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Inactivation kinetics of *Bacillus cereus* and *Aspergillus niger* spores in dehydrated onion shreds after pulsed light and infrared treatments

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Abstract

Fresh onions are dehydrated to increase their shelf-life. Primarily, open dehydration techniques like solar dehydration come with the problem of contamination through natural air convection. A solar conduction dryer that uses conduction, convection, and radiation for dehydration of food samples is exploited in this study. The food samples are often contaminated by *Bacillus* and *Aspergillus* species spores. As a remedy, pulsed light treatment as a non-thermal technology and infrared treatment as a thermal technology are studied and compared. *Bacillus cereus* and *Aspergillus niger* spores are chosen as a representative of bacterial and fungal contamination in onions. Dehydrated onion shreds with varying water activities (0.4, 0.5, 0.6) were treated. The spore inactivation was best described by Weibull model as compared with first-order model. Scanning electron microscopy images of the microbial cells showed surface distortions on the bacterial and fungal spores. The effect of the treatment technologies on the colour, flavour (thiosulphinate and pyruvic acid concentration), total phenolic and flavonoid content, and ascorbic acid concentration are compared. Overall, pulsed light treatment showed promising inactivation with a maximum log reduction of 4.5 log *B. cereus* spores·g^{-1} and 3.1 log *A. niger* spores·g^{-1} at 2.131 J·cm^{-2} in samples with water activity 0.6. The inactivation rate increased with an increase in water activity. The colour was better retained in pulsed light treated samples. The thiosulphinate content (9.24 µmol·g^{-1}), total phenolics (0.268 mg GAE·g^{-1}), and flavonoid content (0.344 mg QE·g^{-1}) in the sample were improved upon pulsed light exposure.

Keywords Decontamination, Inactivation constant, Thermal, Nonthermal, Pyruvic acid

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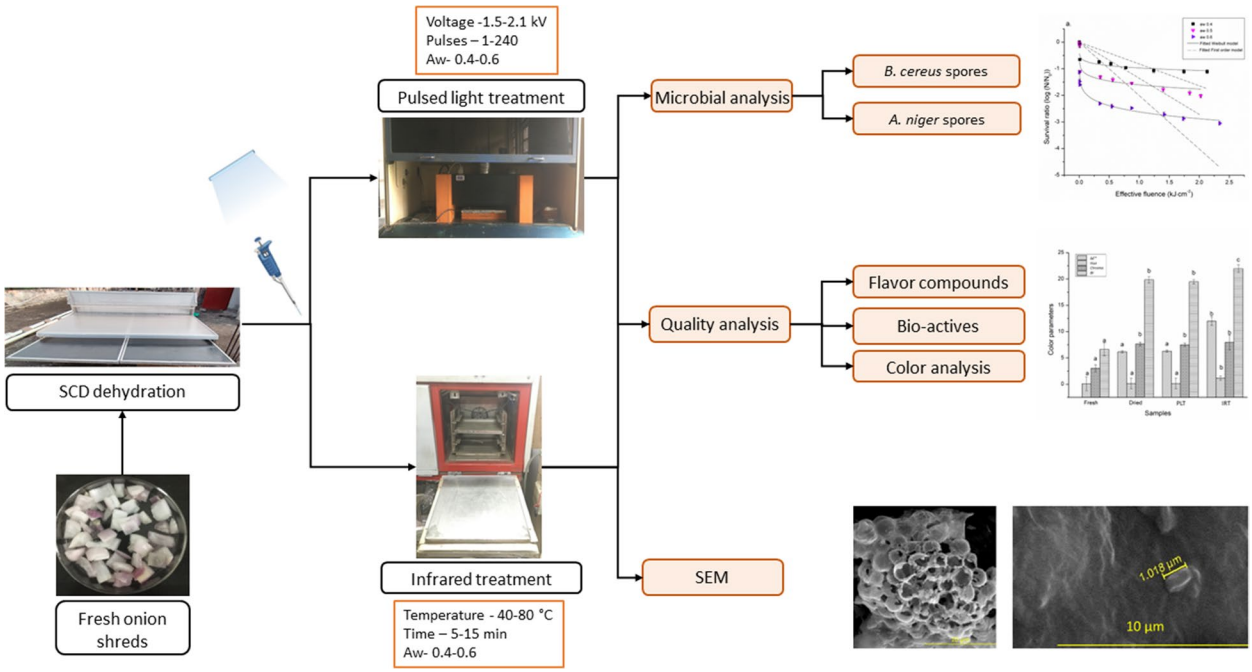
Graphical Abstract



Introduction

Onion preservation by dehydration is the most popular strategy to reduce production loss due to spoilage. Dehydrated onion products like flakes, powders, slices have been reported to be contaminated by bacterial spore-formers such as *Bacillus cereus*, and some fungal spore-formers such as *Aspergillus, Fusarium, Penicillium, Botrytis* species (Pezzutti et al. 2005). *B. cereus* causes foodborne illness such as diarrhea, nausea, and vomiting and has been reported in onion onion powders, minced onions, and onion soup mix (Hariram & Labbe 2015). *A. niger* causes black mold in onion. *A. niger* spores are the most resistant to UV-C radiation among the radiation-resistant fungal spores (Cortesão et al. 2020). Heat sensitivity of *A. niger* spores was estimated by Belbahi et al. (2015) on fresh date fruit surface (Belbahi et al. 2015). However, heat sensitivity of *A. niger* on dehydrated surface has not been studied so far. A log reduction of 1.6 CFU·g^{-1} of vegetative *A. niger* during rotary drum drying of garlic was achieved by Kar et al. (2019).

Contamination could occur during post-harvest processing of onions. Such spore formers can survive even below the water activity (a_w) of 0.6 because of having an increased thermal resistance (Syamaladevi et al. 2016). The solar conduction dryer utilizes a pioneering technology featuring a polycarbonate sheet that enables the passage of solar radiation. This radiation serves to heat both the conduction plate and the internal air. As a result, natural draft conveys the air, generating convective motion. Within this system, food samples undergo dehydration through the combined effects of radiation, convection, and conduction (Fig. 1). However, it's important to note that the convective air remains unfiltered, presenting a potential risk of microbial contamination. Some direct passive solar dryers such as cabinet and greenhouse dryers; indirect passive solar dryers like forced convection dryer; active solar dryers that require an exhaust; and hybrid solar dryers also possess the same problem (Feili et al. 2012; Udomkun et al. 2020).

Any dehydration technique that uses air convection may face spore contamination. Dehydrated onion products often catch moisture during transit or due to improper packaging, converting the spore formers into vegetative cells, causing spoilage (Savitha et al. 2021a, b). Masotti et al. (2019) have described the food industry airborne contamination caused by bioaerosol. Bioaerosol is a mixture of bacterial endospores and exospores like *Bacillus*, *Clostridium;* vegetative cells of Gram-positive bacteria, molds like *Penicillium* and *Alternarium;* and yeasts like *Saccharomyces.* Post-harvest spoilage in onions includes Blue mold rot caused by *Penicillium allii*. Spoilage during storage is reported to be caused

Fig. 1 Various modes of heat transfers take place during the dehydration of onion shreds in the Solar conduction dryer used in this study

by spore formers such as *Penicillium* sp., *Botrytis* sp., *Fusarium oxysporum*, *Alternaria* sp. *Aspergillus awamori* (Chang et al. 2018). Apart from this, proliferation of the *Aspergillus* species can prove to be pathogenic and cause Aspergillosis on consumption. Bacterial species such as *Staphylococcus*, *Bacillus* sp., *Pseudomonas* and *Escherichia coli* can cause food spoilage (Orpin & Mzungu 2017).

Inactivating bacterial spores is a challenge due to their characteristic spore coat. The spore coat has low moisture content, high diploconic acid content, divalent ions for chelation, and small acid soluble proteins (SASPs) that protect the cell. Fungal spores possess trehalose and mannitol that protect them from reactive oxygen species. These also possess heat, cold, desiccation, and oxidative shock proteins (Pinto et al. 2020). Spores can be inactivated through thermal, non-thermal, biological or chemical decontamination techniques. A common thermal treatment technology is infrared (IR), in which the sample surface is heated by the radiation, causing the food molecules to vibrate, leading to thermal damage to the DNA, RNA, proteins, and cell wall (Eliasson et al. 2014). IR does not need any medium to reach the food surface. As the food sample is dehydrated, it acts as a black body, absorbing and emitting radiation. Inactivation models are used to describe the trend of microbial survival influence by the treatment conditions. Such trends allow extrapolation and hence prediction of the effect of treatment conditions on the microorganism. Models also describe the effect of individual parameters, helping design treatment technologies for different products and dimensions (Vurmaz & Gündüz 2020). Inactivation model at the sample surface by IR treatment was described with first order kinetics for the inactivation of *Conidia* species (Trivittayasil et al. 2011), yeast cells (Huang et al. 2009), *S.* Typhimurium and *A. flavus* (Shirkole et al. 2020).

