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REVIEW ARTICLE OPEN ACCESS

Comprehensive Study of Light-Emitting Diodes (LEDs) and Ultraviolet-LED Lights Application in Food Quality and Safety

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Abstract

Light-Emitting Diodes (LEDs) and Ultraviolet Light-Emitting Diodes (UV LEDs) consist in a semiconductor of light, that are emerging in the market, due to their singular characteristics, as being a solid-state cold source of light, which has potential application in food preservation. For this reason, this study lens to provide a review of the effects of LED and UV LED application in fresh fruits and vegetables, under refrigeration storage. Analyzing the LED role, in extending the shelf-life of postharvest food, these present the capability of improving the quality physicochemical and microbiological of fruits and vegetables, such as: color (chlorophyll), weight loss, total phenolic and flavonoid content, phenylalanine ammonia-lyase activity and total soluble solids. In addition, it's able to stop chemical reactions and increasing the activity of fruits and vegetable defenses. UV LED light, on the other hand, operates in an effective and straightway in the inactivation the food pathogens, such as *Escherichia coli, pseudomonas fluorescens* and *Salmonella spp*, for example. Therefore, UV LED light can be applied to delay the senescence of foods, however, the wavelength must match the target organism, depending on the food.

Keywords: LED, UV LED, Food preservation, Food safety, Refrigeration, Food storage

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INTRODUCTION

Food waste is one of the great concerns to sustainability, mainly due to higher losses in food production (circa of 1/3 is lost every year), which provides around of 1.3 billion tons of food lost in a year[1]. One of the main reasons for food waste, is the damage caused during the food production, transportation and the short shelf-life of fruits and vegetables. Furthermore, their inaccurate expiry date and high rate of discard, due to quality aspects, contribute to a high volume of waste. Moreover, it represents not only an economic loss for the producers but also the consumers, meaning an inefficient use of the soil sources[2].

The main concern, in the matter of food industry, is the balance between the reduction of food waste without compromising food safety[3], combining strategies to decontaminate fruits and vegetables, keeping safe for consumption[9]. This is an emerging concern in the world scenario, which involves food degradation in physical, chemical, and biological parameters[4-7]. For this reason, new techniques and technologies have been studied and developed to increase food shelf-life and safety. Light-Emitting Diodes (LED) and UV LED lights are technologies that possess special features that provide benefits for fresh fruits and vegetables. Aiming the importance of new technologies and their active role in food, in order to preserve quality and safety, LED lights associated with refrigeration systems, a well-known approach for food preservation[8], can improve food shelf-life.

LED and UV lights can maintain postharvest quality and improve the photochemical and nutrient components[9]. Also, LED lights are semiconductors that, when an electric current pass through their system, can emit visible light[10], without providing heat liberation. Those features qualify the LED lights to be used in the refrigeration systems because it does not provide heat exchanges between the lamps and the ambient.
LED lights can present several colors, in different wavelengths, with range from 400 to 760 nm, sub-divides on blue (450 – 500 nm), green (590 – 610 nm), orange (590 – 610 nm), red (610 - 760 nm), violet (400 - 450 nm) and yellow (570 – 590 nm)[61]. Each wavelength causes different effects on fruits and vegetables, such as maintain the physicochemical properties (vitamin C, chlorophyll stimulation, color, weight loss reduction, water activity and pH). UV lights, on the other hand, are responsible for the surface microbial counts reduction, by avoiding yeast, mold and bacteria proliferation[26], responsible for accelerate food decay.

Therefore, LED lights has the capacity of efficiently attend the food industry, according to their specifications and needs, being an increasingly inexpensive approach for food safety and preservation[11]. This review study highlights the effects of LED and UV lights in fruits and vegetables postharvest preservation. The main characteristics of LED and UV lights, and its mechanisms of action in food, to extend shelf-life and enhance properties, are presented. The industrial application of LED in food preservation are also presented.

Principles of led mechanism in food

The LED system works by the principle of passing an electrical current through the device in one direction and blocking the current flow that comes from the opposite, being capable of emitting light with narrow emission wavelength bandwidths, high photoelectric efficiency and photon flux or irradiance[9]. In addition, the LED has non-breakable glass envelopes, low heat irradiation, higher efficacy, and can be used in postharvest preservation[11].

