzer (Instron 4302 Universal Testing Machine, Canton MA, USA) (Jaiswal *et al.*, 2012b). The texturometer was mounted with a 500 Newton (N) load cell and equipped with a Warner-Bratzler Blade (V-notch blade) which cut through the sample at a download speed of 50 mm/min. A 5 g sample was placed on two parallel bars with a gap of 10 mm between them. The maximum force (N) required to shear the sample was used as an indication of firmness. Data were analyzed by using Bluehill software. The firmness of 12 samples was measured individually and an average firmness value was calculated.

2.7 Instrumental colour analysis

The colour of the raw and MW processed cabbage was analyzed using Colour Quest XE colourimeter (Hunter Laboratory, Northants, U.K.). Before measuring, the hunter meter was calibrated using a white reference tile and a light trap (black tile). 50 g sample was filled in a transparent plastic bag (20×25 cm) (in duplicate) and five random areas were measured through the plastic pockets and mean values (total 10 readings/sample) were

reported for each treatment. The Hunter Lab co-ordinates [L^* (lightness, 0 for black to 100 for white), a^* (red-green) and b^* (yellow-blue)] were measured using the L^*, a^* and b^* Hunter scale parameters. Chroma was calculated according to the equation (1)

$$a^{*2} + b^{*2} \quad \text{(Eq. 1)}$$

2.7.1 Mathematical models and kinetic analysis

The degradation kinetics of York cabbage phenolic content, flavonoid content, different AO capacity, texture (firmness) change and colour change were described by fitting a zero order (Eq. 2) or a first-order kinetic model (Eq. 3) to the experimental data (Martins *et al*., 2000; Gonçalves *et al*., 2010)

$$A = A_0 - kt \quad \text{(Eq. 2)}$$

$$\frac{A}{A_0} = e^{-kt} \quad \text{(Eq. 3)}$$

Where, A is the parameter to be estimated, the sub index 0 indicates the initial value of the parameter, t is the MW processing time, and k is the rate constant at MW power (W). For the parameter estimation, the individual measured concentrations were used instead of mean values of duplicate or triplicate experiments, thus taking into account variability within the samples.

2.8 Statistical analysis

All experiments were done in triplicate and replicated twice unless otherwise stated. Results are expressed as mean values ± standard deviation. All the statistical analysis and data were fitted to models using STATGRAPHICS Centurion XV software. Values of P

< 0.05 were considered as statistically significant. The coefficient of determination (R^2) and mean square error (MSE) were used as criteria for adequacy of fit.

3. Results and discussion

3.1 The influence of MW processing on phytochemical content

TPC of fresh York cabbage was determined to be 147.5±6.63 mg GAE/100 g (fw). This value is within the range reported for fresh cabbage (Kim *et al*., 2004). In this study, variation in TPC of cabbage was observed upon the application of different MW processing conditions (Fig. 1A). For all of the MW processing power studied, processing for up to 2 min resulted in a severe loss of phenolic compounds, which accounted for almost 33.3-36.3% reduction as compared to fresh cabbage. The degradation continued up to 12 min of processing time resulting in a total reduction of 82.2-86.5%. As the processing time increased beyond 12 min (until 14 min), there was a further reduction of up to 2-3% for all MW powers studied. Reduction in TPC can be attributed to the better absorption of microwave energy, which increases temperature inside the plant cells, resulting in breaking of the cell walls and releasing compounds into the processing water.

The TFC of Fresh York cabbage was 95.4±8.40 mg QE/100 g (fw). The level of TFC reported was within the range observed by Lin and Tang (2007) and Andarwulan *et al.* (2010). Andarwulan *et al*. (2010) studied the flavonoid content of 11 vegetables from west Java, Indonesia and found that the level of TFC varied from 0.3 to 143 mg/100 g (fw) whereas Lin and Tang (2007) reported variation from 4.1 to 133.1 mg QE/100 g (fw). MW processing induced significant changes (P < 0.05) in cabbage flavonoid content. In the present study, TFC reduced by 14.6-15.9% after 2 min of MW processing at 400-800W and reached a final loss of 74.3% after 14 min of processing (Fig. 1B). It was also evident that an average loss of 5.8% per min was observed during initial

processing time (up to 4 min) which further reduced to 3.52% per min as the processing time increased beyond 4 min, therefore, the loss of TFC is almost double within the first 4 min of MW processing as compared to the rate after 4 min.