While thermal treatment methods show promise in decontamination, they often lead to compromised food quality due to the high temperatures involved. This is evident in the loss of colour, flavour, and texture. As a result, non-thermal technologies gain significance as alternatives in this context. There are few non-thermal technologies in which the dehydrated sample can be exposed to the energy source and the microbial inactivation occurs in the food sample. The examples include plasma, UV, and pulsed light treatments. Plasma technology uses ionized gas to react with the cell biomolecules to cause cell death. *Bacillus cereus* and *Aspergillus brasiliensis* spores have been inactivated in onion powder using microwave-powered cold plasma (Kim et al. 2007b). Ultraviolet (UV) rays and pulsed light causes crosslinking of pyrimidine nucleoside bases (thymine dimers) in the DNA, disrupting DNA replication (Rifna et al. 2019). About seventy proteins on the spore coat's outer, inner and core protect *B. subtilis* (Clair et al. 2020). Pulsed light (PL) has proven to degrade major proteins in the protective spore coat of *Bacillus subtilis* (Clair et al. 2020). It causes irreversible DNA damage due to its photothermal, photophysical, and photothermal effect (Dhar et al. 2022). PL for *Bacillus subtilis* inactivation in spices such as caraway powder, red and black pepper powder was implemented by Nicorescu et al. (2013). Pulsed light plasma has been used for decontamination of red pepper powder from indigenous bacteria (Lee et al. 2020a, b) and of red pepper flakes from *Aspergillus flavus* spores and *Bacillus pumilus* spores (Lee et al. 2020a, b). Aflatoxin content was reduced by 98.9% in peanuts using PLT at 1.2 J/cm^2 (Abuagela et al. 2019). Implementing PL technology for decontamination onion bulb and its products is yet to be explored. Study of inactivation of *B. cereus* spores and *A. niger* spores in onion products under PL or IR treatments is not attempted yet.

This study explores the potential of thermal (infrared treatment) and non-thermal (pulsed light treatment) technologies for decontamination of dehydrated onion shreds. *Bacillus cereus* and *Aspergillus niger* spores were taken as representative microoraganisms in bacterial and fungal categories as targets. Both have been reported in the state of art to contaminate onions. Three levels of water activities (a_w of 0.4, 0.5, and 0.6) of the dehydrated onion shreds were considered. Inactivation kinetics of the *B. cereus* and *A. niger* spores by PLT and IRT was explored. Besides, various quality attributes such as colour profile, pyruvic acid, thiosulphinate, total phenolics, total flavonoid, and ascorbic acid content of the PL or IR treated dehydrated onion shreds were compared.

Materials and methods

Decontamination

Sample preparation

Red onions (*Allium cepa* L.) with 40–50 mm bulb diameter were selected from 1 kg of onion using a vernier calliper from the local supplier near Matunga, Mumbai, India. Firm unrotten onions with dry skin and without mold were selected. Onions were peeled, cut into halves and diced into dimensions 1 cm × 1 cm shreds using a dicer. These were divided into 3 groups of 400 g each, which were to be labelled as O1, O2, O3. These were dried in solar conductive drier (SCD, Science for Society Techno Services Pvt. Ltd., Mumbai, India) and collected once the water activity (a_w) of 0.6, 0.5, and 0.4 for O3, O2, and O1, respectively (Savitha et al. 2023). As mentioned above, spore formers can survive below a_w 0.6 (Syamaladevi et al. 2016), proliferation of microorganisms is not evidence below a_w 0.4 (Rahman et al. 2020). A set of preliminary experiments were conducted where the onion shreds were dried and the a_w and moisture content were estimated at various intervals. Based on the results, samples O3, O2, and O1 were removed from the dryer after a definite interval, following a confirmatory measure of the a_w using a water activity meter (AquaLab, Series 3 TE). Three samples of O1, O2, and O3 were taken and were named as O1x, O1y and so on. The a_w of O1x, O1y, O1z were 0.404 ± 0.001, 0.403 ± 0.001, 0.402 ± 0.001, respectively. Similarly, a_w of O2x, O2y, O2z were 0.501 ± 0.001,0.503 ± 0.001, 0503 ± 0.001, and a_w of O3x, O3y, O3z were 0.601 ± 0.001, 0.602 ± 0.001, 0.601 ± 0.001, respectively. It is known that food systems with $a_w \leq 0.6$ are said to be safe from microbial proliferation. Hence the upper limit of a_w was chosen as 0.6 for this study. Moisture content of the dehydrated onion shreds was maintained below 8% as per Food Safety and Standards Authority of India guidelines (FSSAI 2019). Following the dehydration process, the dried onion shreds underwent microbial inoculation. The dehydrated onion shreds were subsequently categorized into two groups, Group A and Group B, for the inoculation of *B. cereus* spores and *A. niger* spores, respectively. *B. cereus* and *A. niger* spores have been found to contaminate onion products (Pezzutti et al. 2005). Each group consisted of three subgroups of dehydrated onion shreds with varying water activity levels: a_w 0.4 (A1), a_w 0.5 (A2), and a_w 0.6 (A3) for the samples inoculated with *A. niger*. Similarly, there were B1, B2, and B3 samples for *B. cereus* with three water activity levels.

Spore culture preparation

Bacillus cereus ATCC 10876 was obtained from Himedia Pvt. Ltd., India. Broth cultures were prepared in tryptic soy broth and incubated at 36 °C for 24 h (Kim et al. 2017a). Calcium nitrate (0.02%, w/v) was added to initiate and increase the sporulation rate (Monteiro et al. 2014). Microscopy confirmed sporulation, and the culture was centrifuged at 3600 × g at 4 °C for 20 min. The supernatant was discarded, and the pellet was washed with distilled water twice by centrifugation. The pellet was dispersed in distilled water for inoculation (Kim et al. 2017a). The *B. cereus* spore count was estimated to be ~ 6.0 log spores/mL.

Aspergillus niger ATCC 6888 was purchased from Himedia Pvt. Ltd., India. Potato dextrose agar plates were streaked with the same and were incubated at 30 °C for 3–4 days. Ten mL of tween 80 (0.1%, w/v) was added to the culture plates to scrape out the colonies gently. The suspension was collected and centrifuged at 4000 × g at 23 °C for 5 min. The pellet was washed twice with distilled water, followed by centrifugation. The estimated *A. niger* spore count was ~ 6.0 log spores/mL (Lee et al. 2020a, b).

Inoculation of spores

Dehydrated onion shreds (A1, A2, A3, B1, B2, B3) were sterilized under UV in the laminar chamber for 20 min. The UV was exposed on both sides of the shreds to eliminate the background microbial load. The UV treatment time was selected based on some preliminary experiments conducted between 5 and 40 min (Gündüz & Korkmaz 2019; Watson et al. 2020). The UV exposure time of 20 min reduced the colony counts in natural microbiota below the detection limit. Three samples were kept as control to detect any residual CFU after UV exposure. UV exposed onion shreds were sprayed with the spore culture and left under the laminar blower for an hour to air dry. About 6.0 log spore·g^{-1} was inoculated on A1, A2, and A3 samples (for *A. niger*) and B1, B2, and B3 samples (for *B. cereus*), respectively.

Pulsed light treatment

Samples were taken for pulsed light treatment (PLT) in a bench-top pulsed light system (X-1100, Xenon Corporation, USA) having a xenon flash lamp source. The lamp (ϕ 2.45 × 40.6 cm, LH-480, B-type, mercury-free) emits light between wavelengths of 200–1100 nm, with a maximum of 3 kV voltage. The onion shreds were arranged in a 2.5 cm thick horizontal line parallel to the lamp in petri plates where the maximum intensity of the light fell. Treatment conditions set for experiments were four voltages – 1500, 1800, 2100, and 2200 V; treatment time durations were 1, 75, and 120 s with a frequency of 2 Hz and pulse width of 400 µs. The number of pulses were 2 (1 s), 150 (75 s), and 240 (120 s). The voltage range and treatment time duration was selected based on the preliminary tests conducted. At voltage higher than 2100 V, the sample got burned after just 1 s of PL exposure. Treatment longer than 240 s at 1500 V also burnt the sample. Short bursts of pulsed light were bombarded directly on the uncovered sample without any packaging for decontamination. As the sample was exposed to UV rays on both sides, and confirmed for the absence of natural microbiota, the spore culture was inoculated on the top of the sample only. Turning the sample upside down was avoided to prevent contamination. PLT was also employed at the top of that surface only, to achieve accuracy in the spore count. In this study, PL was exposed to the surface on one face of the petri plate. To achieve uniformity, there should be some vibration so that the sample can be flipped over during treatment for uniform exposure. Sample surface temperature was measured using an infrared and contact thermometer (Fluke-561) before and immediately after the treatment. Samples were analysed immediately after the treatments.