Among the LED lights advantages, are the capability to control the spectral output, light intensity and the possibility to select several wavelengths that match the absorbance of plant photoreceptors[62] (Fig. 1), which can be used to improve the physicochemical and microbiological components and consequently the shelf-life and the food quality during postharvest stage.

Visible LED

LED is a semiconductor that can produce light by using a safer approach because is a cold lightning and does not have glass envelopes or mercury in their composition[12]. In addition, is environmentally friendly and energetically efficient[13], one of the characteristics of the LED is that it can provide different colors, depending on their composition. Red, green, yellow and orange lights are made of indium, gallium, aluminum and phosphide, while blue lights of gallium, nitride and silicon carbide[9].

LED lights are a solid-state lighting that provides a non-conventional source. Due to the capability of monitor their spectral and temporal properties, color and wavelength, which possess several applications, as well as automobiles, communication, agriculture, medicine and food preservation[14].

The cost benefit of LED light has become very attractive in the food industry due to its price and efficiency[9]. Moreover, the directed light provided by LED, allows the use of LED at its highest lighting efficiency, with a large amount of light and color emitted, yet still presenting energy savings[15]. Each one of the LEDs several colors is used in the food industry for cultivation and postharvest preservation. Analyzing this last factor, LED can provide an increase in the physicochemical properties and bacterial inactivation, responsible for food degradation, therefore extending the shelf-life of fresh foods.

Blue light (emission spectrum: 455-465 nm) may be responsible for regulating the biomass production, leaf expansion and stomatal opening of plants[16], also being able to protect the food against harmful pathogens, such as *Salmonella spp.* on fresh-cut pineapple slices[17], for example. Also, vegetables such as cabbage, when exposed to blue LED present higher levels of vitamin C, total polyphenolic contents[18] and chlorophyll content[19].

Red LEDs act in the wavelength of 660 nm, which is similar to the absorption of plants. Therefore, is responsible for assisting the photosynthetic apparatus of fresh food[16], increasing de plant growth, besides, this light color can increase the phenolic compound in vegetables, such as broccoli, for example[20]. On the other hand, the green light has a positive effect on the chlorophyll content[18], mainly present in green vegetables, such as lettuce and cabbage, for example.

UV LED

UV LEDs are a light source based on the conversion of electricity to photons[21]. Those photons are absorbed by the food genetic material and form dimers, inhibiting the transcription and replication of the cell[22]. This light can possess wavelengths of 100 – 400 nm and is typically made of aluminum nitride (AlN) or aluminum gallium nitride (AlGaN)[23], the wavelengths are divided into UV A, UV B and UV C light.

UV LEDs have been receiving attention in the last decade, those can be used instead of conventional low-pressure mercury lamps[21], and also due to their many advantages compared with the traditional UV lamps[24]. Besides been a green source of light, UV LEDs are also compact, have a fast start-up and less energy consumption, are a cold source of light and possess a long lifetime of 100,000 hours and 75% wall-plug efficiency, due to new improvements in this technology[25].

Therefore, UV LEDs may be applied in the food industry[26], mainly due to their potential of inactivating pathogens, on the surface food, without producing undesirable by-products[24], which can be an effective mechanism for food safety, preserving the food in postharvest stages[9].

