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Effect of plasma-activated water on dough rheology and bread quality characteristics of sunn pest (*Eurygaster integriceps*)-damaged wheat flour

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ABSTRACT

The effects of plasma-activated water (PAW) on the rheological and bread quality characteristics of sunn pest (*Eurygaster integriceps*) damaged wheat flour (SDWF) were investigated in this study. PAW was produced by subjecting water to argon gas for 0, 30, 60, 120, and 180 s (PAW-0, PAW-30, PAW-60, PAW-120, PAW-180). Plasma treatment significantly increased pH, oxidation reduction potential, hydrogen peroxide, nitrite, nitrate, and alkalinity, particularly at PAW-120 and PAW-180. SDWF had significantly higher SMS/Kieffer dough and gluten extensibility values than PAW-0, correlated with plasma application time. SMS/Chen-Hoseney dough stickiness increased at PAW-30 and PAW-60 and decreased at PAW-180. PAW led to a reduction in wet and dry gluten and water-binding capacity but remarkably increased the gluten index. The protein, total phenolics, loaf volume, crust and crumb L* and b* showed an increase, while the moisture, water activity, and antioxidant activity of SDWF-breads (SDWB) demonstrated a decrease with the usage of PAW. The hardness and adhesiveness of the SDWB decreased significantly at PAW-180. The SEM images of SDWB revealed the most compelling result in PAW-180, where starch particles were uniformly distributed, suggesting a well-developed gluten network. Fourier Transform Infrared Spectroscopy (FTIR) results indicated that PAW was most effective at PAW-180. Consequently, we propose that a 180-s application of argon plasma to water may enhance the rheological properties of SDWF, thus improving processing efficiency and the quality of SDWB.

1. Introduction

Sunn pest (*Eurygaster integriceps*) is an agricultural pest that significantly affects the yield and quality of wheat and other crops in various regions, mainly in Central and Western Asia, Eastern Europe, and North Africa. This pest seriously reduces wheat production by damaging terminal buds and spikes, resulting in yield loss and consequently causing both quantitative and qualitative damage to wheat grains. Nymphs and adults extract sap from leaves, stems, and, crucially, developing grains, which diminishes grain weight and results in shrivelled or vacant seeds, causing in lower yields and compromised technological quality. Wheat that is infested may be deemed unsuitable for milling or may be rejected (Noori and Shahrokhi, 2012; Davari and Parker, 2018). The sunn pest introduces protease enzymes into the wheat grain, which degrade gluten components, alters the rheological properties of the dough (Grădinaru et al., 2017) and makes it challenging to produce high-quality bread. Consequently, the pest incurs substantial economic losses in wheat production and necessitates alterations in bread-making methods. So far, research has looked into many ways to make bread and dough better in SDWF. These include biological, chemical, and post-harvest treatments, utilising oxidising or reducing agents, enzymes, and hydrocolloids to boost the gluten's strength and improve the rheology of SDWF (Dizlek and Gül, 2007; Dizlek and Özer, 2016; Dizlek and Özer, 2023).

Thermal methods are effective technologies for inactivating proteolytic enzymes; however, they can adversely affect the viscoelastic properties of gluten. Consequently, there is a growing focus on research aimed at developing non-thermal technologies that enhance safety and cost-effectiveness by eliminating the need for chemical additives in food products. In this regard, cold plasma technology represents a promising advancement that has the potential to accomplish consumer expectations. A recent study conducted by Ulutürk and Gül (2025) indicates that cold plasma treatment has the potential to enhance the quality of wheat flour affected by sunn pest damage.