The total fluence (F_0, J·cm^{-2}), when the fluence rate is constant at a time, can be calculated using Eq. 1.

$$F_0 = E_0 \times t \tag{1}$$

Here, E_0 is the fluence rate (W·s^{-2}), and *t (s)* is the exposure time.

In case of solid foods, the fluence is affected by the thickness or depth (x mm) and exposure time (t). So, the fluence can be estimated using Eq. 2.

$$F_0 = E_0 e^{-ix} \times t \tag{2}$$

Here, i is the extinction coefficient (mm^{-1}).

There are several factors that affect the fluence rate such as the petri factor (PF), divergence factor (DF), reflection factor (RF), water factor (WF), and germicidal factor (GF) at a specific wavelength (λ). In case of dehydrated onion shreds, the DF and WF can be removed. Considering these factors, the fluence rate can be calculated using Eq. 3.

$$E_a = PF \cdot \int_{\lambda_1=200}^{\lambda_2=1100} (w_\lambda \cdot E_{\lambda x} \cdot RF_\lambda) \cdot d\lambda \tag{3}$$

So, the effective fluence (F_e, J·cm^{-2}) is the product of fluence rate, number of pulses (N_p), and pulse width, τ (Dhar & Chakraborty 2023; Gómez-López & Bolton 2016).

$$F_e = E_a \times N_p \times \tau \tag{4}$$

Infrared treatment (IRT)

The dehydrated onion flakes were treated under infrared radiation at 40 °C, 60 °C, and 80 °C for 5, 10, and 15 min in IR tray dryer (Model 01, Litel, Pune, India). Temperature higher than 80 °C and treatment time longer than 15 min burnt the sample; hence the temperature and time were restricted to the mentioned range. The chamber contained a sensor that measured the chamber temperature and cut-off the heating once the set temperature was reached. The sample distance from IR lamp was 20 cm. The sample temperature during the holding period was ensured to be in the range of ± 1 °C from the set chamber temperature, hence considered isothermal heating.

The humidity in the chamber air was recorded using a temperature and humidity transmitter (Vaisala HMD82D, Cole-Parmer India Pvt. Ltd., Mumbai, Maharashtra, India). The air velocity inside the chamber was measured using a vane anemometer (VT100, Kimo Instruments). Post-treatment, the samples were covered immediately and taken for enumeration.

Enumeration

For *B. cereus* spore enumeration, 10 g of treated samples were taken in 100 mL of 0.85% saline and heated in hot water bath at 80 °C for 10 min. For *A. niger* spore enumeration, 0.1% tween 80 in 0.85% saline was used. Sample dilutions were prepared and spread on tryptic soy agar (Himedia) plates for *B. cereus* spore enumeration and on potato dextrose agar (Himedia) for *A. niger* spore enumeration. A colony counter (Labline, Model No. 37) was used for counting the colonies. A set of dehydrated samples with only UV decontamination was taken as control samples to detect any residual CFU after this UV exposure. This sample is considered as the sample treated at 0 fluence for PLT and room temperature for IRT.

Kinetics of microbial inactivation

In case of PL, the kinetics of survival ratio of microorganisms was determined using the Weibull model (Eq. 5) (Dementavicius et al. 2016). The survival population, N (spores·g^{-1}) after an exposure of fluence intensity at time t, and the initial survival population, N_0 (spores·g^{-1}) were considered in this model. The total fluence (F, J·cm^{-2}) is the light energy exposed on unit surface area of the food. The shape factor is n and the fluence based inactivation is k_F (Buzrul 2022; Dhar et al. 2022). The inactivation constant was calculated using Eq. 6. Hence, the survival ratio data was also fitted into first order model and compared.

$$\log\left(\frac{N}{N_0}\right) = -k_F F_e^n \tag{5}$$

$$k = k_F \times E_a = \frac{2.303}{D} \tag{6}$$

Here, E_a is the fluence rate in W·cm^{-2}, and D is the is the decimal reduction time in s.

In case of IRT, isothermal heating was exposed to the sample for microbial inactivation. The kinetics of microbial survival ratio after time t (min) was determined using Weibull model as described in Eq. 7. The decimal reduction time, D (min) was estimated using Eq. 6.

$$\log\left(\frac{N}{N_0}\right) = -k \times t^n \tag{7}$$

The effective heating time (t_e) was estimated using Eq. 8.

$$t_e = \int_0^t 10^{\left(\frac{T-T_{ref}}{z}\right)} \cdot dt \tag{8}$$

Here, T is the sample temperature (°C), T_{ref} is the maximum temperature the sample reached during the treatment, z is the temperature increase to achieve 10-fold reduction in the D value.

The RMSE was estimated using Eq. 9, where ypred is the model predicted log reduction and Y_{act} is the experimental log reduction achieved.

$$RMSE = \sqrt{\frac{1}{m}\left(\sum_i^m \left(y_{pred} - y_{act}\right)^2\right)} \tag{9}$$

SEM analysis

Treated onion shreds were platinum coated using an autofine coater (JeOL JFC-1600) for 60 s. Further, the structural analysis was conducted using Environmental Scanning Electron Microscopy (FEI, Quanta 200).

Quality analysis of decontaminated onion shreds

Ascorbic acid (AA) content was estimated spectrophotometrically using 2,6-dichloroindophenol dye reduction principle following the protocol explained by Khan et al. (2016) and was reported in dry basis (db). Pyruvic acid (PA) content in the sample was estimated spectrophotometrically using (2,4-Dinitrophenylhydrazine) DNPH reduction principle as detailed by Metrani et al. (2018). Thiosulphinate (TS) concentration was estimated spectrophotometrically using hexane as the extraction solvent (Kaymak-Ertekin & Gedik 2005). Total phenolic content (TPC) was estimated spectrophotometrically following the protocol explained by (Salamatullah et al. 2020). In the reaction mixture, extract, Folin–Ciocalteau reagent, and 20% Na_2CO_3 were added. Absorbance was taken at 735 nm using a UV–visible spectrophotometer. TPC was expressed as mg equivalent gallic acid. Total flavonoid content (TFC) was estimated spectrophotometrically using the method explained by Edith et al. (2018). The reaction mixture consisted of extract, 10% aluminium chloride, and potassium acetate. The flavonoid content was expressed in mg equivalent quercetin per g of shreds.

Colour analysis

Colour parameters, L^* (lightness), a^* (red to green) and b^* (yellow to blue) of the onion shreds were estimated using Hunter-lab colourimeter (LabScan-XE LX17375, Hunter Associates Laboratory, USA). The colour change (ΔE^*) and browning index (BI) were calculated using the below-mentioned equations (Dhar et al. 2021; Shrestha et al. 2020).

$$\Delta E^* = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \tag{10}$$

$$BI = \frac{(x - 0.31)}{0.172} \times 100 \tag{11}$$

$$x = \frac{(a^* + 1.75L^*)}{(5.645L^* + a^* - 3.012b^*)} \tag{12}$$

Here, x is the chromaticity coordinate. The subscript '*0*' refers to the respective colour indices of the control sample.

Quercetin quantification

The effect of PL and IR after dehydration was assessed on the quercetin content of onion shreds. Ten grams of dehydrated onion shreds were crushed using pestle and mortar and kept in shaking in 100 mL of methanol for 2 h. The shreds were then and filtered using Whatman filter paper Grade 1. The filtrate was filtered using a syringe filter of 0.45 µm pores size and collected in 1 mL glass vials. Methanolic sample extract (1 mL) was taken for HPLC analysis adapting the method explained by Albishi et al. (2013). The sample was separated in C18 column (250 mm × 4.6 mm) with 5 µm particle size. An injection volume of 1 µL underwent a flow rate of 1 mL·min^{-1}. The mobile phase consisted of water: formic acid (95:5, v/v) and 100% methanol and a ratio of 40:60 was run, respectively, keeping the concentration constant. Absorbance was taken at 360 nm and the retention time and area under the curve was considered for quercetin quantification. Quercetin standard (Oxford Lab Fine Chem LLP, Maharashtra, India) was prepared from 20–100 ppm concentrations to understand the retention time. Quercetin concentration (mg·g^{-1}) was estimated as ((area under the curve) − 34.94)/0.038, $R^2 = 0.95$, limit of detection = 0.00085 mg·g^{-1}, limit of quantification = 0.0025 mg·g^{-1}.