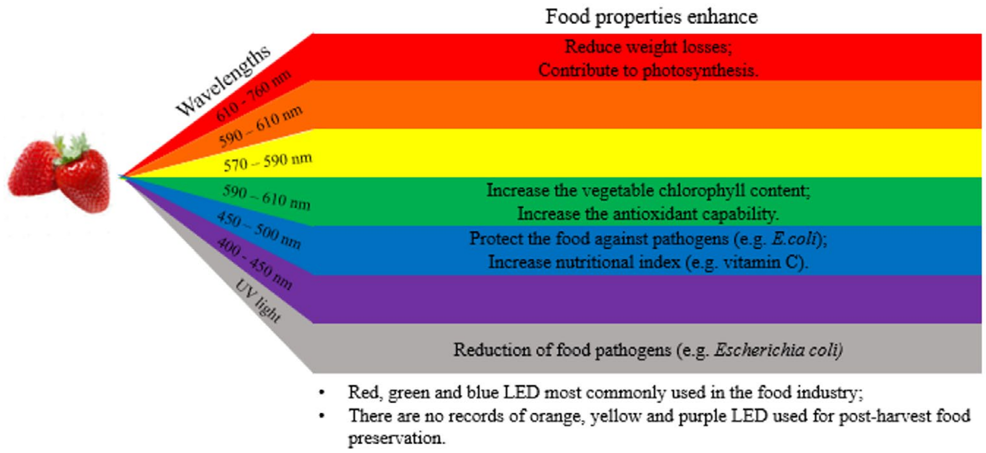

Fig 1. LED and UV-LED wavelengths and applications over food properties.

Table 1. Effects of UV LED over postharvest food properties.

UV LED treatment	Food	Findings	Ref.
UVA-LED, wavelength 365 nm, output 12.5 x 10^2 W m^{-2}	Cabbage	Log survival ratio of *E. Coli* was reduced of - 0.41, -1.87 and -3.23 log CFU g^{-1} after 30, 60, and 90 minutes, respectively.	30
Near ultraviolet /visible (NUV – vis) light, with a centre wavelength of 395 ± 5 nm, a bandwidth of 12 nm full-width at half maximum and a half intensity beam angle of 30°.	Chicken	Exposure of skinless chicken fillet for 1 or 5 min at 3 cm distance reduced C. jejuni by 2.21 and 2.62 log_{10} CFU g^{-1}, respectively. A maximum reduction of 0.95 log_{10} CFU g^{-1} was achieved for *C. jejuni* following 10 min exposure at 12 cm.	31
UV-C (254 nm) and NUV–VIS with a centre wavelength of 395 ± 5 nm, a bandwidth of 12 nm full-width at half maximum and a half intensity beam angle of 30°.	Ricotta Cheese	Over the shelf life, these values remained between 1 and 3 log below the control, and after 5 days the levels were 5.24 ± 0.14 and 4.40 ± 0.70 log_{10} CFU g^{-1} for UV-C and NUV–vis, respectively, while for the control, they were 7.55 ± 0.10 log_{10} CFU g^{-1}.	32
Pulsed and continuous UVC-LED irradiation were determined by inactivation mechanism analyses. Thecombination of 20-Hz frequency and 50% duty ratio.	White mushrooms	At the highest UVC-LED dosages, 2 mJ/cm^2 for *E. coli* O157:H7 and 5 mJ/cm^2 for *S. Typhimurium* and *L. monocytogenes*, 3- to 5-log-unit reductions were achieved with continuous and pulsed UVC-LED treatments.	33
UV-C and UV-A (280/365 nm)	Apple Juice	For clear apple juice the highest inactivation 4.4 log_{10} CFU mL^{-1} obtained for *E. coli* K12 was achieved using the wavelength of 280 nm for 40 min exposure time. And using a combination of lamps emitting light at 280 and 365 nm (2 lamp/2lamp) were resulted in 3.9 ± 0.2 log_{10} CFU mL^{-1} reductions.	22
Continuous UV-C LED light at an emission peak of 265 nm for 1 min (20.4 mJ cm^{-2}) and 3 min (61.2 mJ cm^{-2}).	Chicken	After irradiation with UV-C LED light for 1 min, a mean reduction in *C. jejuni* of log 2.0 ± 0.5 CFU mL^{-1} was observed, while after irradiation for 3 min the reduction was log 3.1 ± 1.0 CFUmL^{-1}. The mean reduction in Enterobacteriaceae was log 1.5 ± 0.3 CFU mL^{-1} after 1 min of irradiation and log 1.8 ± 0.8 CFU mL^{-1} after 3 min.	64
UV-C, with intensity of light ranged from 200 to 280 nm, with a peak at 254 nm	Seafoods	In the early stage of UV-C irradiation (0–60 s), little microorganism inactivation was observed, whereas about 4-log reduction of *L. monocytogenes* was achieved with 1000 s of UV-C treatment.	65

Therefore, it can provide better quality and shelf-life of fresh food, without compromising product safety[27].