Bread is a fundamental food that is appreciated globally, with its history and variety representing many cultural traditions. Bread consumption greatly varies by nations, Gül and Gül (2011) determined the

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consumption of bread as 78 g per person per day, and Gül et al. (2017) calculated 188.79 g per day in Isparta (Turkey) province. Water constitutes about 40 % of the bread dough and plays a crucial role in the dough development process during bread making. Water quality significantly affects the hydration, elasticity, dough formation, and fermentation processes, which ultimately impacts the quality of the finished bread. On the other hand, the use of PAW as an innovative approach to bread making offers many important benefits by improving both the quality and safety of the final product. PAW contains many reactive components with low pH, high conductivity and redox potential (Shi et al., 2022). The electrical discharge in the gas phase interacts more with water. Direct contact of the gas with water leads to the emergence of reactive species of different types and concentrations. With the formation of PAW, reactive oxygen and nitrogen species such as nitrates, nitrites, hydrogen peroxide, hydroxyl radicals are released regardless of the system (Zhang et al., 2016).

The use of PAW in breadmaking enhances consumer attributes such as flavour, texture, and appearance, thereby increasing the bread's attractiveness. It also improves resistance to microbiological spoilage, inhibits mould growth, and extends shelf life; consequently, it minimises losses and waste in the bread supply chain, particularly when used with wheat flour with inferior baking qualities (Pivovarov and Mykolenko, 2021). Furthermore, it prolongs freshness by up to two days, reduces grain soaking time by 30 %, increases crumb hydrophilic properties by 17–60 %, and ensures safety by meeting heavy metal and mycotoxin content requirements (Pivovarov et al., 2018). It reduces the presence of mesophilic-aerobic and facultative-anaerobic microorganisms, as well as mould fungi, which are responsible for spoilage during storage.

Although there are a limited number of studies on the effects of PAW on wheat flour, dough, and bread, to the best of our knowledge, there is no study about the effects of PAW on dough and bread quality of SDWF. This study aimed to investigate the effects of PAW on the rheological properties of dough made from SDWF and on various physical, chemical, textural, FTIR, total phenolics, antioxidant activity and SEM properties of breads produced from this dough. By performing a series of these experiments, we aimed to provide valuable information on the role of PAW in improving dough rheology and bread quality of SDFW.

2. Materials and methods

2.1. Material

Sunn pest-damaged wheat (Bayraktar variety) was procured from Hediye Flour Factory in Isparta, Turkey. The tempering and milling of this wheat were conducted as outlined in our previous research (Ulutürk and Gül, 2025), and the physicochemical characteristics (such as sedimentation, delayed sedimentation, etc.) and rheological properties of this flour are also discussed in that study. Protein content (9.96 %) of SDWF were determined by using a Dumatherm Nitrogen-Protein analyser (Gerhardt Analytical Systems, Germany). Its farinograph characteristics, namely water absorption (54.8 %), dough development time (2 min), dough stability (3.4 min), and degree of softening (83 BU) were measured by following AACC Method 54.21.01 (AACC, 2010). Salt and baker's yeast (commercial yeast obtained by purification of "*Saccharomyces cerevisiae*" culture and having at least 70 % dry matter) with properties in accordance with the Turkish Food Codex were purchased from local markets. All other chemicals and solvents utilised in the experiments were of analytical grade purity.

2.2. Activation of water with plasma

Argon gas of 99 % purity and 7 kV discharge power with a frequency of 50 kHz was used in the activation of water by plasma. Argon plasma was generated using 2 mm diameter glass tubes. To enhance the surface area for plasma aapplication, 20 mL of the tap water sample was placed in a 100 mL wide-mouthed beaker, and plasma was administered by adjusting the application distance to 1 cm. The water samples were treated with argon plasma for durations of 30, 60, 120, and 180 s, referred to as PAW- 30, PAW-60, PAW-120, and PAW-180, respectively at a flow rate of 5 L/min (Fig. 1). Water sample without any plasma treatment was taken as control and refererred to as PAW-0. PAW-treated water was transferred into pre-sterilised test tubes with lids, which were subsequently employed immediately for analysis or for the preparation of dough/bread.

