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Original article

Effects of TiO_2–UVC photocatalysis and thermal pasteurisation on microbial inactivation and quality characteristics of the Korean rice-and-malt drink sikhye

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Summary Sikhye is a popular Korean rice-and-malt drink. This drink is prepared using a specific traditional process and has short shelf life. Commercial processing using ultra-high temperature affects characteristic colour and flavour attributes and disturbs the traditional method of sikhye preparation. The objective of this study was to compare the effect of TiO_2–UVC photocatalysis (TUVP) nonthermal processing with heat-pasteurised and untreated sikhye samples during storage at 4 and 10 °C. TUVP and heat treatments were both sufficient to inhibit regrowth of total aerobic bacteria and coliform during storage. Hunter colour parameter values showed that the colour of sikhye was less affected by TUVP treatment compared to the heat treatment. Higher sensory scores for flavour, taste and overall preference were attained for low-dosage TUVP-treated (0.24 J cm^{-2}) samples than for heat-treated samples but without a significant difference. TUVP treatment effectively controlled the microbial growth during storage at 4 °C for more than 18 days which was reported a serious microbiological safety issue. In summary, TUVP showed its suitability for commercialisation possibilities of fresh sikhye drink by inactivating the main micro-organisms and thus increasing significantly its shelf life with minimum impact on quality characteristics.

Keywords Characteristic quality, microbes, nonthermal processing, shelf life, sikhye, TiO_2–UVC photocatalytic reaction.

Introduction

Sikhye (alternative names of ‘dansul’ and ‘gamju’) is a popular traditional rice-and-malt drink in Korea. Home-made fresh sikhye is usually served as dessert at Korean restaurants (Kim *et al*., 2012). This drink is believed to promote digestion and to control weight (Hur & Choi, 2007). Sikhye is traditionally prepared from steamed rice and fermented barley-malt water following a unique complex process (Fig. 1). β-Amylase activity on rice starch produces maltose, which accelerates microbial growth during storage. Thus, pathogenic micro-organisms can easily grow in sikhye due to high maltose content if no processing treatment is applied. Sikhye has a short shelf life of 2–4 days, even under refrigerated storage.

A number of manufacturing companies have developed processed sikhye (retort and frozen types) to extend the shelf life and ensure microbiological safety. The retort type of sikhye is commercially packaged in aluminium cans or retort pouches and is sterilised. In contrast, the frozen type does not involve sterilisation and is only boiled for 5–20 min, then distributed in a frozen form. Although the frozen type sikhye maintains a good flavour, there are serious concerns regarding the growth of micro-organisms, particularly after thawing. Moreover, mass production of sikhye involving commercial-scale sterilisation diminishes the characteristic product taste and also alters the process of traditional sikhye preparation (Kim *et al*., 2012). Researchers have expressed interest in maintenance of a native taste and quality characteristics of sikhye to increase product competitiveness in Korea and for globalisation of this traditional beverage. The drink is also globally available at Korean grocery stores (Hur & Choi, 2007).

Heat treatment of fruit beverages has been reported to result in undesirable quality characteristics that the processing industry must address. Hence, there is growing interest in nonthermal pasteurisation

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Step 1: Mix barley malt powder with warm water and let stand for 2 h. All the malt should sink to the bottom. Prepare steamed rice in a cooker.

Step 2: Pour the clear liquid from the malt powder mixture over the cooked rice through cheese cloth. Incubate the mixture at 55-60 °C for 3-4 h.

Step 3: Put the rice into a large pot and add sugar and ginger. Cook for 15-20 min over medium high heat. Remove rice from liquid. Cool and store the liquid at 4-5 °C before serving.

Figure 1 Processing scheme for the preparation of home-made sikhye (Kim *et al.*, 2012).

processes that can contribute to product safety without affecting product quality (Corbo *et al.*, 2009; Gabriel *et al.*, 2015; Mohideen *et al.*, 2015). The titanium dioxide (TiO_2) photocatalytic reaction generates an oxidising potential when illuminated under u.v. light at wavelengths less than 385 nm. The bactericidal properties of TiO_2–UVC photocatalysis (TUVP) have been reported (Hashimoto *et al.*, 2005). Zhang *et al.* (2014) made a comparison of different disinfection processes for *Bacillus subtilis* spores and reported the potential of TUVP treatment for significant microbial inactivation via a synergistic effect. Benabbou *et al.* (2007) reported that the level of inactivation of *Escherischia coli* in combination with TiO_2 was significantly higher under UV-C than under UV-A or UV-B irradiation. Kim *et al.* (2012) found that modified tyndallisation with CO_2 was more effective than conventional heat treatment to reduce the number of *Bacillus cereus* spores in sikhye. Sikhye is not an expensive drink. Therefore, economic and practical aspects should be considered for processing. Advantages of u.v. irradiation include low equipment and energy costs and easy maintenance (Santhirasegaram *et al.*, 2015).

The objectives of this study were to evaluate the efficacy of nonthermal TUVP treatment, an alternative to conventional heat pasteurisation for control of microbial growth, to extend product shelf life and to preserve the characteristic quality of sikhye. The effect of TUVP treatment at different dosages was investigated on microbiological, physicochemical and sensory properties of sikhye during storage under different temperature conditions, and results were compared with heat-pasteurised and control (untreated) samples.

Materials and method

Fresh sikhye samples

Sikhye, a freshly prepared drink in a home-made style, was purchased from a local store famous for traditional foods in Seoul, South Korea. The processing scheme for preparation of home-made style sikhye is shown in Fig. 1. The drink was filtered through cheese cloth for the separation of rice residue. The filtered drink was poured into an autoclaved stainless steel bowl under refrigeration temperature and immediately subjected to further processing. Untreated sikhye samples were used as a control.