The levels of retention and losses of phenolic compounds during the different MW processing conditions can be understood by the lixiviation phenomenon that drives phenols into the processing water, which can be defined as the loss of organic or inorganic metabolites from the plant parts by the leaching into aqueous solution. This process is a function of temperature, time, and volume of cooking water (Andlauer *et al.*, 2003; Rocha-Guzmán *et al.*, 2007). These results was further confirmed my estimating the TPC and TFC of leached water, which showed the presence of polyphenols in significant concentrations which subsequently increased in line with processing time. Conclusions regarding the effects of microwave processing on TPC are not consistent in the literature. For example, Turkmen *et al*. (2005) showed that TPC of broccoli, spinach, green beans and pepper increased during microwave heating; suggesting that the application of heat could contribute to releasing more flavonols. Variations in the results obtained in this study with other published work could be also due to differences in processing conditions in addition vegetable type. However, López-Berenguer *et al*. (2007) have reported similar findings to those observed in the present study while processing broccoli. Similarly, Zhang and Hamauzu (2004), reported that raw broccoli floret contained 34.5 mg/100 g FW of total phenolics and the florets cooked for 5 min by microwave cooking retained 28.4% of total phenolics.

3.1.1 HPLC-DAD analysis of polyphenolic compounds

Fig. 2 shows the HPLC chromatogram at 280 nm for the polyphenolic compounds present in the fresh and processed (400W for 0 to14 min) York cabbage. Similar chromatogram

patterns were observed for the other applied powers. The basic reason to compare the phenolic profile with HPLC-DAD is to confirm the findings of the spectroscopic methods as Folin-Ciocalteu phenol reagent can be influenced by various interfering materials such as fats, terpenes, sugars and chlorophyll. Furthermore, it provides insights into how MW processing affects individual phenolic compounds.

In a previous study (Jaiswal *et al.*, 2012a), it was found that York cabbage contains a mixture of more than 20 phenolics and similar chromatogram were observed in this study. Five peaks were identified as hydroxybenzoic acid derivatives, four peaks as hydroxycinnamic acid derivatives, six peaks as flavones, two as polymethoxy flavonoid, and one peak of glycosylated flavonols and polymethoxylated flavonols (Jaiswal *et al.*, 2012a). While studying the chromatograms by comparing the peak area of processed and fresh York cabbage samples, the content of polyphenols was lower in MW processed as compared to fresh samples.

As evident from the magnified view of the chromatogram (Fig. 2), processing power and time had a significant effect on phenolic compounds and as the processing time increased there was a continuous reduction in the area of individual compounds belonging to hydroxybenzoic acid derivatives, hydroxycinnamic acid derivatives, flavones, polymethoxy flavonoid, glycosylated flavonols and polymethoxylated flavonols. This result is in agreement with the TPC and TFC results as estimated by spectroscopic methods. However, the concentration of some compounds belonging to flavonoid derevatives such as those eluted at 56.8, 59.8 and 60 min increased as a result of MW processing, but the increment was not significant as compared to total loss in phenolic compounds.

3.2 Kinetic analysis of phytochemical content

Degradation kinetic of the phytochemical content was modelled using zero-order (Eq. 2), and first-order (Eq. 3). Mean square error (MSE) and coefficient of determination (R^2) were used as statistical measures for comparison of the experimental and model simulated values. First-order kinetic model fitted the experimental data with high R^2 value, ranging from 0.96-0.97 for TPC and 90- 96 for TFC at 400 to 800W with lower MSE (Table 1).

Experimental and predicted (First-order kinetic models) data for degradation of TPC and TFC due to processing at the three power levels (400, 560 and 800W) are presented in Fig. 3A and 3B, respectively. For the TPC, the degradation rate constant (*k*) increased 1.4 times (0.150-0.214 min^{-1}) as the power increased from 400 to 800W. TFC degradation rate also showed a similar trend as rate constant increased from 0.144-0.197 min^{-1} as a consequence of the power increment. Ramesh *et al*. (2002) observed that the maximum temperature attained is directly proportional to the level of MW power. In order to evaluate the relationship between processing power and phytochemicals degradation, a graph was plotted between MW power and degradation kinetic parameter estimates (Not shown). The results showed a linear relationship between processing power and phytochemical degradation with the coefficient of determination (R^2) ranging from 0.94-0.99 for TPC and TFC, respectively; which confirms the strong relationship between processing power and phytochemical degradation.

3.2.1 The influence of MW processing on antioxidant capacity

Four *in vitro* methods based on different mechanisms of determination of the AO capacity were used to test phenolic compounds from York cabbage. AO capacity of MW processed samples was lower than fresh samples indicating that processing influenced the AO capacity of the York cabbage. Similar findings were also observed by Zhang and

Hamauzu (2004), these authors observed that the AOs in broccoli floret and stem decreased with the duration of thermal processing, no matter whether the cooking was carried out with conventional methods or MW heating. Chuah *et al.* (2008) studied the effect of processing including MW on the AO property of coloured peppers and reported that processing in the water reduced the AO property.