2.3. Bread production

AACC Method 10–10.03 (AACC, 2010) was used in bread production with some modifications. SDWF, 1.5 % salt, 3 % yeast, and water, determined by Brabender farinograph (Brabender, Duisburg, Germany) was used for dough making. Dough was kneaded in a spiral mixer (Günsa, İzmir, Turkey). They were left to proof fermentation at 65–70 % humidity and 25 ± 1 °C for 30 min. Then dough was divided into 10 equal parts, shaped, placed in the baking mould and left to fermentation (90 min). Baking were applied in a stone-based, electric, convectional oven (Enkomak, Antalya) at 260 °C for 15 min.

2.4. PAW analysis

Multiparameter (Adwa AD14 pH/ORP meter, Romania) was used to measure pH and the oxidation reduction potential (ORP), Perx® (ColorKim, İstanbul Türkiye) H_2O_2 test strips was employed to assess the H_2O_2 contents. Nitrite, and nitrate and alkalite were measured by using Aquax® total water hardness test kit (ColorKim, İstanbul, Türkiye).

2.5. SMS/Kieffer dough and gluten extensibility test

The maximum force (Rmax), extensibility (Ext) and area under the curve (A; Rmax/Ext) of the sunn pest damaged wheat flour dough (SDWD) were measured using SMS/Kieffer dough and gluten extensibility rig (Kieffer et al., 1998) and on a texture analyser (TA.XT Plus, Stable Micro Systems Ltd., Godalming, Surrey, UK) with a 5-kg load cell, pre-test speed 2.0 mm/s, test speed 3.3 mm/s, post-test speed 10.0 mm/s, distance 75 mm, trigger force type 5 g and data acquisition rate 200 pps.

2.6. SMS/Chen-Hoseney dough stickiness test

The SDWD prepared with PAW was analysed by texture analyser using a Chen-Hoseney Dough Stickiness Rig (A/DSC) with pre-test speed 0.5 mm/s, test speed 0.5 mm/s, post-test speed 10.00 mm/s, spacing 4 mm, force 40 g, a 25 mm perspex cylinder probe (P/25P), and 5 kg load cell. The stickiness, work of adhesion, and dough strength were determined.

2.7. Gluten analysis

The wet and dry gluten content, gluten index, and water binding capacity (WBC) of SDWD were evaluated following AACC Method 38–12.02 (AACC, 2010). WBC of the gluten is measured by the weight difference between total wet gluten and total dry gluten.

2.8. Bread analysis

2.8.1. Chemical analysis

Moisture of the SDWB were masured by following AACC Method 44–01.01. Water activity (a_w) was determined by using the Testo 650 a_w device. Protein analyses were performed according to the Dumas (Gerhardt Dumatherm, German) method. Nitrogen factor was used as 5.7 in protein analysis (AOAC 992.23-1992, 1998).

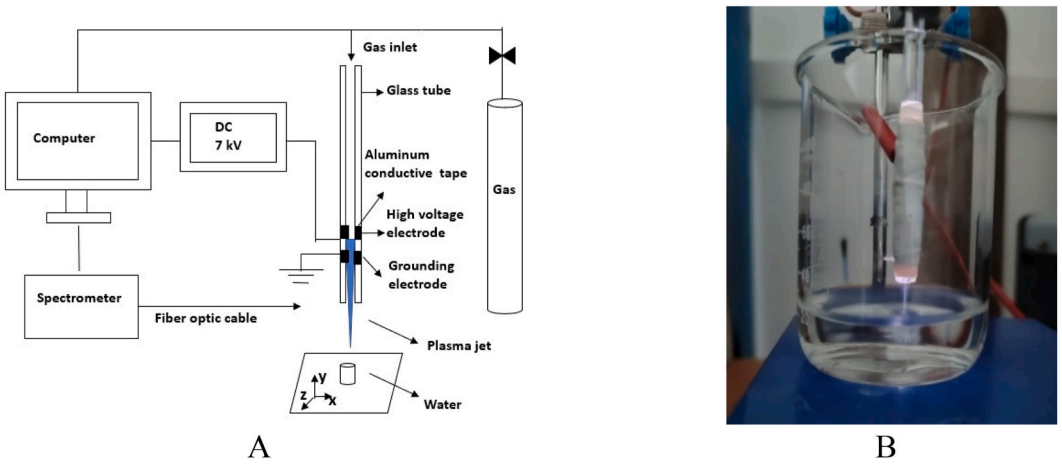


Fig. 1. 2D schematic representation (Fig. 1A) of the activation of water with plasma (Kutlu et al., 2018) and the process of obtaining plasma activated water (Fig. 1B).