Processing treatments

Sikhye samples were subjected to traditional thermal pasteurisation and nonthermal TUVP processing.

Thermal treatment

Sikhye samples were thermally pasteurised in a stainless steel beaker using a water bath (KSB-201; Sunileyela, Seongnam, South Korea) at 90 °C for 10 min. The beaker containing the sample was immediately cooled in iced water at the end of this treatment.

Nonthermal treatment using a TUVP process

A continuous-type photocatalytic reactor assembled at TaekyengUV Co. Ltd. (Namyangju, South Korea) was used for nonthermal product treatment (Fig. 2). The reactor was comprised of eight serially connected stainless steel chambers, and TiO_2-coated quartz tubes equipped with 16 W u.v. lamps having a peak emission at 254 nm (Sankyo Denki Co. Ltd., Hiratsuka, Japan). U.v. dosages of 0.24–0.48–0.96 J cm^{-2} were applied to samples in different chambers. The u.v. dosage was varied in this range by changing the number of chambers.

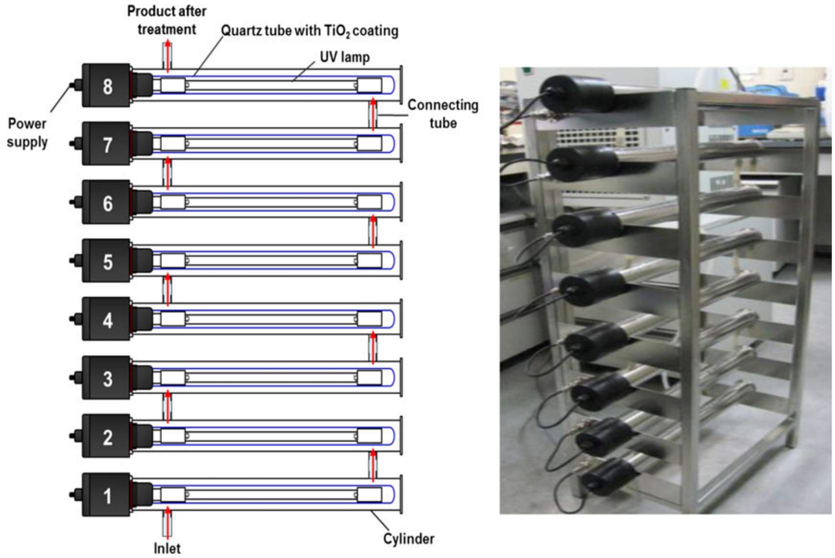

Figure 2 Schematic diagram of a continuous-type TiO_2–UVC photocatalytic reactor. The u.v. dosage during TUVP treatment varied in the range of 0.24–0.96 J cm^{-2} based on changing the number of chambers (0.24 J cm^{-2}: two chambers, 0.48 J cm^{-2}: four chambers, 0.96 J cm^{-2}: eight chambers).

U.v. dosages were calculated following the procedure of Tran & Farid (2004) as follows:

$$U = It/A$$

where I represents the u.v. intensity of the lamp (16 W), t is the u.v. exposure time (s) for sikhye, A is the u.v. exposure surface area (cm^2) with $A = \pi DL$ cm^2 for which D is the inner diameter of quartz tube (D = 1.96 cm), and L is the length of quartz tube (L = 34.5 cm). The flow rate in the system was maintained using a peristaltic pump (RP-1000; Eyela, Tokyo, Japan). A magnetic stirrer was used during u.v. irradiation to ensure homogenous treatment. The reactor was autoclaved before use and cleaned after every treatment using tap water for 20–30 min with the UV-C lamp on.

Packaging and storage for shelf life study

Both treated and untreated samples were poured into 125 mL polypropylene sterile bottles, tightly closed and stored at 4 and 10 °C for 22 and 10 days, respectively. Microbiological, sensory and physicochemical analyses were carried out at different intervals.

Sample analyses

Microbiological inactivation analyses (total aerobic and coliform bacteria)

Total aerobic bacteria and coliform counts in sikhye samples were enumerated using sample-ready 3M™ petrifilm™ aerobic count plates (3M, St. Paul, MN, USA) after serial dilution with 0.85% sterilised saline water. Aerobic bacteria and coliform count petrifilms were incubated at 37 °C for 24 h before colony counting. All experiments were performed in triplicate, and results were expressed as log CFU mL^{-1} (Medina & Jordano, 2014).

Sensory analysis

Sensory analysis was conducted at the Biomaterial Process Engineering Laboratory of Yonsei University. An untrained panel comprised of 30 male and female students (aged 20–30 years) voluntarily collaborated in sensory analyses. All participants were regular consumers of the tested beverage. Panellists were provided with appropriate information about the research project and intended objectives. Required definitions for sensory parameters were elaborated prior to testing. Treated and control drink samples marked with random three-digit numbers were placed on white paper plates in a randomised order to minimise carry-over and order effects. Approximately 25 mL of a drink sample at 4 °C was offered to panellists in a plastic cup with a 5 min interval frequency. Panellists were given deionised water and unsalted crackers for palate rinsing during the interval. Sensory attributes, including colour, flavour, taste and overall preference were rated on a 5-point scale from 'like extremely = 5' to 'dislike extremely = 1'. Data were expressed as the mean values of scores (Ryu *et al*., 2008).