Statistical analysis

Experiments were conducted in duplicate and analysed in triplicate. The non-linear curve fitting tool in Origin Pro 8.5 was used for kinetic modelling. One-way analysis of variance (ANOVA) and Tukey's HSD test were conducted to visualise the significant differences between the mean values at 95% confidence interval. Statistical analysis was conducted using SPSS version 16.0.

Results and discussion

The magnitude of microbial inactivation was estimated and compared between a_w 0.4, 0.5, and 0.6. For PL treatment, the total fluence was determined for the respective treatment conditions i. e. three voltages – 1500, 1800, 2100 V; treatment time durations were 1, 75, and 120 s with a frequency of 2 Hz. Treatment at 2200 V exposed the samples to extremely high fluence and the respective white light spectra resulted in an undesirable sensory profile (primarily the smell and colour) of the onion shreds. Hence, the PL treatment was conducted at a lower voltage than 2200 V. Dhar and Chakraborty (2020) described the inactivation kinetics of aerobic mesophilic bacteria and yeast and mold inactivation with Weibull model and determined the fluence based rate constant (k_F). This concept is adapted to determine the k_F for the microbial inactivation caused by PL. For IR treatment, the effect of chamber temperatures of 40, 60, and 80 °C for 5, 10, and 15 min was evaluated for onion shreds having a_w 0.4, 0.5, and 0.6.

Inactivation of *A. niger* and *B. cereus* spores using PLT

The extent of *A. niger* spore inactivation increased with an increase in the total fluence of pulsed light exposure. The log reduction range was 0.01–1.11, 1.12–2.60, and 1.13–3.05 log spores/g for A1, A2, and A3, respectively. An effective fluence on sample A1 ranged between 0.003 ± 0.3 and 0.010 ± 0.2. For sample A2, the log reduction ranged between 0.331 ± 0.4 and 0.777 ± 0.9, and for sample A3 it ranged between 1.241 ± 0.3 and 2.131 ± 0.5 J¨cm^{-2}, respectively. When the number of pulses was 240, the fluence per pulse was seen to be slightly higher, given a much higher total fluence. Overall, the log reduction of *A. niger* spores in PLT dehydrated onion shreds was in the order A3 (a_w 0.6) > A2 (a_w 0.5) > A1 (a_w 0.4).

When the data was fitted in first order model, keeping $n = 1$ (Eq. 1), the R^2 came out to be very low ($R^2 \leq 0.7$). The first order model fit was poor. The Weibull model was a good fit for samples A1, A2 and A3 with an $R^2 \geq 0.98$. The shape factor was computed as 0.14 i.e., $n < 1$, which gives a concave shape to the curve, showing a tailing effect along with the effective fluence (Fig. 2). A tailing trend describes the resistance offered by the microorganism against the inactivation treatment. A sample showing least resistance will show higher inactivation rate and this is supported by a high k value of 0.54 s^{-1} for inactivation of sample A3. As compared to A3, sample A2 and A1 showed lower k value of 0.32 s^{-1} and 0.18 s^{-1}, respectively (Table 3).

Similarly, *B. cereus* spore inactivation increased with increase in the total fluence. Log reduction of *B. cereus* spores in sample B1, B2, and B3 ranged between 1.26–2.5, 3.01–4.44, and 3.02–4.50 log spores/g, respectively. Unlike the inactivation of *A. niger* spores, increasing log reductions were observed within the same voltage condition with an increase in pulses of PL. As the fluence increased, the inactivation increased by ~ 1.5 log spores/g. Overall, the log reduction in *B. cereus* spores was in the order of B3 (a_w 0.6) > B2 (a_w 0.5) > B1 (a_w 0.4).

In the Weibull model fitting, samples B1, B2, and B3 had an n value of 0.05 describing a prominent tailing effect. Such a resistance in inactivation could be due to the unavailability of moisture. The sample that had high resistance to inactivation treatment showed higher inactivate rate. Hence, the k of sample B3 and B2 was highest, 0.81 s^{-1} followed by sample B1 (0.33 s^{-1}), hence explaining the order of inactivation of *B. cereus* spores. It is noteworthy that the impact of PL on samples B2 and B3 showed similar inactivation kinetics. The data fitted in first order had a low R^2 of < 0.7 and χ^2 of 745.69. Hence,

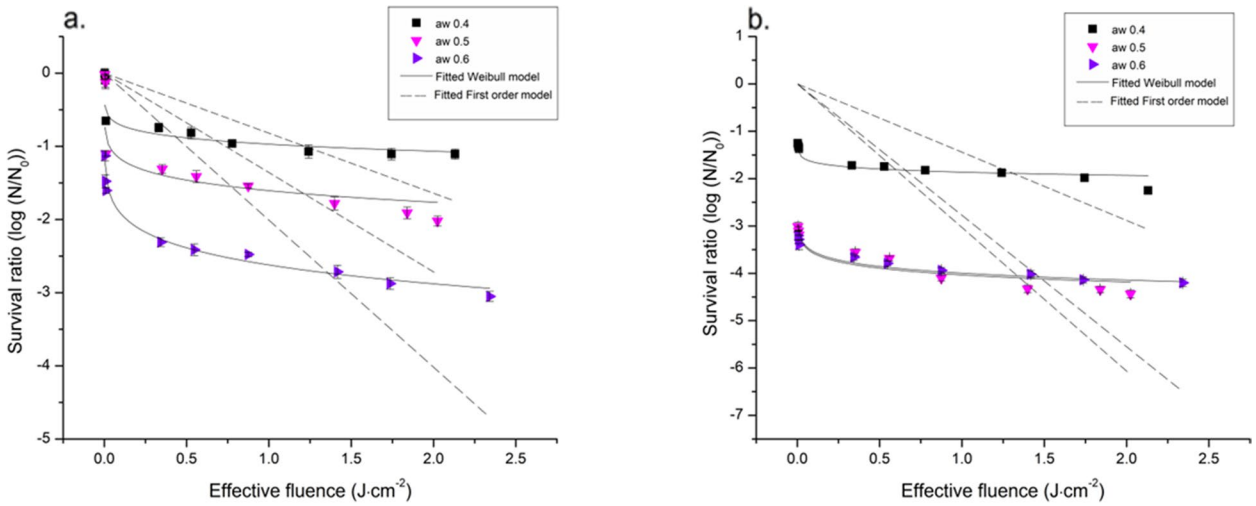


Fig. 2 Fitting of the survival fractions of different spores in onion shreds to Weibull and first order kinetic models after pulsed light treatment. **a** *A. niger* and **b**) *B. cereus*

the data fit was found to be poor in first order, and Weibull model was suitable. Figure 2 shows the Weibull model and first order fit of survival ratio of *A. niger* and *B. cereus* spores inactivated using PLT. The PLT conditions for *A. niger* and *B. cereus* spore inactivation are mentioned in Table 1.

Xu et al. (2013) utilized PLT on green onions at 56.1 J/cm^2 for 60 s and achieved 4.6 log spores/g reduction in *Escherichia coli* O157:H7. Log reduction in *B. cereus* on plum, tomato, cauliflower, and strawberry was reported to be 1.4–1.8 log spores/g (Luksiene et al. 2012). PLT at 1.8 J/cm^2 is reported to achieve 5 log reduction in *B. cereus* spores spread on agar plates. *A. niger* spores have seen to be more susceptible to PLT than the bacterial spores in general (Levy et al. 2012). Also, vegetative cells are more susceptible to PLT than spores. The spore-coat is affected by the UV-C part of PL spectrum resulting in the formation of a photoproduct called 5-thyminyl-5,6-dihydrothymine. Apart from this, single and double strand breaks in the genetic material and cyclobutene pyrimidine dimerization occurs on UV-C exposure. Enzyme activity is also inhibited due to the formation of superoxide and hydroxyl radicals, which leading to oxidative stress (Dhar et al. 2022).