The AO capacity of 100 g fresh York cabbage in various AO systems were 187.6±8.08 mg AscE, 312.7±6.56 mg AscE, 667.8±109.9 mg BHTE and 26.4±0.13 mg TE for DPPH free radical scavenging capacity, LPO inhibitory ability, H_2O_2 scavenging capacity and FRAP value, respectively. During MW processing the DPPH free radical scavenging capacity (Fig.4A) decreased with longer MW processing time and higher power levels applied and pronounced loss was evident in the first 4 min of MW processing. The reduction was in the range of 18.4 to 25.1% for the first 2 min and 6.40 to 12.4% in the next 2 min at 400, 560 and 800W. Further reductions were observed but significantly less (3 to 4% per min) until 14 min of processing.

Higher reduction in AO capacity may be contributed by the free phenolic (flavonoids) which are easily available to leach into processing water, while cell wall bound phenolics such as hydroxycinnamic acid derivatives (caffeic, p-coumaric and ferulic acids) required higher MW power in order to liberate in the processing water. While comparing the DPPH free radical scavenging capacity at various power levels, results showed that there were no significant differences ($P > 0.05$) between the DPPH free radical scavenging capacity of cabbage processed at 400 and 560W, but it was significantly different ($P < 0.05$) from the samples processed at 800W for up to 6 min, however, significant differences became obvious among the various power levels beyond this processing time.

A similar trend was observed for LPO inhibitory ability (Fig. 4B). The reduction was in the range of 13.4 to 22.2% for the first 2 min and then 6.2 to 10.7% in the next 2 min at 400, 560 and 800W, and subsequently decreased until 14 min of processing. Initially (up to 8 min), there were no significant differences ($P > 0.05$) evident between the LPO inhibitory ability of cabbage processed at 400 and 560W but there was a significant difference ($P < 0.05$) from the 800W processed samples; however, after 8 min of MW processing, significant differences became obvious for the 3 power levels studies with respect to LPO inhibitory ability. It was anticipated that alterations in the polyphenol concentration lead to the overall reduction in the AO capacity. Since polyphenols vary in their chemical structures, and each type has distinct radical scavenging properties; losses in individual polyphenols at different extents can affect the various AO system in different proportions.

Generally, processed vegetables are assumed to have lower AO activity compared to their fresh counterparts due to degradation or leaching of its phytochemical content in the surrounding water during processing and a similar trend was also evident for H_2O_2 scavenging capacity (Fig. 4C) and FRAP value (Fig.4D). Different processing powers led to different results in the degradation of H_2O_2 scavenging capacity and FRAP value of cabbage. The higher the power applied, the lower the H_2O_2 scavenging capacity and FRAP value observed. It was assumed that the compounds responsible for H_2O_2 scavenging capacity were highly sensitive to MW processing and only approx 10% activity left after 14 min of processing.

3.2.2 Kinetic analysis of antioxidant capacity

AO capacity analysis was modelled using zero-order (Eq. 2) and first-order (Eq. 3). Different AO systems showed a high degree of fit for all of the models studied with first-

order kinetic model being the most suitable with highest R^2 value, ranging from 0.95 to 0.97 for DPPH free radical scavenging capacity, 0.98 to 0.99 for H_2O_2 scavenging capacity, 0.96 to 0.99 for LPO inhibitory ability and 0.97 to 0.99 for FRAP assay at 400 to 800W with lower MSE (Table 2). Experimental and predicted (first-order) data for the deterioration in AO capacity due to MW processing at 400, 560 and 800W is presented in Fig. 5. For the entire AO capacity analysis, the degradation rate constant increased as the processing power raised from 400 to 800W (Table 2) confirming the impact of MW processing power on the reduction of AO capacity.

Rate of reduction in AO capacity showed a similar trend as phytochemical loss; degradation rate constant increased up to 1.44 times for DPPH free radical scavenging capacity, 1.85 times for H_2O_2 scavenging capacity, 1.59 times for LPO inhibitory ability and 1.51 times for FRAP assay as a result of the power rise from 400 to 800W (Table 2). A strong linear relationship between MW power and kinetic parameter estimates was found (R^2 of 0.99, 0.99, 0.97 and 0.98 for DPPH free radical scavenging capacity, H_2O_2 scavenging capacity, LPO inhibitory ability and FRAP assay, respectively).

3.2.3 The influence of MW processing on colour

Fresh York cabbage heads were bright green as indicated by the CIE scale parameters: co-ordinate a^* was −3.45; b^* was 20.3 and the L^* co-ordinate, associated with lightness, was 64.7 with a chroma value of 23.9±1.52. Results showed that MW processing had an adverse effect on chroma; as the processing time and power levels increased, the value of chroma decreased. There are numerous references on the kinetics of colour of food materials in the literature. The majority of these works reported zero-order (Eq. 2) or first-order (Eq. 3) degradation reaction kinetics.