Physicochemical analyses (pH, °Brix and Hunter colour)

The pH values of samples were measured using a pH meter (Orion 520A; Orion Research Inc., Boston, MA, USA). The degree Brix value was measured at 20 °C by placing 1 mL of a drink sample on the dry lens of an automatic refractometer with the automated temperature compensation function enabled (Smart-1; Atago Co., Tokyo, Japan). Sample colour was measured using a colorimeter with a CR-400 head following the Hunter system (Konica Minolta Inc., Tokyo, Japan). The col-

orimeter was calibrated using a white standard plate. Colour values were expressed as L^* (lightness/brightness/darkness of the product), a^* (redness/greenness of the product) and b^* (yellowness/blueness of the product). The total colour difference (ΔE) was determined as follows:

$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2},$$

where L_0, a_0 and b_0 denote colour values of control samples.

Statistical analysis

A one-way ANOVA and multiple comparisons using Newman–Keuls test were carried out using the Statistical Package for the Social Sciences software (SPSS version 18; IBM Corp., Armonk, NY, USA). The ANOVA test was performed for all experimental runs to determine significance using a 95% confidence interval. All experiments were performed in triplicate. Results were considered significantly different at $P < 0.05$.

Results and discussion

Effects of TUVP treatment on microbial inactivation and shelf life extension of sikhye during storage

Petrifilm plate methods have gained popularity due to a number of advantages over conventional agar plate methods for microbiological analyses of many food matrices, including beverages. The efficiency of these methods has been reported for reproducible and consistently accurate results (Medina & Jordano, 2014). The effect of TUVP treatment on microbial survival against that of heat-pasteurised and control samples is shown in Figs 3 and 4. The mean initial population for both total aerobes and coliform bacteria in untreated samples was 2.82 ± 0.29 log CFU mL^{-1}. Microbial counts were significantly reduced ($P < 0.05$) following processing treatments, compared with controls. A reduction of 1.12–2.74 log in total aerobes, and 1.11–2.23 log in coliform bacteria, compared with initial counts, was identified with an increase in the TUVP dosage from 0.24 to 0.96 J cm^{-2}. In contrast, heat treatment completely killed coliform bacteria, while total aerobe counts dropped by 1.76 log, compared with initial levels. Figures 3 and 4 illustrate regrowth curves of microbial populations in treated and untreated sikhye samples. Microbial growth was generally increased under both 4 and 10 °C storage conditions. Counts of total aerobes in untreated samples increased during storage and even reached 5.0 log CFU mL^{-1} on the 8th day of storage at 10 °C (Fig. 3). On the other hand, TUVP effectively controlled the microbial regrowth rate and significantly

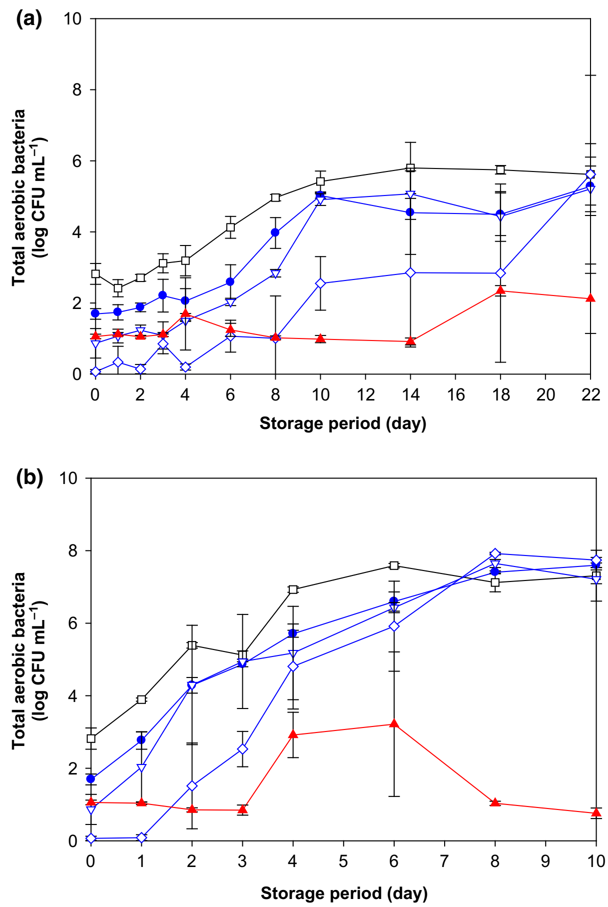

Figure 3 Counts of total aerobic bacteria in sikhye after nonthermal and thermal treatments and subsequent storage at (a) 4 °C and (b) 10 °C. Error bars represent standard deviations. No treatment/control (□), heat treatment (▲), TUVP 0.24 J cm^{-2} (●), TUVP 0.48 J cm^{-2} (▽), TUVP 0.96 J cm^{-2} (◇).

($P < 0.05$) lower CFU values were observed during storage, compared with controls.

The storage temperature was important for microbial activity throughout the shelf life study. Samples stored at 4 °C showed relatively slow microbial regrowth, compared with samples stored at 10 °C. On the other hand, coliform bacterial growth remained constant up to the fourth day of storage, then decreased (Fig. 4). TUVP treatment at medium (0.48 J cm^{-2}) and upper (0.96 J cm^{-2}) dosage levels was sufficient to restrain microbial growth during storage. Similarly, heat treatment also effectively inhibited the regrowth of coliform bacteria during storage. In short, processing using the TUVP photocatalytic reaction and a controlled temperature of 4 °C efficiently restricted microbial regrowth during storage for up to 18 days (Figs 3 and 4). Previously, Kim *et al.* (2012)