Inactivation of *A. niger* and *B. cereus* spores using IRT

The treatment conditions for IR inactivation of *A. niger* and *B. cereus* spores are mentioned in Table 2. Inactivation using IR depends on the increase in temperature of sample (ΔT). Log reduction of *A. niger* spores fell in ranges 0.01 to 1.55 in sample A1, 0.46 to 1.60 in sample A2, and 0.90 to 2.06 in sample A3. Overall, the log reduction increased with an increase in temperature. The log reduction in *A. niger* spores was in order A3 (a_w 0.6) > A2 (a_w 0.5) > A1 (a_w 0.4).

Table 1 Treatment conditions for inactivation of *B. cereus* and *A. niger* spores in onion shreds using pulsed light

Voltage	No of pulses	F_e (J·cm^{-2})	Average Fluence rate (W·cm^{-2}, × 10^{-2})	Treatment time (s)	Temperature rise (°C)
1500	1	0.003 ± 0.3	0.262 ± 0.001	0.5	3.0 ± 0.3
1500	150	0.006 ± 0.6		75	7.2 ± 0.1
1500	240	0.010 ± 0.2		120	10.1 ± 0.2
1800	1	0.331 ± 0.4	0.518 ± 0.001	0.5	5.0 ± 0.3
1800	150	0.528 ± 0.8		75	9.2 ± 0.1
1800	240	0.777 ± 0.9		120	11.1 ± 0.2
2100	1	1.241 ± 0.3	1.420 ± 0.001	0.5	7.0 ± 0.3
2100	150	1.344 ± 0.7		75	10.2 ± 0.1
2100	240	2.131 ± 0.5		120	15.1 ± 0.2

F_e Effective fluence ($F_e = E_a \times N_p \times \tau$, J·cm^{-2}), E_a Fluence rate, N_p Number of pulses, Pulsed width = 400 µs, frequency = 2 Hz

Table 2 Treatment condition for *B. cereus* and *A. niger* inactivation using infrared treatment

Chamber temperature (°C)	Time (min)	Sample temperature (°C)	Come up time (s)
40	5	39.6 ± 0.2	27 ± 2
40	10	39.8 ± 0.2	30 ± 2
40	15	39.7 ± 0.2	28 ± 2
60	5	59.7 ± 0.2	103 ± 3
60	10	59.8 ± 0.2	105 ± 3
60	15	59.6 ± 0.2	104 ± 2
80	5	79.7 ± 0.2	154 ± 2
80	10	79.8 ± 0.2	153 ± 3
80	15	79.6 ± 0.2	155 ± 2

A. niger spore inactivation was described by Weibull model and first order model with an R^2 of 0.93 and 0.91, respectively. Under the Weibull fit, the *n* value was 0.81 ± 0.06 implying to a concave nature of inactivation. A tailing effect was observed in samples of all three activities. The *k* values for A1, A2, and A3 were 0.32 ± 0.03 s^{-1}, 0.59 ± 0.05 s^{-1}, and 0.95 ± 0.05 s^{-1}, respectively. Under the first order fit, the *k* values were 0.23 ± 0.01 s^{-1}, 0.47 ± 0.02 s^{-1}, and 0.81 ± 0.03 s^{-1} for A1, A2, and A3, respectively. This can be seen in the Weibull fit for *A. niger* and *B. cereus* spore inactivation using IRT in Fig. 3. The inactivation rate constants are mentioned in Table 3.

B. cereus spore inactivation showed a slight concave nature with $n = 0.32$. The tailing effect described by the Weibull fit had an R^2 of 0.98, showed a gradual decrease in the survival ratio due to IRT. The *k* values of B1, B2, and B3 were 0.23 ± 0.03 s^{-1}, 1.45 ± 0.04 s^{-1}, and 1.87 ± 0.04 s^{-1}, respectively, showing an increase in inactivation rate with increase in temperature. The first order fit had an R^2 of 0.77 showing poor fit. The *k* values were 0.11 ± 0.05 s^{-1}, 0.96 ± 0.08 s^{-1}, and 1.26 ± 0.08 s^{-1}, for samples B1, B2, and B3, respectively. The log reduction in *B. cereus* spores was in order B3 (a_w 0.6) > B2 (a_w 0.5) > B1 (a_w 0.4). Far-IR treatment on whole white and yellow onions achieved 3.3 log CFU/cm^2 reduction in a mixture of *Salmonella* species (*S. enteritidis*, *S. infantis*, and *S. typhimurium*) after 120 s of treatment at 80 °C (Coskun et al. 2021). El Darra et al. (2021) achieved a log reduction of 2.5 CFU/g by IRT for 30 min.

The allowable *B. cereus* count in food products is 10^3 CFU/g, while ≥ 10^5 CFU/g is considered unsafe for human consumption (Amor et al. 2018; FSSAI, 2018). As the initial spores count was 6 log cycle, treatment conditions achieving ≥ 3 log reduction is desirable. In case of PLT, the desired reductions of ≥ 3 log cycles in *B. cereus* population were achieved at all treatment conditions in samples B2 and B3. While in sample B1, only one treatment combination of 2100 V and 240 pulses at 2 Hz could achieve 3 log reduction, receiving an effective fluence of 2.131 ± 0.5 J·cm^{-2}. Other non-thermal technologies such as high microwave density cold plasma has proven to achieve 2.1 log spores/cm^2 reduction in 40 min of treatment (Kim et al., 2017b). On the other hand, microwave plasma achieved 3.4 log spores/g reduction of *B. cereus* spores in red pepper powder (Kim et al. 2014).

The presence of *Aspergillus* species in food samples may lead to the formation of Aflatoxins which is

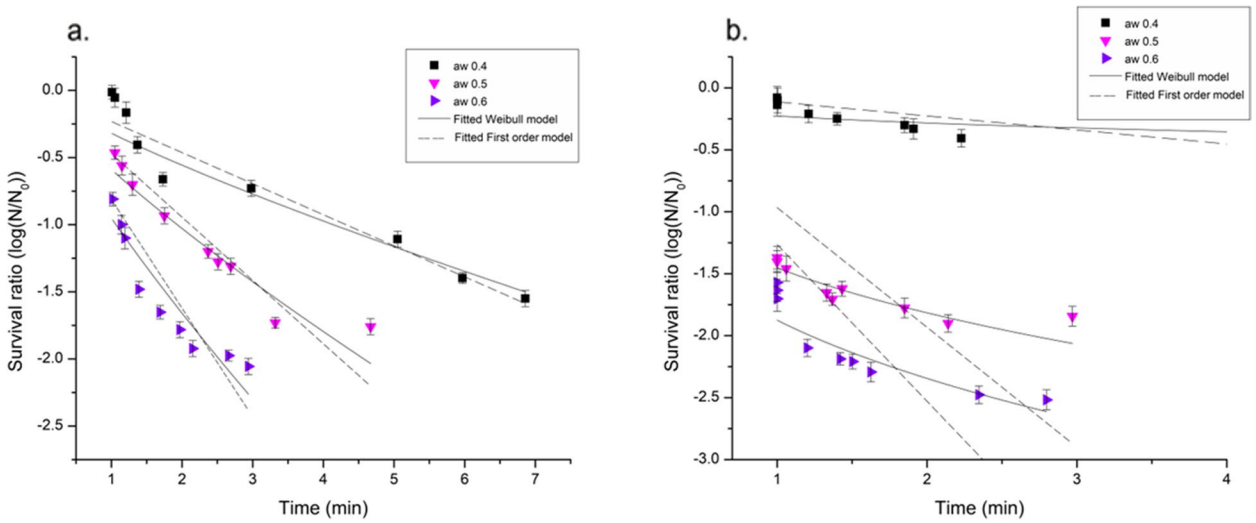


Fig. 3 Fitting of the survival fractions of different spores in onion shreds to Weibull and first order kinetic models after infrared treatment. **a**) *A. niger* and **b**) *B. cereus*

Table 3 Rate constants of PLT and IRT samples as described by Weibull and first order model