2.8.2. Physical analysis

Width, length, and height of the SDWB, were measured using dijital calliper. Loaf volume was determined using the displacement principle with birdseed (AACC Method 10–05.01). The specific volume was calculated by dividing the volume of SDWB by its weight. Crust and crumb color values of the SDWB were measured with a color device (Minolta CR-410 Chroma Meter, Konica Minolta, Tokyo, Japan). The colour scale was used as L* value [(0) Black - (100) White], a* value [(+) red, (−) green] and b* value [(+) yellow, (−) blue].

2.8.3. Total phenolic content and antioxidant activity

The Folin-Ciocaltaeu method was used to colorimetrically quantify the total phenolic content (TPC). A spectrophotometer (Thermo-Scientific Genesis 10s UV–Vis, USA) was used to measure the absorbance of the solutions at 765 nm. The total phenol content was found by measuring the amount of gallic acid in grammes of extract (mg GAE/g) (Slinkard and Singleton, 1977). A 2,2-diphenyl-1-picrylhydrazyl (DPPH) was used to test for antioxidant activity (Ulutürk and Gül, 2025), and a ThermoScientific Genesis 10S UV–Vis spectrophotometer (USA) was used to measure absorbance at 517 nm. The antioxidant activity (AA) was calculated by employing the following formula:

$$AA = (1 - [\text{A of sample} \ / \ \text{A of control}]) \times 100.$$

2.8.4. Texture profile analyses (TPA) of SDWB prepeared with PAW

TPA values (hardness, adhesiveness, springiness, cohesiveness, gumminess, chewiness) of SDWB were performed on a texture analyser using a 36 mm diameter cylindrical probe with the test parameters as; pretest speed: 1 mm s-1, test speed: 1.7 mm s-1, final test speed: 10 mm s-1, penetration depth: 40 %.

2.8.5. FTIR spectroscopy

FTIR (IRTracer-100, Shimadzu, Japan) was used to collect the infrared spectra, which were obtained at frequencies between 400 and 4,000 cm-1, with a resolution of 4 cm-1, a scan rate of 45 and scan speed of 2 mm/s. The spectra analysed to determine the types of possible compounds and functional groups.

2.8.6. Microstructure (scanning electron microscope, SEM) analysis

The SEM (Quanta FEG 250, FEI, USA) was used to analyse the microstructure of bread samples. Prior to analysis, bread samples were cut into approximately 1 cm^3 and dried in a lyophiliser (Labconco Freezone 6 Plus, US) at −40 °C for 3 h. Magnification ratios of the samples were taken as ×5000. The imaging was performed at 20.00 kV.

2.9. Statistical analysis

Variance analyses of the data collected for all assessed attributes of the dough and bread samples were conducted applying "SPSS" statistical software (SPSS, 2019). All studies were carried out with three replications, and averages were compared utilising the Duncan multiple range test.

3. Results and discussion

3.1. Chemical properties of PAW

Some chemical properties, including pH, ORP, H_2O_2, nitrite, nitrate, and alkalinity levels of PAW samples are presented in Table 1.

The pH of the PAW did not show a statistically significant difference between the PAW-0 and PAW-30. While a steady increase at pH was observed when plasma application was increased to 60 s and upper durations. On the other hand, there was no statistically significant difference between PAW-120 and PAW-180. The increase in pH value with plasma application can be attributed to the fact that argon gas shows reducing properties and contains high concentrations of reducing species such as $H\bar{O}$ or low concentrations of oxidising species such as $NO2^-$, $NO3^-$, H_2O_2, etc. (Rezaei et al., 2018). However, $H\bar{O}$ are short-lived reactive species that exist at the liquid, gas, and gas-liquid interfaces, making them unstable (Kurake et al., 2017). The significant instability and transient nature of the reactive species $H\bar{O}$ impeded a more pronounced elevation in pH, which did not exceed 8.0.