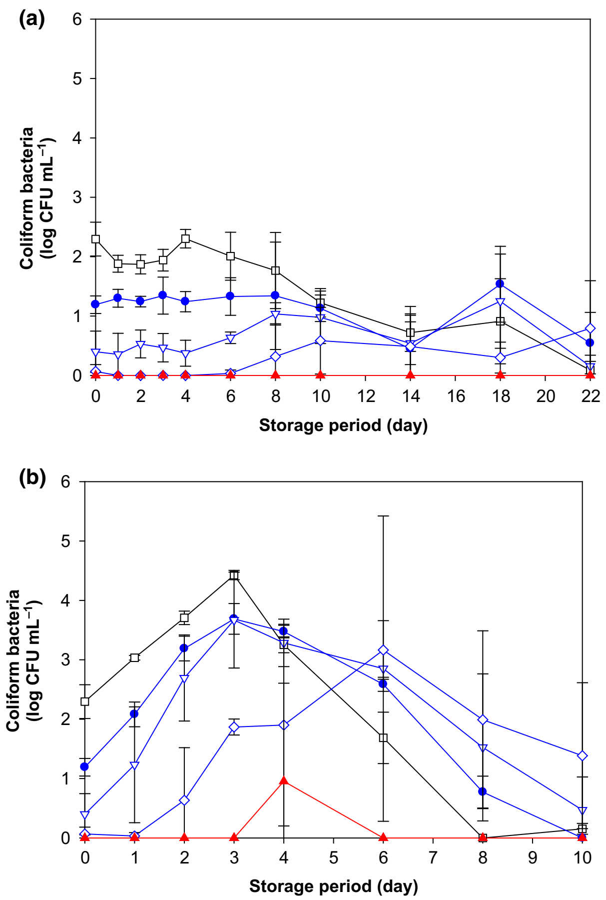

Figure 4 Counts of coliform bacteria in sikhye after nonthermal and thermal treatments and subsequent storage at (a) 4 °C and (b) 10 °C. Error bars represent standard deviations. No treatment/control (□), heat treatment (▲), TUVP 0.24 J cm^{-2} (●), TUVP 0.48 J cm^{-2} (▽), TUVP 0.96 J cm^{-2} (◇).

reported that survival of micro-organism in sikhye was a significant issue particularly after thawing.

Photocatalysis is an oxidative process involving generation of reactive chemical species at the interface of a semiconductor when illuminated under u.v. and visible light (<385 nm). Electron–hole pairs, involving an electron in a conduction band (e^-_{cb}) and a hole in a valence band (h^+_{vb}), are formed on the surface of TiO_2 under u.v. illumination and photon absorption. The e^-_{cb} creates hydroxyl radicals via a reductive pathway. The e^-_{cb} reduces oxygen to a superoxide radical, followed by a subsequent reduction to hydrogen peroxide, and finally to a hydroxyl radical. The h^+_{vb} generates hydroxyl radicals through an oxidative pathway. The h^+_{vb} reacts with hydroxyl ions or water to form the hydroxyl radical, which decomposes organic compounds and causes damage to micro-organisms (Cho *et al.*, 2005). Hydroxyl radicals have a stronger oxidising power (2.80 V) than ozone (2.07 V), hydrogen peroxide (1.78 V), hypochlorous acid (1.49 V) and chlorine (1.36 V) (Srinivasan & Somasundaram, 2003; Hashimoto *et al.*, 2005; Nakata & Fujishima, 2012; Ângelo *et al.*, 2013; Vasilache *et al.*, 2013). A number of studies have reported that reactive oxygen species (ROS), such as hydroxyl radicals and hydrogen peroxide generated by TiO_2 photocatalytic reactions, attack polyunsaturated phospholipids in bacteria and catalyse site-specific DNA damage, which results in cell death (Hirakawa *et al.*, 2004). Cell death is caused by a significant disorder in cell permeability and structural damage to the cell wall (Cho *et al.*, 2005). Partial decomposition of the cell wall allows penetration of photo-generated ROS into the cytoplasmic membrane, which leads to peroxidation of membrane lipids, direct oxidation of a co-enzyme and inhibition of cell respiration that subsequently causes damage to intracellular macromolecules and cell death (Srinivasan & Somasundaram, 2003). However, it is necessary to determine the optimum conditions of TUVP to maximise the quality and microbial safety of food.

Review articles have discussed numerous applications of TiO_2 photocatalysis in a broad range of fields, including water and environmental purification due to compatibility with modern technology (Nakata & Fujishima, 2012; Ângelo *et al.*, 2013; Vasilache *et al.*, 2013). Benabbou *et al.* (2007) studied the efficiency of photocatalytic oxidation reactions against *E. coli* under different domains of u.v. light and concentrations of TiO_2. Inactivation of *E. coli* was more efficient under UV-C irradiation. However, the disinfection efficiency increased as a function of light intensity independent of TiO_2 concentrations and u.v. domains. In the present study, UV-C light of 254 nm wavelength was used as it is known to be more effective against micro-organisms than other u.v. domains (Benabbou *et al.*, 2007). In another study, Chai *et al.* (2014) found that a combination of TiO_2 photocatalysis and high hydrostatic pressure was highly effective against microbes in freshly squeezed vegetable juice. Results reported herein were in agreement with a study conducted by Santhirasegaram *et al.* (2015) in which both thermal and u.v. light processing of mango juice provided significant reductions in microbe numbers and extension of juice shelf life. Kim *et al.* (2009) reported that TUVP processing reduced counts of natural microflora and inoculated pathogenic bacteria on iceberg lettuce immediately after treatment, as well as during storage at different temperatures, and prolonged the product shelf life. Gündüz *et al.* (2015) found that UV-C treatment was effective to reduce levels of mould spores on citrus fruit surfaces and can be included as a step in the HACCP system. After the application of a disinfection treatment, one population of micro-organisms may be killed, another population

may survive, and a third population may be sublethally injured. Injured cells are potentially important, and they can resuscitate and become functionally normal in a favourable environment. Moreover, bacterial cells continue to multiply over the storage period of a product, leading to increased numbers (Wu, 2008).