Treatment	Sample	Weibull model fitting					First order model fitting			
		k (s^{-1})	D (s)	n	R^2	χ^2	k (s^{-1})	D (s)	R^2	χ^2
PLT—*A. niger*	O1 (a_w 0.4)	0.18 ± 0.01	12.9 ± 0.1	0.14 ± 0.02	0.93	14.56	2.24 ± 0.01	12.4 ± 0.1	< 0.7	256.31
	O2 (a_w 0.5)	0.32 ± 0.01	7.0 ± 0.2				1.14 ± 0.02	7.1 ± 0.1		
	O3 (a_w 0.6)	0.54 ± 0.01	4.3 ± 0.1				0.93 ± 0.04	4.6 ± 0.1		
PLT—*B. cereus*	O1 (a_w 0.4)	0.33 ± 0.02	6.8 ± 0.1	0.05 ± 0.05	0.98	4.78	0.33 ± 0.01	6.8 ± 0.1	< 0.7	745.69
	O2 (a_w 0.5)	0.81 ± 0.01	2.8 ± 0.3				0.75 ± 0.03	3.0 ± 0.1		
	O3 (a_w 0.6)	0.81 ± 0.01	2.8 ± 0.1				0.49 ± 0.01	3.3 ± 0.1		
IRT—*A. niger*	O1 (a_w 0.4)	0.32 ± 0.03	7.2 ± 0.2	0.81 ± 0.06	0.93	11.73	0.23 ± 0.02	10.0 ± 0.1	0.91	11.73
	O2 (a_w 0.5)	0.59 ± 0.05	3.9 ± 0.1				0.47 ± 0.02	4.9 ± 0.1		
	O3 (a_w 0.6)	0.95 ± 0.05	2.4 ± 0.3				0.81 ± 0.03	2.8 ± 0.1		
IRT—*B. cereus*	O1 (a_w 0.4)	0.23 ± 0.03	10. ± 0.3	0.32 ± 0.04	0.98	2.34	0.11 ± 0.06	20.9 ± 0.1	0.77	32.55
	O2 (a_w 0.5)	1.45 ± 0.04	1.6 ± 0.1				0.96 ± 0.08	2.4 ± 0.1		
	O3 (a_w 0.6)	1.87 ± 0.04	1.2 ± 0.2				1.26 ± 0.08	1.8 ± 0.1		

PLT Pulsed light treatment, *IRT* Infrared treatment, R^2 Coefficient of determination, k Inactivation rate constant, D Decimal reduction time

carcinogenic and can cause stunting. The death rate of *Aspergillus conidia* has been proven to increase with an increase in a_w (Molekul et al. 2022). According to US standards, 20 ppb of aflatoxin concentration is regulated in food products (Singh & Cotty 2017). Hence inactivation of *Aspergillus* spores is essential to avoid toxin presence and to qualify for regulatory standards.

Overall, the extent of microbial inactivation increased with an increase in the a_w. Inactivation by PLT has triple the effects of photothermal, photophysical, and photochemical. By photothermal effects, the biosynthetic proteins of the cells are degraded, hampering the metabolic pathways required for cell sustenance. The photophysical effects degrade the biomolecules of the plasma membrane and cause cell burst, releasing the cell organelles. Photochemical effects cause permanent DNA dimerization and hamper the replication process for cell proliferation (Dhar et al. 2022). Clair et al. (2020) reported that some spore coat proteins in *Bacillus subtilis* were degraded by PLT at 1.8 J/cm^2, achieving 2 log reduction. Genes responsible for spore coat proteins, such as *cotE*, *cotG*, *spoVID*, were found to have defects after PL exposure.

Surface morphology

The *A. niger* spores existed in an average diameter of 3 µm. The surface morphology of *A. niger* spores in the untreated dehydrated onion shreds was smooth and spherical. The surface was distorted, showcasing a roughness upon PL exposure at 2.131 ± 0.5 J·cm^{-2} (Fig. 4a). The spore coat was also seen to be broken completely, causing cell death (Fig. 4b). On the other hand, the spore-coat was distorted by IRT, thus causing pits in the cell (Fig. 4c). Similar observations were observed by Oliveira et al. (2021) using mercury pressure lamps. The *B. cereus* spores were observed to be rods of an average length of 1 µm. On PLT at 2.131 ± 0.5 J·cm^{-2}, the spore-coat was seen to be damaged and a hollow cell was observed (Fig. 5a). Similar observation was seen in IRT samples (Fig. 5b). Cracks, pits, and completely damaged spore coat are a result of the thermal effects of the treatment. Apart from that, the photochemical effects of PLT damage the cell enzymes and protective proteins that build the spore-coat (Clair et al. 2020).

Colour profile

Change in colour parameters were estimated considering the overall colour change (ΔE^*), hue, chroma and browning index of dehydrated and PL or IR treated samples with the fresh onion shreds. Dried samples showed a ΔE^* of 6.16 ± 0.19, due to the increase in redness during dehydration (Fig. 6). Generation of furfural derivatives from non-enzymatic Maillard browning reaction during drying might lead to the sample's redness (Maftoonazad et al. 2020). A minimal change in ΔE^* (1.42 ± 0.0.08) was observed in PLT samples from dehydrated samples. On the other hand, IRT samples had a ΔE^* of 2.38 ± 0.02 with respect to the dehydrated samples. The larger ΔE^* in IRT samples was due to the shift in a value from 7.58 ± 0.36 to 3.12 ± 0.34. A lower a* value of the dehydrated onion shreds indicates shifting from red to green. The change in b^* value also contributes to ΔE^* of IRT samples as the value increased from 1.03 ± 0.06 to 7.31 ± 0.20, increasing the yellowness. Maftoonazad et al. (2020) dehydrated onion slices in hot-air and microwave hot-air dryers. They observed

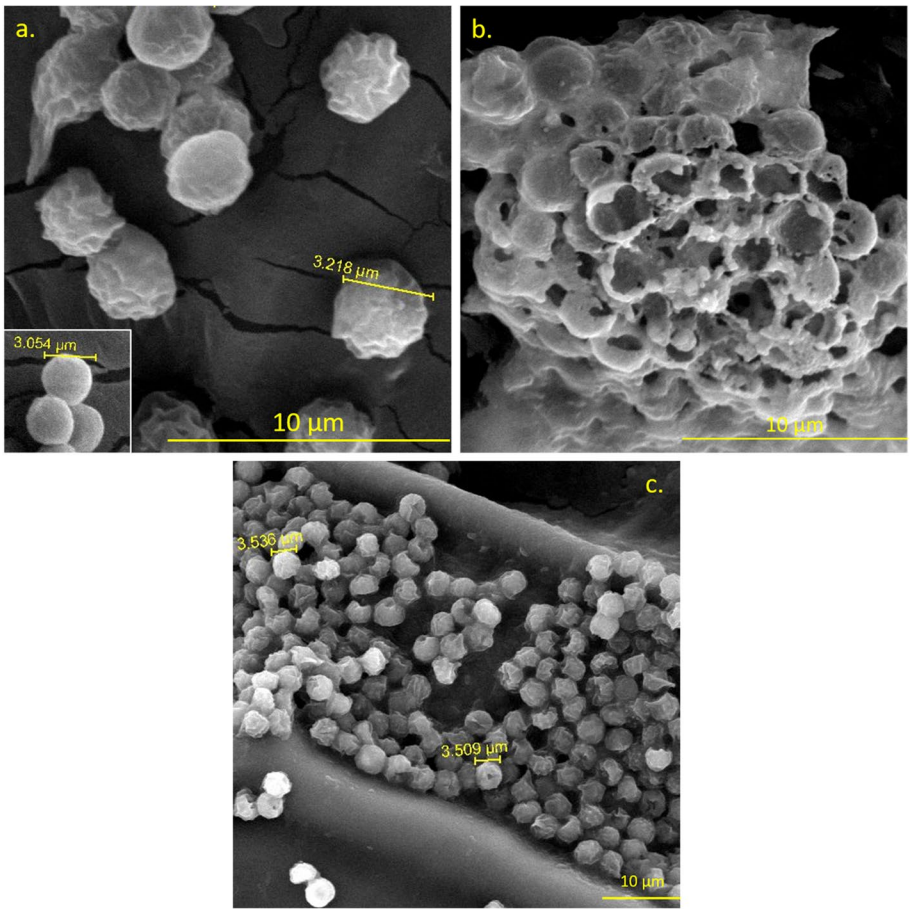


Fig. 4 Effect of pulsed light and infrared treatment on *A. niger* spores. **a**) and **b**) Spores affected by PLT. **c**) Spores affected by IRT. Inside image shows the spores in untreated samples

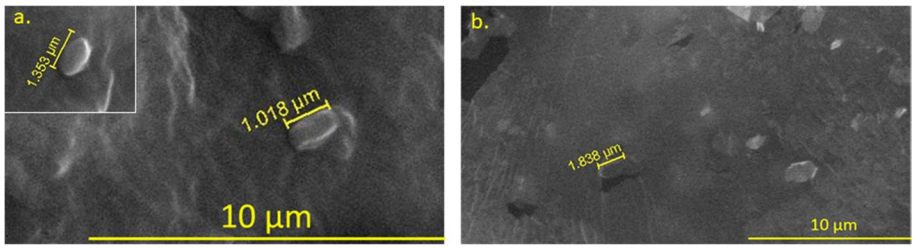


Fig. 5 Effect of PLT and IRT on *B. cereus* spores. **a**) Spores affected by PLT. **b**) Spores affected by IRT. Inside image shows the spores in untreated samples

an increase in redness on dehydration due to the furfural compounds generated from Maillard reaction on dehydration. Coskun et al. (2021) treated whole onions with Far-IR treatment at 80 °C for 120 s and did not find significant changes in the L^*, a^*, and b^* values of fresh and treated onions. This could be because whole onions with the peels were treated and no further processing was carried out. Green onions did not show immediate changes in colour on PL-surfactant treatment, but the b^* values decreased on storage showing reduction in yellowness (Xu et al. 2015).