ORP values of all samples are positive, thus they have oxidation potentials. Furthermore, the results are in the optimal range for ORP (~+150 to +250 mV). Optimal ORP favors yeast metabolism, while excessive oxidation inhibits microbial activity. The +150 to +250 mV range reflects the aerobic conditions ideal for *Saccharomyces cerevisiae* activity, where oxygen supports efficient ATP production (via oxidative phosphorylation) while avoiding excessive oxidative stress (Köhler and Wieser, 2013). Extreme oxidation (>+300 mV) can inhibit yeast by damaging cellular components (e.g., membrane lipids, enzymes), while highly reducing conditions (<−100 mV) shift metabolism toward anaerobic pathways (e.g., glycerol production), reducing CO_2 efficiency (De Souza and Gomes, 2019).

It was concluded that ORP values were consistent between PAW-0 and PAW-30. Nonetheless, an increase was observed with the duration of plasma application, with the peak value attained at PAW-180. This can be attributed to the heightened presence of reactive chemical species, which play a vital role in enhancing its oxidative capabilities. The main reactive oxygen species causing the increase in ORP value are

Table 1
Some chemical properties of PAW.

Water Sample	pH	ORP (mV)	H_2O_2 (mg/L)	Nitrite (ppm)	Nitrate (ppm)	Alkality (meq/L)
PAW-0	7.40 ± 0.01^{c}	224.67 ± 0.57^{d}	8.00 ± 0.00^{c}	0 ± 0.00	0 ± 0.00	0 ± 0.00
PAW- 30	7.40 ± 0.00^{c}	225.00 ± 0.57^{d}	8.67 ± 0.57^{c}	0 ± 0.00	0 ± 0.00	0 ± 0.00
PAW-60	7.48 ± 0.00^{b}	228.00 ± 0.01^{c}	8.83 ± 6.35^{c}	0 ± 0.00	0 ± 0.00	0 ± 0.01
PAW-120	7.55 ± 0.00^{a}	229.00 ± 0.01^{b}	10.00 ± 1.00^{b}	0.5 ± 0.00^{a}	0.5 ± 0.00^{a}	1 ± 0.00^{a}
PAW-180	7.57 ± 0.01^{a}	232.33 ± 0.20^{a}	11.17 ± 1.25^{a}	0.5 ± 0.00^{a}	0.5 ± 0.00^{a}	3 ± 0.00^{b}

The me^{a}n values in the same column of the table with differing superscripts and lowercase letters are significantly different at $P < 0.05$a.

atomic oxygen, ozone, hydrogen peroxide, and hydroxyl radical (Zhang et al., 2016). It was noted that increasing the plasma discharge time and discharge power resulted in an increase in ORP (Zhang et al., 2024). A higher ORP might promote the oxidation of thiol groups in gluten proteins, hence forming disulphide bonds that strengthen the gluten network and increase dough elasticity. ORP may also influence the viscosity of the dough; higher oxidation levels might produce a more stable and less sticky dough. Better gas retention made possible by a well-formed gluten structure increases loaf volume and produces a more desired crumb texture (Li et al., 2013). Therefore, by optimising ORP with PAW during dough preparation, bakers can enhance gluten development, improve dough handling characteristics, and ultimately produce higher quality bread, particularly from SDWF, which displays inadequate bread-making quality. This also meets the demands of consumers requesting cleaner labelled products by minimising the use of oxidising agents frequently used to strengthen the gluten in bread production. The H_2O_2 concentrations were found statistically similar in PAW-0, PAW-30, and PAW-60, but exhibited a steady increase in PAW-120 and PAW-180. Nitrite, nitrate and alkalinity values were not detected at PAW-0, PAW-30, and PAW-60.