Effect of TUVP treatment on physicochemical characteristics of sikhye during storage

Physicochemical characteristics of food are important due to potential impacts on sensory evaluation parameters. Application of a processing treatment may cause changes in these parameters that ultimately define the quality and acceptance of food (Barba *et al*., 2012). Total soluble solid content, pH and colour are the main quality parameters that are indicative of product freshness. Furthermore, pH is affected by the rate of microbial growth and survival during storage (Corrales *et al*., 2012). Untreated sikhye had a pH value of 6.22, which was high enough to allow bacterial growth. The pH values of samples were slightly decreased nonsignificantly from 6.22 to 6.00 immediately after the heat treatment, then remained static throughout storage under both temperature conditions (Fig. 5). The pH values of untreated samples fell sharply from 6.00 to 5.22 after 6 days at 4 °C and after 2 days at 10 °C, and continued decreasing significantly throughout the storage period. On the other hand, the decrease in pH during storage was less pronounced in TUVP-treated samples where pH values never fell below 5.00 for low and medium TUVP level treated samples until day 14, and for high TUVP level treated samples until day 22 of storage at 4 °C (Fig. 5a). Tran & Farid (2004) also reported a low impact of UV-C light on the pH of treated orange juice.

TUVP-treated samples exhibited lower °Brix values than controls (Fig. 6). A nonsignificant difference was observed in °Brix values of samples when the irradiation dosage increased from 0.24 to 0.48 J cm^{-2}. °Brix values further decreased in samples treated with high TUVP dosage of 0.96 J cm^{-2} (Fig. 6). In brief, °Brix values remained unchanged throughout the storage period, independent of the processing treatment (Fig. 6). Santhirasegaram *et al*. (2015) also reported no significant change in the total soluble solids content of freshly squeezed mango juice after UV-C and thermal treatments.

Appearance, including the colour, is a primary sensory factor. In brief, the colour of sikhye was less affected by TUVP treatment than by heat treatment. Thermal processing significantly changed *a** values, indicating the greenness/redness of the drink, immediately after treatment and also during storage. On the other hand, this colorimetric parameter remained unchanged or only slightly affected throughout storage

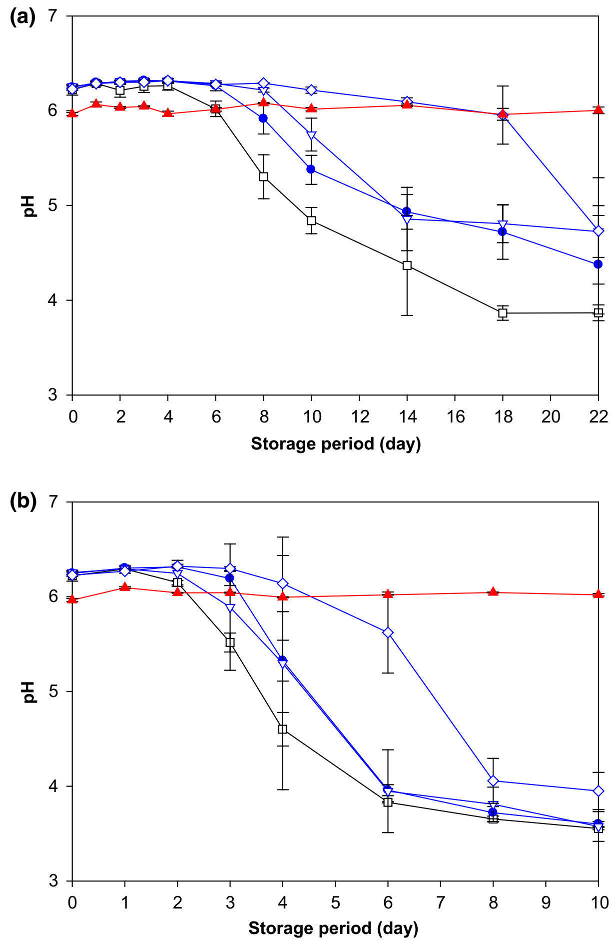

Figure 5 Effects of nonthermal and thermal treatments on pH values of sikhye and subsequent storage at (a) 4 °C and (b) 10 °C. Error bars represent standard deviations. No treatment/control (□), heat treatment (▲), TUVP 0.24 J cm^{-2} (●), TUVP 0.48 J cm^{-2} (▽), TUVP 0.96 J cm^{-2} (◇).

for all other sample types (data not shown). Similarly, Corrales *et al.* (2012) also observed slight changes in *a** colour coordinate for UV-C-treated horchata during storage. The *L** value of untreated samples increased during storage. The relative visual yellow colour parameter (*b** value) decreased at a faster rate than for TUVP-treated samples. Hence, TUVP proved effective for preservation of the colour of sikhye, which was significantly changed by heat treatment (Table 1). The combination of *L**, *a** and *b** parameters were determined as a total colour difference value (ΔE) that is used to compare changes in colour over time. Total colour difference values increased during storage because of changes in *L** and *b** values. However, the total colour difference was highest for heat-treated samples, confirming degradation of visual