The hue angle describes the amount of redness and yellowness. Only a slight increase of 0.9 in the hue angle of IRT samples was observed due to the reduction in redness and increase in the yellowness as compared to the dehydrated and PLT samples. The chroma values describe the colour saturation that increased over dehydration and were comparable in case of dehydrated

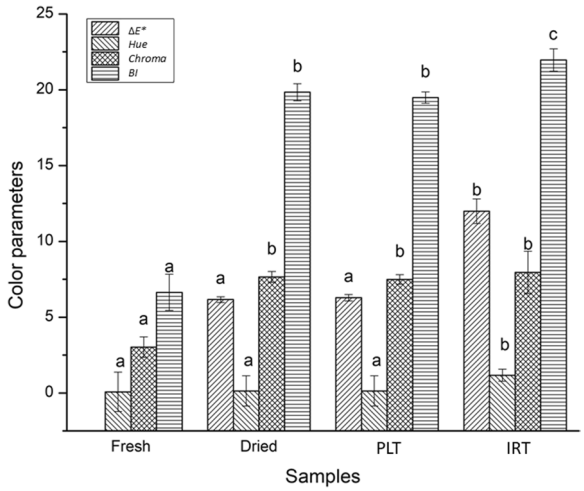


Fig. 6 Change in overall colour (*ΔE**), hue, chroma and browning index (BI) of dried, pulsed light treated, and infrared treated dehydrated onion shreds from fresh onion shreds

and treated samples. The browning index of dehydrated samples increased due to moisture loss, which further increased in case of IRT, but was nearly the same for PLT samples. The BI of dehydrated and PL treated samples was 19.84 ± 0.56 and 18.96 ± 0.05, respectively. While the BI of IRT sample was 16.81 ± 1.55. The BI index is majorly affected by redness and lightness as seen in Eq. 11. The redness of dehydrated and PLT samples ranged between 7.0 and 7.9, and that of IRT ranged between 2.8 and 3.6. Similarly, the lightness of dehydrated and PLT samples ranged between 30.8 and 32.2, and that of IR was 45.68. Hence the browning of IRT onion shreds was higher than dehydrated and PL treated onion shreds. Apart from onion, PL-plasma treatment on red pepper powder (Lee et al. 2020a, b) and red pepper flakes (Lee et al. 2020a, b) has proven to retain the colour and preserve the carotenoid content, the source of the colour.

Flavour analysis

Key flavour compounds responsible for the characteristic pungency in onions are thiosulphinate and pyruvic acid content (Mitra et al. 2015). The S-substituted L-cysteine sulphoxide derivative compounds react with alliinase enzymes to give unstable sulfenic acid compounds along with pyruvic acid and ammonia. Quantifying pyruvic acid directly estimates the flavour compounds and helps characterize the onion as mild/sweet and strong/pungent (Metrani et al. 2018). The sulphenic compounds further react to produce odour producing compounds, majorly in the form of thiosulfinic acids (Savitha et al. 2021a, b). Thus, quantifying pyruvic acid and thiosulphinate gives a judgment of the overall pungency of the onion.

The pyruvic acid concentration of fresh onion shreds was 78.99 mmol/g (db) (Table 4). Dehydration reduced the concentration to 11.89 mmol/g (db). After the PL exposure of 2.131 ± 0.5 J·cm^{-2}, the pyruvic acid decreased to 15.78 mmol/g, while in the case of IRT onion shreds, a decrease of 3.11 mmol/g from that of dehydrated onion shreds was noted. The decrease in pyruvic acid after treatment was mainly due to its degradation by PLT and IRT. Metrani et al. (2018) quantified the pyruvic concentration in red onion juice to be between 7.82 and 11.29 mmol/g. Pyruvic acid concentration in various varieties of onion powders ranged from 9–12 µmol/g, which decreased on dehydration at 70 °C to 4.9–6.4 µmol/g (Seifu et al. 2018). Such a loss could be due to degradation of alliinase on high temperatures (70 °C).

The thiosulphinate concentration in fresh onion shreds was 25.39 ± 0.03 µmol/g (db). On dehydration, it reduced to 8.19 ± 0.07 µmol/g (db). Degradation of alliinase at drying temperatures caused decrease in the flavour compounds. On PL treatment at 2.131 ± 0.5 J·cm^{-2}, an increase in thiosulphinate concentration from that of dehydrated onion shreds was observed. However, IRT led to degradation of bioactive compound and decreased the thiosulphinate concentration to 2.02 ± 0.03 µmol/g. Overall, PLT increased the thiosulphinate content by 12.82%, while it decreased the pyruvic acid content by 18.23% as compared to the dehydrated onions shreds. Mitra et al. (2015) vacuum dried onion slices and quantified the thiosulphinate concentration to be around 3–4 µmol/g. The effect of PLT on pyruvate or thiosulphinate content is not yet studied as per the authors' knowledge. PLT can excite

Table 4 Concentrations of bioactive compounds affected by dehydration, pulsed light and infrared treatment

Sample	Thiosulphinate (µmol·g^{-1})	Pyruvic acid (mmol·g^{-1})	Total phenolics (mg GAE·g^{-1})	Total flavonoids (mg QE·g^{-1})	Ascorbic acid (µg·g^{-1})
Fresh	25.39 ± 0.03^{b}	78.99 ± 0.16^{a}	0.106 ± 0.002^{a}	0.050 ± 0.001^{b}	108.97 ± 0.502^{a}
Dried	8.19 ± 0.07^{c}	19.33 ± 0.00^{c}	0.123 ± 0.000^{b}	0.278 ± 0.001^{c}	21.315 ± 0.73^{a}
PLT	9.24 ± 0.03^{d}	15.78 ± 0.16^{b}	0.268 ± 0.001^{d}	0.344 ± 0.000^{d}	20.946 ± 0.542^{a}
IRT	2.02 ± 0.03^{a}	16.22 ± 0.31^{b}	0.194 ± 0.000^{c}	0.019 ± 0.000^{a}	18.682 ± 1.09^{a}

The lower case letters tell about the significant difference along the rows

PLT Pulsed light treatment 2.131 ± 0.5 J·cm^{-2}, *IRT* Infrared treatment at 80 °C, 15 min

amino acids like tyrosine, tryptophan, methionine, and cysteine, which cause reduction of disulphide bonds and affect thiosulphinate concentration (Alhendi 2021).

Total phenolics and flavonoid content

The total phenolics and total flavonoid content of fresh, dehydrated and treated onion shreds are mentioned in Table 4. The total phenolics content of fresh onion shreds were 0.106 mg GAE/g (db), which increased slightly on dehydration to 0.123 mg GAE/g (db). Similar trend in total flavonoid content was observed. At dehydration temperatures, bioactive compounds come to the surface changing from their conjugate form, increasing the concentration. Additionally, the enzymes that degrade the bioactives remain inactive in dehydrated form, hence do not reduce the concentration of the phenolics. Enzymes functionality depends on the hydration level. The catalytic activity and interaction of enzyme with the substrate requires a certain threshold level of hydration, typically 0.2 g of water for 1 g of protein (Kurkal et al. 2005). Hence, there is an increase in total phenolics and flavonoid content concentration due to bioactives coming to the surface and preventing their breakdown due to inactive enzymes on dehydration (Salamatullah et al. 2020).

On the contrary, Bamba et al. (2020) reported the total phenolic content in onion powder dried in oven to be 9.46 mg QE/g (db). On PLT at 2.131 ± 0.5 J·cm^{-2}, 0.145 mg GAE/g (db) increase in total phenolics and 0.228 mg QE/g (db) of increase in total flavonoid content was observed. The increase in concentration total phenolics and total flavonoid might be due to the photochemical reactions occurring during PLT (Kwaw et al. 2018). Moreover, an increase in total phenolics after PLT was reported in the case of fruit beverages (Dhar & Chakraborty 2020). The mild stress applied by the PL induces release of phenolics by activating the biosynthetic pathway in the food sample (Denoya et al. 2020). On IRT, the total phenolic content increased slightly by 0.071 mg GAE/g (db), while the flavonoid content reduced by 0.259 mg QE/g (db). Overall, PLT improved the total phenolics and flavonoids concentration of the dehydrated onion shreds.