Experimental data for chroma was fitted to different kinetic models. Non-linear regression analysis was applied for the kinetic equations of zero and first-order. Zero-order kinetic model (Eq. 2) was found to be appropriate for modelling the effect of MW processing on York cabbage chroma with higher R^2 ranging from 0.88 to 0.98 and lower MSE (Table 3). Experimental and predicted (zero-order) data for all the processing power and time combination on chroma are presented in Fig.6A. Results showed that the degradation rate constant increased up to 2.34 times (0.248 to 0.580 min^{-1}) as the MW power level increased from 400 to 800W.

Processing power showed very strong correlation (R^2= 0.98) with degradation rate constant, indicated that MW processing for longer time reduced the colour of vegetables. Similar findings were observed by Viña *et al*. (2007) and Lespinard *et al*. (2009). These authors studied the effects of water blanching on the colour of Brussels sprouts and mushrooms and found that blanching led to fading of colour from dark to light with increased temperature. The reduction in chroma could be due to degradation of chlorophyll accompanied with a loss of the liberated colouring compounds by migration into the processing water.

3.2.4 The influence of MW processing on textural properties

The sensory qualities of fresh vegetable are dependent on their texture, in particular, firmness, which correlates well with the freshness of the produce (Rawson *et al.*, 2012) and usually measured as the shearing force required to cut through the vegetable sample. In the present study, the maximum shearing force for fresh York cabbage was recorded as 73.1N and it reduced progressively during all the MW processing power levels applied.

A reduction of 8.33% was observed at 400W after 2 min of MW processing which reduced up to 25.7% when MW power increased to 800W, indicating that application of

higher power leads to severe loss in texture. Consistently increasing in MW processing time also leads to the continuous loss in texture and after 14 min approximately 58.8-66.3% reduction in the texture was observed. A similar finding was noticed by Cunningham *et al.* (2008); these authors observed that MW processing decreased potato texture.

The kinetic changes in firmness were analysed, and results showed that degradation in York cabbage firmness followed zero-order kinetics for all the MW processing levels studied as seen in Fig. 6.B. A good correlation was observed between experimental and model predicted values (Table 3) with R^2 ranging from 0.89 to 0.97. During heat processing, the reduction in firmness could be due to a number of chemical and physical changes in the cabbage cell structure such as loss in turger pressure caused by cell membrane disruption or due to the changes produced in cell wall polymers, particularly the pectin substances (Greve *et al.*, 1994; Annie and Keith, 1997), which are involved in holding the plant cells together (Ryden and Selvendran, 1990). During prolonged MW processing, cells may become completely separated resulting in major loss of textural strength.

The results presented clearly demonstrated that MW processing leads to significant losses in total phenolics, flavonoids, AO capacity, colour and texture of York cabbage which can be attributed to destruction or release of food components. Reduction in these physiochemical parameters were more pronounced with the increment in MW processing power and the duration of processing. Generally, in the home or industry, texture (firmness) of vegetables is the most important factor for the consumer to decide if the product has had enough processing or not. This study indicated that a processing at lower MW power (400W) for short duration (6-8 min) resulted in a high quality end product

whereby firmness of the York cabbage remained intact (72.3%) and can be considered as acceptable texture. Furthermore, there was no significant difference ($P > 0.05$) recorded for firmness at 560W and 400W, however, processing at high MW power (800W) for 6-8 min showed significantly lower firmness (50% retention). It was also evident that at lower processing power and time, the retention of polyphenols (35-57%) and AO capacity (57-60%) was high. For the industrial prospects where the volume of vegetables is high; the application of lower power level for short duration could potentially save a lot of time and electrical energy.

4. Conclusions

The present study demonstrated that the contents of polyphenols, flavonoids, AO capacity and physical properties such as colour and texture of York cabbage were significantly reduced by MW processing. Degradation kinetics for the polyphenolic content and AO capacity follow the first-order kinetic model while colour (chroma) and texture showed zero-order reaction. It is concluded that the quality retention of green vegetables while MW processing depends on intensity and duration of power applied. Increasing the power level increases losses of polyphenols and AO capacity in York cabbage and similar results were observed for processing time. A lower power level (400W) for short duration (6-8 min) is recommended to prevent major loss of AO capacity, polyphenols and physical properties such as colour and texture of York cabbage while processing with MW.

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Figure Captions

Fig. 1. Effect of microwave processing power [400 (◆), 560 (●) and 800W (▲)] and time combinations on (A) total phenolic content and (B) total flavonoid content of York cabbage

Fig. 2. Polyphenols overlay spectra of fresh and processed York cabbage (400 W for 0-14 min) at 280 nm (0 min; 2 min; 6 min; 10 min; 12 min; 14 min).