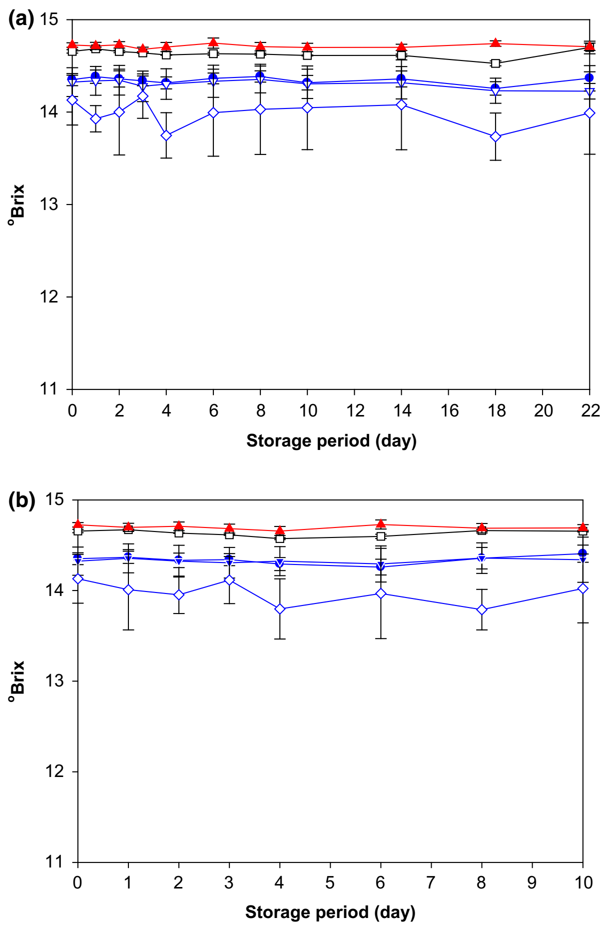

Figure 6 Effects of nonthermal and thermal treatments on °Brix values of sikhye and subsequent storage at (a) 4 °C and (b) 10 °C. Error bars represent standard deviations. No treatment/control (□), heat treatment (▲), TUVP 0.24 J cm^{-2} (●), TUVP 0.48 J cm^{-2} (▽), TUVP 0.96 J cm^{-2} (◇).

colour components of drink samples after thermal processing, compared with untreated and TUVP treated samples (data not shown).

In a similar study, a change in colorimetric parameters (a^* and b^* values increased, while the L^* value decreased) related to the development of enzymatic browning was measured in apple slices after UV-C treatment. However, shelf life extension was strongly dependent on the intensity of u.v. light, whereas a mild intensity treatment was effective for the protection of the quality of fresh-cut apples (Manzocco *et al*., 2011). Ochoa-Velasco *et al*. (2014) demonstrated changes in colour parameters of coconut milk after UV-C light and heat treatments. Similar to this study, UV-C light did not cause significant effects on physicochemical characteristics of coconut milk (Ochoa-Velasco *et al*., 2014). Recently, Mohideen *et al*. (2015) described continuous flow sonication as an alternative to thermal pasteurisation for the preservation of the colour of blueberry juice. Similar to this study, Corrales *et al*. (2012) reported the difficulties in commercialisation of fresh natural horchata, a nonalcoholic traditional beverage that is highly popular in the Valencian region of Spain. Reported issues included a short shelf life and limitations of heat pasteurisation that lead to starch jellification and alterations in the organoleptic properties of horchata. UV-C treatment effectively inactivated up to 3 log cycles of spoilage micro-organisms and maintained the freshness of horchata, measured as a function of pH, to extend its shelf life. Hence, the use of UV-C treatment allowed amelioration of problems associated with commercialisation of the horchata native drink with a minimum impact on product physicochemical quality characteristics.

Recent development in the science and engineering of u.v. light irradiation has shown the potential of u.v. as an alternative to traditional thermal pasteurisation for a variety of liquid foods. U.v. light also presents a possible alternative to chemical disinfection (Chun *et al*., 2013; Syamaladevi *et al*., 2013) due to improvement of quality of liquid foods without a considerable loss in nutritional value. Liquid foods, such as beverages and fresh juices, transmit little u.v. light due to suspension of suspended materials, colour compounds and organic solutes with high absorption coefficients. However, u.v. light can considerably affect the composition of unsaturated fat-based foods due to acceleration of oxidative damage, resulting in the production of free radicals and, ultimately, leading to rancidity (Koutchma *et al*., 2009).

Effect of TUVP treatment on sensory properties of sikhye

Responses from each panellist were obtained for defined sensory descriptors of sikhye. Mean scores with standard deviation values from 30 panellists are shown in Table 2. In general, control samples (untreated) were liked most for taste and overall preference. However, sensory panellists showed more liking for samples treated at the lowest irradiation dosage of 0.24 J cm^{-2} than for heat-treated samples. Samples treated with the lowest irradiation dosage achieved the highest scores for colour and flavour preference. However, panellists did not report marginal differences in colour and flavour among low-dosage TUVP-treated, heat-treated and untreated samples. Similarly, taste scores of low-dosage (0.24 J cm^{-2}) TUVP-treated samples were higher than for heat-treated samples. Samples treated at medium and high TUVP dosage received significantly lower scores for flavour and taste (Table 2). A higher irradiation dosage of 0.96 J cm^{-2} induced an off-taste that led to a strong overall dislike. Panellists also showed a preference for heat-treated

Table 1 Effects of nonthermal and thermal treatments on Hunter colour parameters of sikhye during storage