Ascorbic acid content

The ascorbic acid concentration of fresh onion shreds was 108.97 µg/g (db), which decreased on dehydration to 21.315 µg/g (Table 4). Kim and Min (2017) reported the ascorbic acid concentration of 1.3 mg/g in onion flakes dehydrated in vacuum dryer. Solar dehydration onion was reported to contain 0.58 mg/g of ascorbic acid, whose concentration increased from fresh red onion (Demissew et al. 2018). Microwave dried onions had a higher ascorbic acid content and oven dried onion had concentration same as the fresh onion. Onion powders of different varieties, sweet onions, and prepared by hot air drying had ascorbic acid concentration ranging from 0.0068 to 0.05 mg/g for sweet to pungent onion (Seifu et al. 2018).

On PLT, there was a slight decrease of 1.7% in the concentration of AA from dehydrated onion shreds. However, a decrease of 12.3% AA from the dehydrated sample was observed after IRT. Photothermal and photochemical effects of PLT caused degradation and oxidation, respectively, of the ascorbic acid, thus reducing the AA content in the PL treated onion shreds (Avalos-Llano et al. 2018). However, the heating effect of IR spectrum led to a higher loss in thermosensitive AA in onion shreds.

Quercetin content

Quercetin and its derivative are flavanols responsible for the yellow and brown colour in onions. It has medicinal properties and hence it becomes essential to understand the effects of processing on the quercetin content. It is an antifungal and an antioxidant. It is been proven to prevent lipid peroxidation in humans (Griffiths et al. 2002). The quercetin content in the dehydrated onion shred was 2.25 mg·g^{-1} (db). After PL treatment the quercetin content reduced to 1.37 mg·g^{-1} (db), showing a decrease of 39%. While, after IR treatment, the quercetin content reduced to 1.00 mg·g^{-1} (db), showing a decrease of 55%. The chromatograms showing the concentration of quercetin in dehydrated, PL treated, and IR treated onion shreds are shown in Fig. 7.

The quercetin content varies as per the onion variety. For instance, red onions with high pungency can contain about 33 mg·g^{-1} of quercetin (Albishi et al. 2013). Kwak et al. (2017) quantified the quercetin glycosides in red, yellow, and chartreuse (genetically modified) onion of Korea. Freeze dried red onions contained 32.21 mg·g^{-1} quercetin, followed by 43.85 mg·g^{-1} in yellow onion, and 127.92 mg·g^{-1} in chartreuse onion. In the current study, the onion shreds were dehydrated on SCD for 6–7 h under the sun, unlike the freeze-dried ones as used by Kwak et al. (2017). Hence, the quercetin content depleted during the dehydration process.

Effect of different lights on quercetin content in whole fresh onion, peeled onion and onion pulp was studied by Ko et al. (2015). Individual lights such as fluorescent, blue, red, and UV-A had a positive affect and increased the quercetin content by 50–70%. However, a cumulative effect of pulsed light (UV, visible, and near-IR) in this study may have caused depletion of flavonoids, and hence quercetin. Similarly, the thermal effect of infrared further depleted the quercetin content in the dehydrated onion shreds. A detailed study on all phenolics though LC–MS will be carried out in future separately.

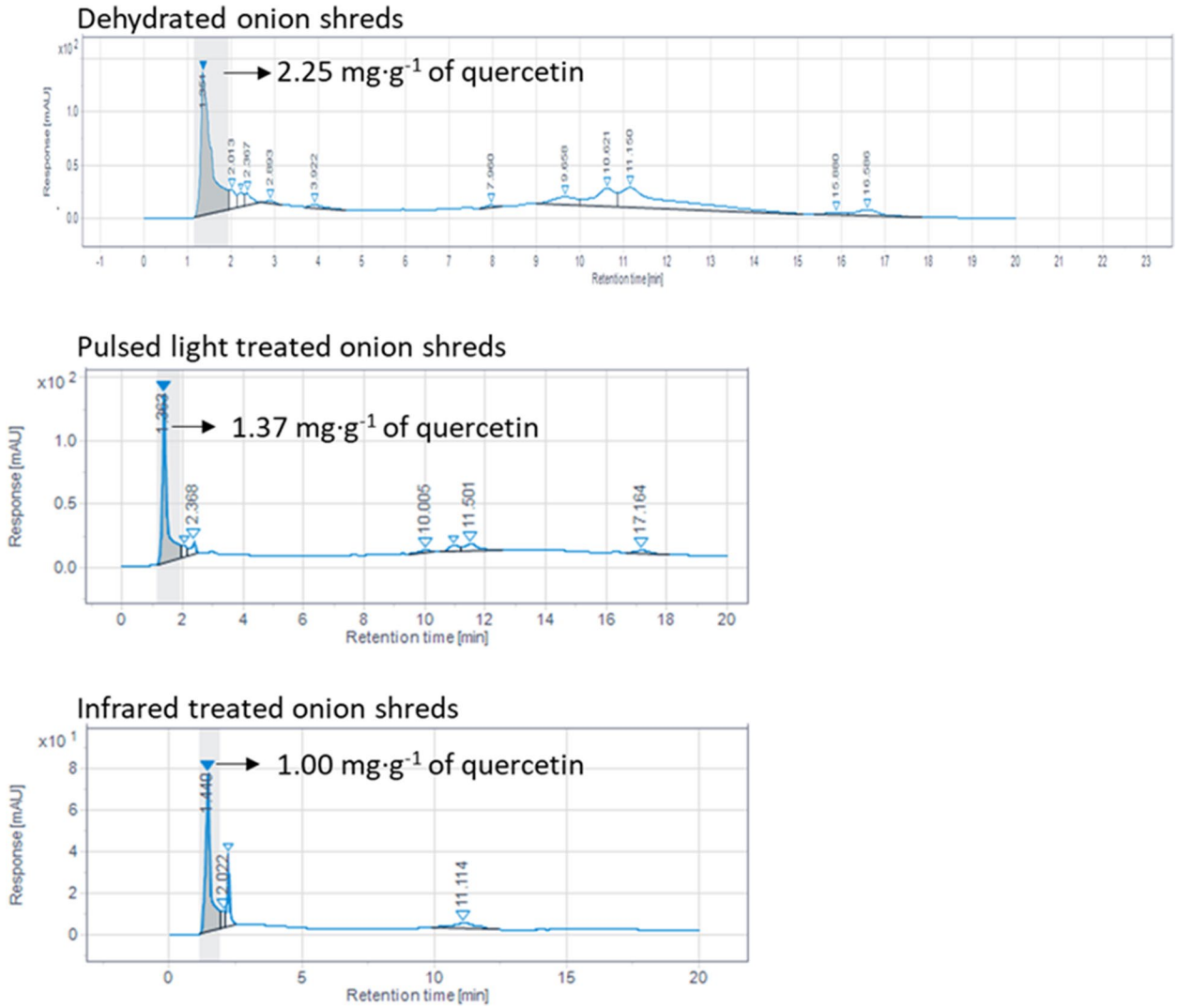


Fig. 7 Changes in quercetin content after dehydration and decontamination of onion shreds

Conclusion

The pulsed light (PL) treatment was more promising than infrared (IR) treatment when inactivation of *B. cereus* or *A. niger* spores in the onion shreds is the major concern. PLT improved the thiosulphinate content, total phenolics and flavonoid content, quercetin content in the shreds. Overall, compared to untreated dehydrated onion shreds, the colour of PL-treated onion shreds showed the least colour change and browning compared to the IR-treated samples. The pyruvic acid content was better retained in IR-treated onion shreds than PL-treated samples. As a future scope, the estimation of the shelf-life of the treated onion shreds is of great interest and is recommended. The outcome of this study is useful for the industry to select and set up the technology and corresponding intensity required to produce decontaminated dehydrated onion shreds while satisfying the regulatory standards.

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Authors' contributions
Srinivasan Savitha conceptualized the project, executed the research and data analysis, and wrote the manuscript. Snehasis Chakraborty supervised and also conceptualized the project. B. N. Thorat provided the resources.

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Availability of data and materials
All data generated and analyzed during the current study are included in this published article.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
There is no conflict of interest among the authors.

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