Fig. 3. Experimental [400 (■), 560 (▲) and 800W (●)] and predicted [400 (), 560 () and 800W ()] data for microwave power and processing time combinations on (A) total phenolic content and (B) total flavonoid content of York cabbage

Fig. 4. Effect of microwave processing power [400 (◆), 560 (●) and 800W (▲)] and time combinations on (A) DPPH radical scavenging capacity (B) lipid peroxidation inhibitory ability (C) H_2O_2 radical scavenging capacity and (D) Ferric reducing antioxidant potential of York cabbage

Fig. 5. Experimental [400 (■), 560 (▲) and 800W (●)] and predicted [400 (), 560 () and 800W ()] data for microwave power and processing time combinations on antioxidant capacity (A) DPPH radical scavenging capacity (B) lipid peroxidation inhibitory ability (C) H_2O_2 radical scavenging capacity and (D) Ferric reducing antioxidant potential of York cabbage

Fig. 6. Experimental [400 (■), 560 (▲) and 800W (●)] and predicted [400 (), 560 () and 800W ()] data for microwave power and processing time combinations on (A) chroma and (B) firmness of York cabbage

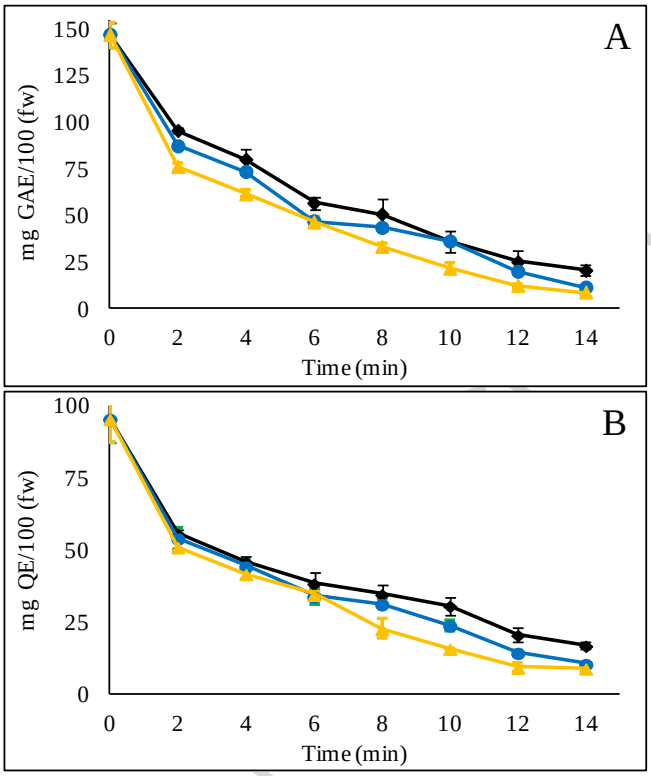
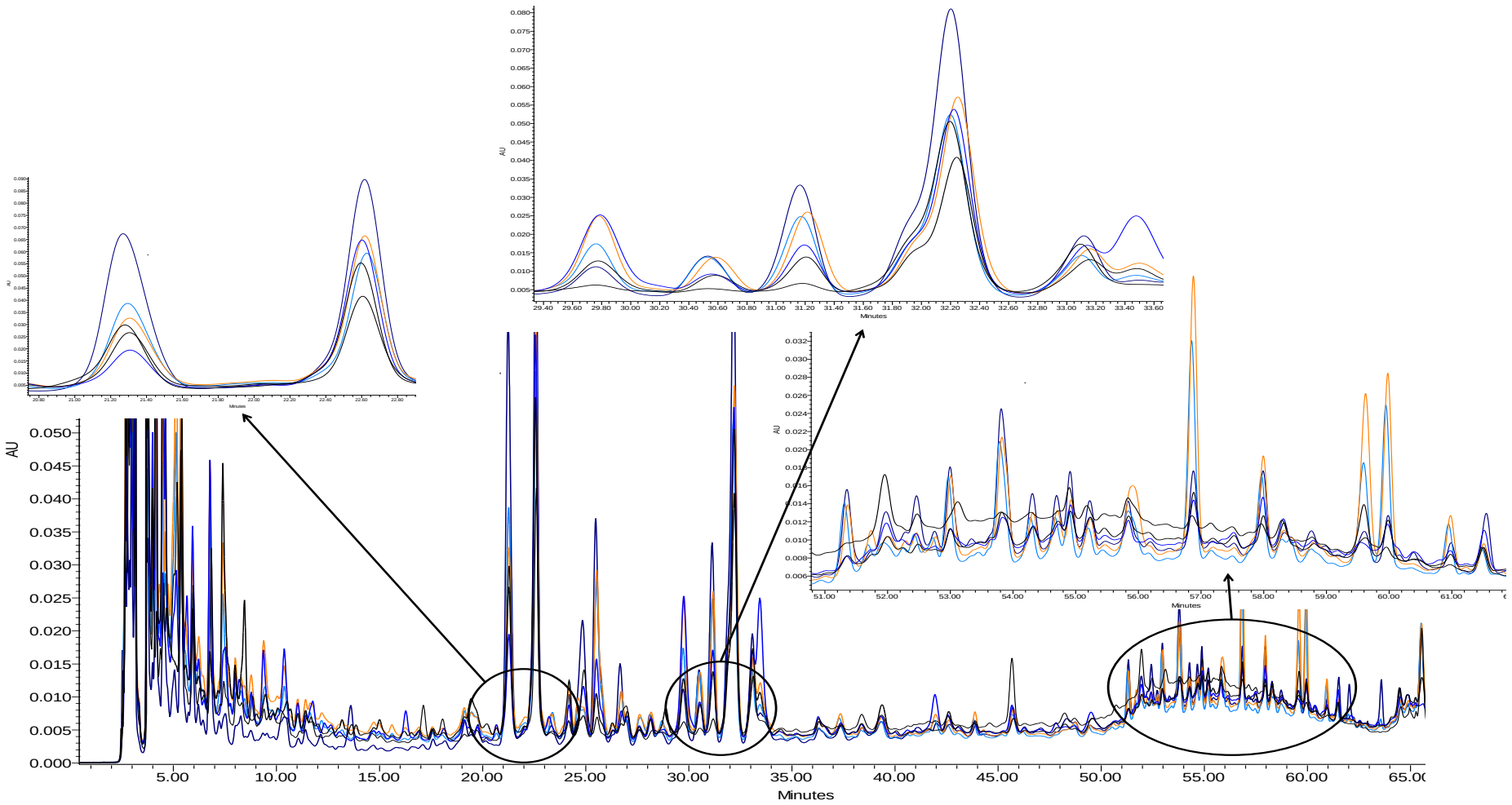