	L^* (lightness)					b^* (yellowness)				
	No treatment	Heat treatment	TiO_2–UVC 0.24 J cm^{-2}	TiO_2–UVC 0.48 J cm^{-2}	TiO_2–UVC 0.96 J cm^{-2}	No treatment	Heat treatment	TiO_2–UVC 0.24 J cm^{-2}	TiO_2–UVC 0.48 J cm^{-2}	TiO_2–UVC 0.96 J cm^{-2}
Storage days at 4 °C										
0	18.91 ± 0.05^{aA}	20.78 ± 0.22^{bA}	20.02 ± 1.16^{cA}	20.23 ± 0.59^{cA}	19.82 ± 0.15^{cAB}	2.66 ± 0.07^{aA}	2.08 ± 0.13^{bcA}	1.98 ± 0.71^{bcABC}	1.82 ± 0.34^{cAB}	2.30 ± 0.07^{bA}
1	19.64 ± 0.09^{aA}	21.68 ± 0.67^{bB}	19.77 ± 0.33^{aA}	20.39 ± 0.93^{cA}	19.74 ± 0.15^{aAB}	2.33 ± 0.13^{aB}	1.40 ± 0.25^{bB}	2.23 ± 0.25^{aAB}	1.93 ± 0.31^{cABC}	2.11 ± 0.10^{acBC}
2	19.70 ± 0.58^{aA}	21.36 ± 0.46^{bBC}	19.85 ± 0.28^{aA}	19.80 ± 0.18^{aAB}	19.55 ± 0.20^{aAC}	2.09 ± 0.39^{aB}	1.48 ± 0.12^{bB}	1.66 ± 0.24^{bcBC}	1.57 ± 0.14^{bcAD}	1.77 ± 0.28^{cD}
3	19.72 ± 0.52^{aA}	21.14 ± 0.49^{bBC}	19.74 ± 0.37^{aA}	19.79 ± 0.30^{aAB}	19.68 ± 0.11^{aAB}	2.26 ± 0.31^{aB}	1.69 ± 0.18^{bBC}	2.09 ± 0.27^{aAB}	2.20 ± 0.17^{aBC}	2.21 ± 0.04^{aABC}
4	19.39 ± 0.46^{aA}	21.54 ± 0.43^{bBC}	18.72 ± 0.73^{aA}	19.22 ± 0.59^{aB}	19.40 ± 0.43^{aC}	2.08 ± 0.40^{aB}	1.48 ± 0.10^{bB}	2.57 ± 0.56^{cA}	2.19 ± 0.10^{aBC}	2.07 ± 0.12^{aC}
6	19.65 ± 0.28^{aA}	21.47 ± 0.69^{bBC}	19.67 ± 0.08^{aA}	19.74 ± 0.30^{aAB}	19.72 ± 0.11^{aAB}	2.09 ± 0.25^{aB}	1.47 ± 0.28^{bB}	2.25 ± 0.01^{acAB}	2.29 ± 0.16^{cC}	2.25 ± 0.02^{acAB}
8	20.17 ± 0.51^{aA}	21.27 ± 0.27^{bABC}	19.65 ± 0.52^{cA}	19.91 ± 0.35^{acAB}	19.99 ± 0.43^{acBD}	2.02 ± 0.29^{aB}	1.57 ± 0.18^{bBD}	2.43 ± 0.37^{cAB}	2.26 ± 0.26^{cBC}	2.32 ± 0.18^{cA}
10	20.17 ± 0.47^{aA}	21.22 ± 0.41^{bABC}	19.81 ± 0.14^{aA}	20.01 ± 0.31^{aAB}	19.92 ± 0.20^{aBD}	2.02 ± 0.27^{aB}	1.79 ± 0.10^{bC}	2.16 ± 0.08^{acAB}	2.13 ± 0.13^{acBC}	2.22 ± 0.11^{cABC}
14	21.80 ± 1.23^{aA}	21.04 ± 0.07^{aAC}	21.24 ± 1.59^{aB}	21.27 ± 0.72^{aC}	20.17 ± 0.36^{bD}	1.19 ± 0.43^{aC}	1.77 ± 0.07^{aC}	1.37 ± 1.00^{aC}	1.22 ± 0.79^{aD}	1.84 ± 0.19^{aD}
18	22.33 ± 0.89^{aA}	21.49 ± 0.55^{aBC}	19.72 ± 1.02^{aA}	20.16 ± 0.15^{aA}	19.91 ± 0.17^{aBD}	0.28 ± 0.35^{aD}	1.37 ± 0.27^{bB}	2.23 ± 0.80^{cAB}	1.93 ± 0.06^{cABC}	2.22 ± 0.08^{cABC}
22	23.99 ± 1.78^{aB}	21.57 ± 0.33^{bBC}	22.29 ± 1.98^{bC}	21.84 ± 1.62^{bD}	21.27 ± 0.28^{bE}	0.17 ± 0.89^{aD}	1.59 ± 0.11^{bBD}	0.71 ± 1.33^{aD}	1.38 ± 0.68^{bD}	1.71 ± 0.12^{bD}
Storage days at 10 °C										
0	18.91 ± 0.05^{aA}	20.78 ± 0.22^{bA}	20.02 ± 1.16^{cA}	20.23 ± 0.59^{cA}	19.82 ± 0.15^{cA}	2.66 ± 0.07^{aA}	2.08 ± 0.13^{bcA}	1.98 ± 0.71^{bcAB}	1.82 ± 0.34^{cA}	2.30 ± 0.07^{bA}
1	19.94 ± 0.82^{aAB}	21.19 ± 0.14^{bAB}	18.89 ± 0.97^{cB}	19.34 ± 0.26^{cdA}	19.59 ± 0.06^{adA}	2.12 ± 0.45^{aBC}	1.62 ± 0.10^{bB}	2.46 ± 0.58^{cAB}	2.01 ± 0.07^{aAB}	2.22 ± 0.13^{acAB}
2	19.39 ± 0.43^{aAB}	21.10 ± 0.21^{bAB}	19.34 ± 0.93^{aAB}	19.69 ± 0.07^{acA}	19.93 ± 0.09^{cA}	2.17 ± 0.13^{aBC}	1.74 ± 0.11^{bBC}	2.34 ± 0.78^{aAB}	2.16 ± 0.04^{aB}	2.10 ± 0.02^{aB}
3	19.59 ± 0.18^{aAB}	21.00 ± 0.11^{bA}	19.20 ± 0.66^{cAB}	19.83 ± 0.06^{aA}	19.73 ± 0.11^{aA}	2.33 ± 0.12^{aB}	1.77 ± 0.06^{bBC}	2.69 ± 0.55^{cA}	2.21 ± 0.12^{aB}	2.31 ± 0.03^{aA}
4	19.75 ± 0.31^{abAB}	21.45 ± 0.50^{cB}	19.26 ± 0.82^{aAB}	20.26 ± 1.22^{bA}	19.88 ± 0.24^{abA}	1.96 ± 0.18^{aC}	1.49 ± 0.12^{bD}	2.49 ± 0.55^{cAB}	2.09 ± 0.53^{aAB}	2.22 ± 0.05^{acAB}
6	20.51 ± 0.20^{aB}	21.45 ± 0.64^{bB}	20.17 ± 1.10^{aA}	21.60 ± 1.70^{bB}	20.25 ± 0.36^{aA}	1.57 ± 0.03^{abD}	1.67 ± 0.29^{abB}	1.91 ± 0.65^{bB}	1.39 ± 0.27^{aC}	1.83 ± 0.33^{bC}
8	26.33 ± 3.08^{abC}	20.90 ± 0.28^{cA}	26.99 ± 1.40^{bC}	26.36 ± 1.88^{abC}	24.64 ± 1.43^{bB}	0.57 ± 0.35^{aE}	1.93 ± 0.14^{bD}	0.43 ± 0.68^{aC}	0.32 ± 0.23^{aD}	0.39 ± 0.24^{aD}
10	23.08 ± 0.18^{aD}	20.86 ± 0.23^{bA}	23.40 ± 0.45^{aD}	23.26 ± 1.06^{aD}	21.62 ± 1.13^{cC}	0.65 ± 0.19^{aE}	1.87 ± 0.11^{bCD}	0.68 ± 0.45^{aC}	0.95 ± 0.25^{cE}	1.75 ± 0.15^{bC}