On the other hand, UV-C is capable of inducing the formation of DNA photoproducts, such as cyclobutane pyrimidine dimers (CPDs) and pyrimidine 6-4 pyrimidone (6-4PP), capable of inhibiting transcription and replication[63], as well as DNA and RNA polymerases. The inhibition of both replication and gene expression, can cause cell death[23]. In addition, UV is ultimately limited by the shading of microbes in protective sites leading to tailing in inactivation curves[66].

In the matter of food preservation, the electromagnetic spectrum possesses several radiation forms, each one has different penetration power, frequency and wavelength, and, for the food industry, the most interesting and passive applications are gamma and ultraviolet radiation[28]. Over the last decade, UV radiation has been used both for water disinfection and microbial decontamination of surfaces for fresh food preservation[29].

The consumer demand for fresh minimal processing food is growing[28]. For this reason, UV LED shows efficiency on slowing the senescence of fresh food and delaying the nutritional loss[22]. Therefore, to ensure the UV LEDs efficiency against food pathogens, the wavelengths should match the target organisms[26], this way, it presents effective results (Table 1).

The principle of the UV LED mechanism to bacterial inactivation works directly on the bacteria DNA, the UV-C light, which provides the wavelength 100 to 280 nm, is considered to have the highest efficiency, due to the bacteria DNA absorbance of 260 nm[34]. The microorganism is hit by the UV light, changing the DNA, and stopping the reproduction, which leads to the bacteria death[35], as presented in Fig. 2. Similar to UV-C, the UV-B spectrum has the ability to partially inactivate bacteria by damaging DNA as well as other cellular structures[23].

In addition, LED UV-A is capable of causing damage to cell structures by forming reactive oxygen species (ROS), causing oxidative damage to lipids, proteins, and DNA[23] (Fig. 2). However, the UV-A gamma is hardly absorbed by native DNA, not inducing severe damage by dimer formation, and can still produce photoproducts or modified DNA by indirect photosensitization reactions[63]. As UV LEDs can possess wavelengths of 250 nm to 365 nm, allows selecting the most effective wavelength to the specific target[36], wavelengths lower than 250 nm have poor penetration power.

LED in food preservation

Over the last years, LED lights have been studied for food preservation, due to their positive effects over the physicochemical and microbiological aspects of food in the postharvest stage, such as the reduction of weight loss and

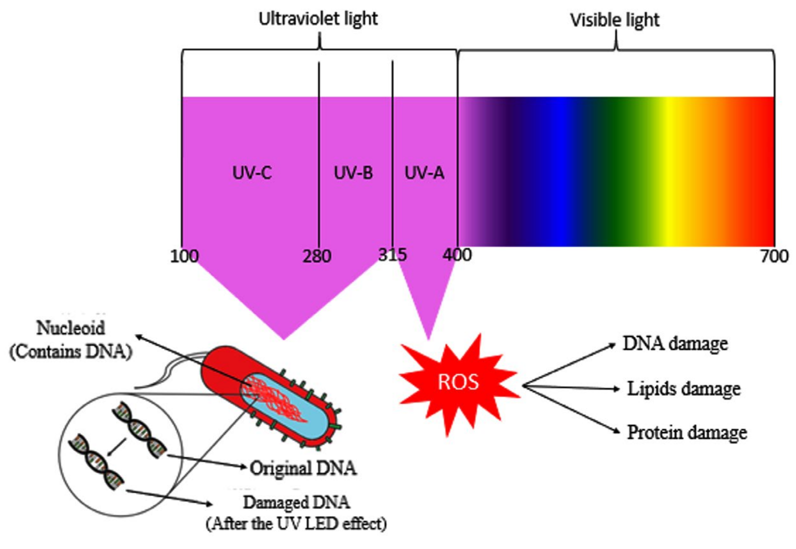

Fig. 2. Illustration of UV LED mechanism to bacterial inactivation.

Table 2. Effects of LED lights in food during postharvest preservation.