Fig. 1. Effect of microwave processing power [400 (◆), 560 (●) and 800W (▲)] and time combinations on (A) total phenolic content and (B) total flavonoid content of York cabbage



Insight showing magnified view of major polyphenols chromatogram (based on area) present in York cabbage

Fig. 2. Polyphenols overlay spectra of fresh and processed York cabbage (400 W for 0-14 min) at 280 nm (0 min; 2 min; 6 min; 10 min; 12 min; 14 min).

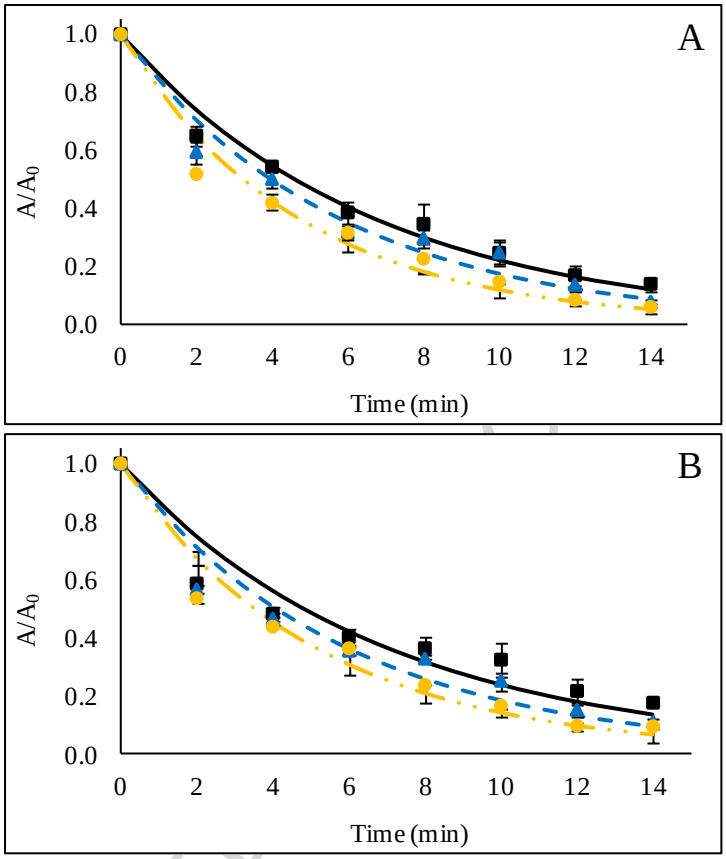


Fig. 3. Experimental [400 (■), 560 (▲) and 800W (●)] and predicted [400 (—), 560 (– –) and 800W (—)] data for microwave power and processing time combinations on (A) total phenolic content and (B) total flavonoid content of York cabbage