Values are expressed as mean ± standard deviation (n = 3).
Mean values with different small letters in the same row are significantly different ($P < 0.05$).
Mean values with different capital letters in the same column are significantly different ($P < 0.05$).

Table 2 Effects of nonthermal and thermal treatments on sensory characteristics of sikhye

Treatment	Colour	Flavour	Taste	Overall preference
No treatment	3.75 ± 0.80[a]	3.63 ± 0.78[a]	4.20 ± 0.78[a]	4.12 ± 0.65[a]
Heat treatment	3.65 ± 0.90[a]	3.68 ± 1.00[a]	3.27 ± 1.22[b]	3.50 ± 1.03[b]
TiO_2–UVC (0.24 J cm^{-2})	3.88 ± 0.73[a]	3.73 ± 1.00[a]	3.45 ± 1.01[b]	3.53 ± 0.85[b]
TiO_2–UVC (0.48 J cm^{-2})	3.57 ± 1.03[a]	2.05 ± 0.98[b]	1.82 ± 1.16[c]	1.87 ± 1.03[c]

Sensory score was based on 5-point scale adopted from Ryu *et al.* (2008) (5 = like extremely; 1 = dislike extremely like).
Freshly prepared home-made style sikhye drink. Untreated samples were used as controls.
Values are expressed as mean ± standard deviation (n = 30).
Mean values with different letters in the same column are significantly different ($P < 0.05$).

samples, probably because they were also consumers of ultra-high temperature-processed sikhye. Results reported herein were in agreement with the report of Gabriel *et al.* (2015) where sensory scores of a UV-C-processed coconut beverage were not significantly different from untreated controls.

Sensory evaluation provides information about attributes of a food product from a consumer perspective that can be used to establish acceptance (Andrés *et al.*, 2015). Colour and overall appearance of foods strongly influence consumer perceptions of quality during preservation and consumption. Moreover, colour perception interacts with other sensory attributes and changes in colour are associated with undesirable changes in other quality parameters. Similarly, flavour affects food acceptance and, hence, is a decisive factor in determining consumer acceptance of a particular product (Shahbaz *et al.*, 2014). In a similar study, sensory panellists did not find a significant difference between untreated and UV-C-treated pears. A higher preference was shown by panellists for control pears based upon appearance, even after 4 weeks of storage (Syamaladevi *et al.*, 2014). During sensory analysis of coconut milk, samples treated with 1.026 kJ m^{-2} UV-C irradiation received acceptance scores similar to control samples. In contrast to this study, heat-treated milk samples were preferred by panellists based on all sensory attributes tested (Ochoa-Velasco *et al.*, 2014).

Conclusion

Nonthermal processing using TUVP protected the pH and colour physicochemical quality parameters of fresh sikhye and inhibited microbial growth during storage for a longer time period than for controls. Thermal pasteurisation and TUVP both suppressed regrowth of microbes to an acceptable level. However, processing limitations related to thermal treatment-based changes in the physicochemical and organoleptic properties of similar-type beverages have been reported. The effect of temperature was significant for the preservation of the quality of sikhye during storage, and better results were obtained for samples stored at a low temperature of 4 °C. Hence, nonthermal processing using TUVP with appropriate optimisation of processing variables can present a practical alternative for addressing processing issues related to microbiological stability and the physicochemical qualities of this traditional drink at both small and industrial scales. The results of this study will be useful in providing manufacturers a processing technique to produce a safe drink with enhanced microbiological safety and characteristic quality. However, a general limitation of TUVP was noticed regarding the sensory aspects of sikhye particularly at high treatment dosage levels. Further research is needed to optimise TUVP processing conditions and to investigate and characterise chemical changes related to the production of undesirable compounds that lead to the development of off-flavours at high treatment dosages. Furthermore, application of TUVP as a nonthermal processing technique can be extended to other beverages that are highly perishable and also heat-sensitive and face commercialisation restrictions.

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Conflict of interest

The authors declare no conflict of interest.

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