LED treatment	Exposure Technique	Food application	Findings	Ref.
Red light	Continuous light irradiation with intensity of 0, 10, 35 and 70 µM m-2 s-1 for 0, 4, 8 and 24 h per day.	Pak choi (*Brassica rapa ssp. Chinensis*)	Leaves irradiated with red light of intensity of 35 µM m^{-2} s^{-1} retained about 85% and 75% chlorophyll on the third and fifth day. All treatments showed significant effects at 8 and 24h of exposure. After the third day the red light of intensity 70 µM m^{-2} s^{-1} inhibited vitamin C depletion the most.	25
Red light	Continuous light irradiation with wavelength of 630 nm for 21 days.	Lettuce	Weight loss (WL) of lettuce were reduced by red LED lightings (5.32%) treatment during storage since the WL was 6.44% in the control group.	40
Red light	Lighting modules of 625 nm, 6,0 W/m, 80 lm/m, 14 lm/W and with photosynthetic photon flux (PPF) level at the top of the broccoli surface of 66 mol m^{-2} s^{-1}.	Brocolli (*Brassica oleracea L. var. italica*)	Red light increased the phenolic content up to 2.5 times after five days of storage. After 15 days the red LED induced phenol accumulation, representing 3.04 g kg-1 of gallic acid equivalents.	41
Red light	Continuous light irradiation with intensity of 50 µmol m^{-2} s^{-1} for 5 days.	Brocolli (*Brassica oleracea L. var. italica*)	The treatment reduced the yellowing after 2 days of storage, approximately 5%, and reduced the chlorophyll degradation, showing a difference of approximately 0.2 mg.g^{-1} more chlorophyll than the control. Also the wight loss was lower in the red LED treatment (~0.025%) compared to the control (~0.03%).	42
Blue light (470 nm)	Continuously irradiated blue light at 465 nm to 478 nm.	Sweet cherries (*Prunus avium L.*)	Treatment with the blue light resulted in the highest total color difference (ΔE), 9.11. The highest increase of phenylalanine ammonia lyase (PAL) was seen for the blue light treatment (almost 5- fold).	43
White and blue LED light	Continuous illumination with white and blue LED of low intensity (20 mmol m2 s1)	Broccoli (*Brassica oleracea L. var. italica*)	The treated samples maintained the highest levels of chlorophyll towards the end of storage, with values 38% and 53% higher than controls in the experiments at 5 °C and at 22 °Crespectively ($p < 0.05$).	44
Blue light	Continuous blue LED light with irradiation dose of 48 W m−2 for 30 days	Habanero pepper (*Capsicum chinense*)	All habanero pepper showed a significant increase ($p < 0.05$) in total flavonoids and phenolic compounds. compared to untreated habanero pepper.	45
Blue light	Continuous blue light treatment at 40 mol m^{-2} s^{-1} for 15 days	Peaches	Blue treatment could maintain a higher level of total soluble solids (TSS) content (~13% at the end of storage) and induce the decrease in total titratable acid (TA) content (~0,8% at the end of storage). Also, a higher level of a* and b* color parameter values was observed at the end of storage.	46
Green light	Lighting modules of 522 nm, 4,1 W/m, 120 lm/m, 29 lm/W and with photosynthetic photon flux (PPF) level at the top of the broccoli surface of 24 mol m-2 s -1.	Brocolli (*Brassica oleracea L. var. italica*)	Green LED (GL) induced an increase in the protein content at 15 days (~8 g kg-1). And a significant chlorophyll accumulation at 10, 15 and 20 days were induced by the exposure to the GL.	41

Table 2. Cont...

LED treatment	Exposure Technique	Food application	Findings	Ref.
Green light	Continuous light irradiation with wavelength of 516 nm for 21 days.	Lettuce	Total soluble solids content of leaf lettuce was measured as 2.30% immediately after harvest and it increased to 3.40% in the samples stored in green LED light.	40
Green light (520 nm)	Continues light-emitting diode (LED) green light at wavelengths of 520 nm (light intensity about 12–13 µmol s-1 m-2).	Broccoli florets	The content of chlorophyll was 59.1% higher in green light treatment than those in control broccoli florets on the 2nd day.	47
Green light	Continuous green (wavelength range $520 < \lambda < 550$ nm) LED lights.	Blueberry (*Vaccinium corymbosum L.*)	Blueberry fruit powder fermented with *B. amyloliquefaciens* or *L. brevis* under green LED light (4.76 ± 0.8 and 4.79 ± 0.8. GAE g^{-1} dw) showed the maximum phenolic content after 72 h.	48

water activity, maintenance of the vitamin C index, color, chlorophyll and pH, as well as inactivation of bacteria responsible for food degradation. Also, for being economical and energetically efficient, which contribute to reduce the fresh food senescence, prolonging food shelf-life[37].