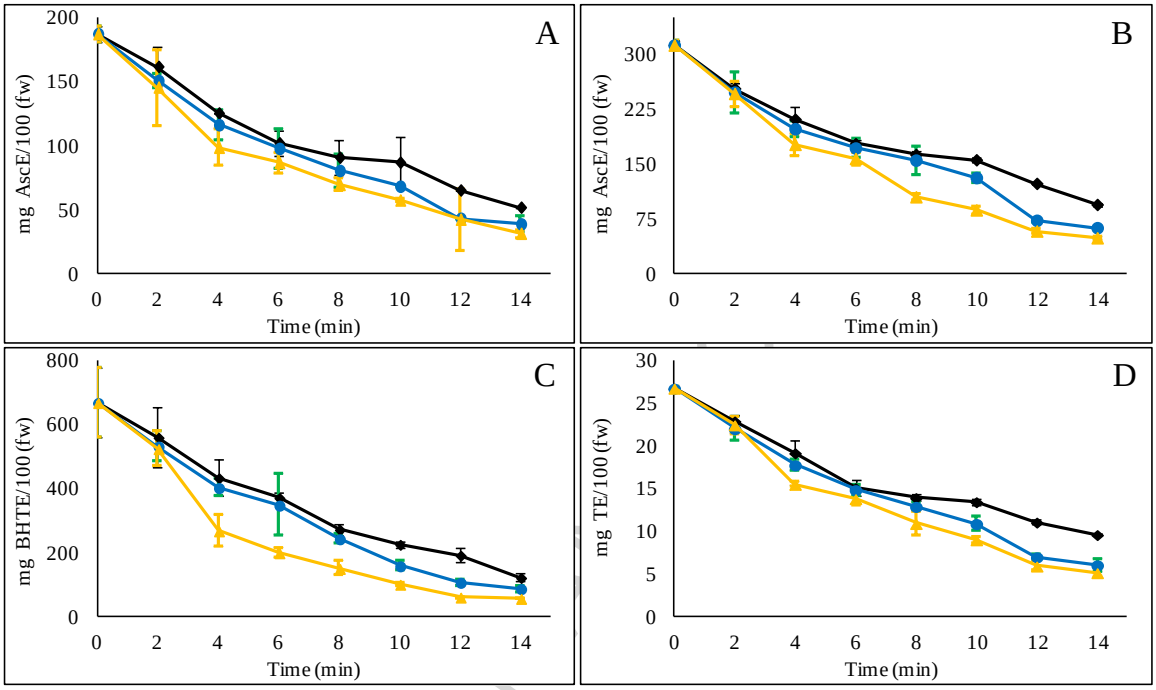
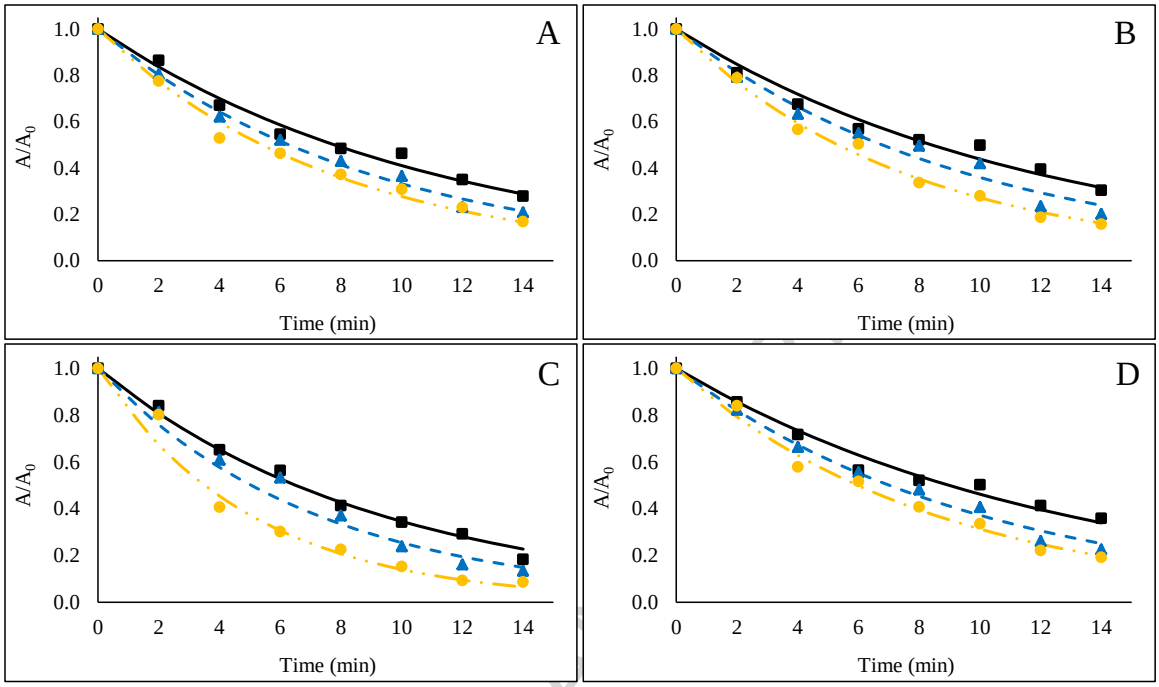


Fig. 4. Effect of microwave processing power [400 (◆), 560 (●) and 800W (▲)] and time combinations on (A) DPPH radical scavenging capacity (B) Lipid peroxidation inhibitory ability (C) H_2O_2 radical scavenging capacity and (D) Ferric reducing antioxidant potential of York cabbage



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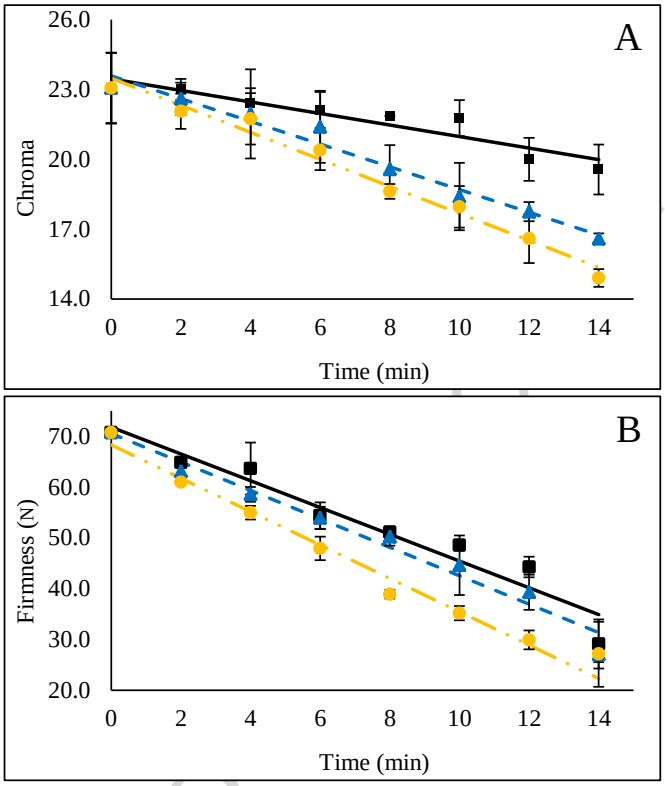

Fig. 6. Experimental [400 (■), 560 (▲) and 800W (●)] and predicted [400 (▬), 560 (▬) and 800W (▬)] data for microwave power and processing time combinations on (A) Chroma and (B) Firmness of York cabbage

Table 1 Kinetic parameter estimates (*k*), corresponding coefficient of determination (R^2) and mean square errors (MSE) of York cabbage phytochemical degradation due to microwave processing at different power levels

	Power	*k*	R^2	MSE
TPC	400W	0.150±0.01	0.969	0.003
	560W	0.174±0.01	0.961	0.003
	800W	0.214±0.01	0.965	0.003
TFC	400W	0.144±0.01	0.896	0.007
	560W	0.169±0.01	0.941	0.005
	800W	0.197±0.01	0.959	0.004

TPC total phenolic content, TFC total flavonoid content

Table 2 Kinetic parameter estimates (*k*), corresponding coefficient of determination (R^2) and mean square errors (MSE) of York cabbage antioxidant capacity reduction due to microwave processing at different power levels

	Power	*k*	R^2	MSE
DPPH	400W	0.089±0.00	0.960	0.003
	560W	0.110±0.00	0.966	0.002
	800W	0.128±0.01	0.949	0.004
H_2O_2	400W	0.107±0.02	0.981	0.002
	560W	0.138±0.02	0.988	0.001
	800W	0.198±0.02	0.986	0.001
LPO	400W	0.082±0.00	0.965	0.002
	560W	0.102±0.00	0.961	0.003
	800W	0.130±0.01	0.986	0.001
FRAP	400W	0.077±0.00	0.971	0.001
	560W	0.099±0.00	0.988	0.001
	800W	0.116±0.01	0.986	0.001

Table 3 Kinetic parameter estimates (*k*), corresponding coefficient of determination (R^2) and mean square errors (MSE) of York cabbage texture (Firmness) and colour (chroma) degradation due to microwave processing at different power levels

	Power	*k*	R^2	MSE
Colour	400W	0.248±0.01	0.882	0.229
	560W	0.488±0.02	0.975	0.174
	800W	0.580±0.01	0.982	0.180
Texture	400W	2.640±0.33	0.891	8.570
	560W	2.800±0.28	0.950	6.112
	800W	3.280±0.33	0.970	5.130

Highlights

- Impact of microwave processing on physio-chemical properties of York cabbage was studied.
- Microwave processing leads to loss in the firmness, color, polyphenols and antioxidant capacity.
- The first-order reaction fitted well for polyphenols and antioxidant capacity.
- Quality retention of green vegetables depends on intensity and duration of power applied.
- Lower power level for short duration (6-8 min) is recommended while microwave processing.