Enhance in food properties

The possibility to select several wavelengths is an advantage to the antibacterial effect[10] and to improve properties, such as vitamin C, total phenolics, color, chlorophyll content, weight losses, total titratable acid and total soluble solids content. Table 2 present some successful applications of LED lights in food preservation. The LED highlight comes from the food waste concern on the postharvest stages, and the LED light application can supply these losses, due to their capability of improving the food shelf-life[38].

Food safety

The concept of food safety has increased due to the importance of microorganism control in food[28]. New policies and regulations, related to food safety, are been constantly developed and updated[49]. In the matter of food industries, the use of LED lights became an attractive source to ensure and keep the safety of food during the cultivation and storage stages[38].

Therefore, the development in food safety is related to environmental protection[50], noticing that the food market needs to ensure the food safety and quality, those may be available from traditional and nontraditional technologies, including the nonthermal lights (LEDs)[28].

UV LED lights, in this scenario, might have an important role in food safety, due to their antimicrobial power to treat food during the storage stage, acting on the food surface and in the air, inhibiting the bacteria and pathogens, the next step for the food industry[23]. For this reason, LEDs and UV LEDs have an industrial and commercial potential if applied in the refrigerator, because of their positive effect over postharvest food[38].

Industrial applications

Since the first household refrigerator development, innovations in food preservation assisted by cold storage became more frequent and necessary. Analyzing the LED light role in the food preservation under refrigeration, domestic refrigerators with LED technology have already been developed and are available in the market.

The LED light "Vitamin Power" technology applied in refrigerators uses green, blue and white LED lights to simulate sunlight and potentialize food vitamins in a process similar to photosynthesis[52]. Vitamin Power works with the principle of pulsed LED lights, attached on the bottom shelves of the refrigerator, the fruits and vegetables, located under the light, have their properties, such as vitamin C and D enhance. Also, with the "Antibacteria Technology" this refrigerator provides an antipathogenic effect. The technology operates with a blue LED light inside the refrigerator to avoid/reduce microorganism proliferation, capable of eliminating 99,99% of bacteria[53], conserving the food for a longer storage time.

The "Smart Side by Side" refrigerator has an air purification based on the Higiene Fresh+ technology, using air purified (odorless and bacteria reduction) by carbon filter and UV LED photocatalyst, with an automatic fan. The Higiene Fresh+ technology is capable of eliminating 99.99% of bacteria, and maintain 88% of fruits and 95% of vegetables moister, keeping the food, inside the refrigerator drawer, fresh for a longer period[54]. Carbon filter has a well-known catalytic property and can be applied to remove gas molecules produced during the food deterioration process[55]. UV light in the bactericidal range (200 to 280 nm) effectively inactivates bacterial microorganisms in the air, as well as in water and surfaces (as food surfaces)[56].

The Nasa-Inspired Air Purification System is an air purification system, based on UV-C light with TiO_2, to reduce bacteria and ethylene gas from the air, maintaining the food freshness. Some studies have shown that TiO_2 nanoparticles have antimicrobial properties[57-59], which is improved in UV light presence[55]. Also, ethylene scavenger activity was already verified in TiO2[60].

CONCLUSIONS

The promising LED and UV LED technologies have several characteristics, capable to enhance the food properties and keep fruits and vegetables fresh for a longer period. Due to the lack of mercury in their composition, LED light became an emerging technic in the matter of food preservation, in an account of being a cold source of light, this device could be attached inside refrigerators as a mechanism for extending food shelf-life and preventing the food waste. The effectiveness of LED light over the physicochemical and microbiological content of food depends on the right combination of color, wavelength and type of food, studies proved that the use of LED lights and UV LED lights can enhance the food properties and inactivates food pathogens. Those factors classify the LED light technology as an efficient method to extend the shelf-life of fresh food, which is already being applied in the refrigerator industry and available in the market.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHORS' CONTRIBUTION

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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DATA AVAILABILITY

All datasets generated or analyzed during this study are included in the manuscript

ETHICS STATEMENT

Not applicable.

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