3.2. SMS/Kieffer dough and gluten extensibility characteristics of SDWD

SMS/Kieffer dough and gluten extensibility characteristics of SDWD are given in Table 2.

The impact of sunn pest damage on the rheological properties of wheat flour is significant, leading to poorer dough quality and baking performance. The proteolytic activity from sunn pest damage results in lower protein content and gluten index, further compromising dough quality (Dizlek and Özer, 2021). The application of PAW in this study has shown promise in restoring SDWF quality. The Rmax, Ext, and A values of SDWF exhibited a considerable enhancement following plasma application in comparison to the control, with both Rmax and A values demonstrating a notable increase correlated with prolonged plasma application duration. The formation of disulphide cross-links in the gluten network enhances dough properties. Disulphide bonds are formed when reactive species in the plasma convert D-glucose into H_2O_2. This hydrogen peroxide subsequently oxidises thiol groups in two cysteine molecules, while the reactive species also oxidise thiol groups in both methionine and cysteine molecules (Rasiah et al., 2005). The increase in the number of disulphide bonds and the reduction in free sulfhydryl group concentration lead to a rise in Rmax and A values. The increase in Rmax value during the 120 and 180-s treatments is associated with higher H_2O_2 levels.

Ext increased in PAW applications compared to the control, and the highest value was obtained at PAW-180. This incrase can be associated with plasma reactive species (Banura et al., 2018). In plasma-induced crosslinking mechanism, a rupture occurs between the reducing ends of two polymeric chains and water molecules are removed. Hydroxyl radicals formed by the dissociation of the water molecule cleave the glycosidic bonds. As a result, reactive species in the plasma corroded the starch and caused a change in the hydrophilic structure by reducing the starch-water barrier (Chaple et al., 2020).

3.3. SMS/Chen-Hoseney dough stickiness characteristics

SMS/Chen-Hoseney dough stickiness characteristics of SDWD are given at Table 2. The stickiness rose in the PAW-30 and PAW-60 relative to the PAW-0, whereas a reduced stickiness was observed at PAW-180. The increase of the stickiness at 30, 60, and 120 s can be attributed the breakage of starch molecules by plasma, leading to the reorganisation of amylose into a more adhesive structure. Zhang et al. (2024) indicated that amylose molecules within starch content underwent reorganisation, resulting in enhanced adhesion. Conversely, the enhancement in stickiness value observed at PAW-180 suggests that the oxidative species present in PAW effectively interact with gluten proteins. PAW promotes the interaction between free sulfhydryl groups and disulphide bonds at an appropriate oxidation state. H_2O_2 in PAW oxidises cysteine residues, improving gluten structure and decreasing stickiness via disulphide bond formation (Ershidat et al., 2024).

Sunn pest damage significantly influences the stickiness of wheat flour dough, primarily because the introduction of proteolytic enzymes through insect activity leads to the degradation of gluten proteins, which are crucial for maintaining dough strength (Grădinaru et al., 2017). This leads to increased stickiness and hence difficulties in shaping and handling the dough and adversely affects the quality of the end product. Thus, in alignment with our findings, we propose that a 180-s application of argon plasma to water may decrease the stickiness of SDWD, enhance processing efficiency, and improve the quality of SDWB.

The adhesion of the SDWD were statistically similar for the PAW-0, PAW-30 AND PAW-60, however a decline was observed in the PAW-120 and PAW-180. The reduction in adhesion can be attributed to the

Table 2
SMS/Kieffer dough and gluten extensibility, SMS/Chen-Hoseney dough stickiness and gluten characteristics of SDWD.

	PAW-0	PAW-30	PAW-60	PAW-120	PAW-180
Rmax (g)	24.73 ± 2.44^{e}	45.05 ± 2.41^{d}	52.44 ± 1.93^{c}	56.42 ± 1.00^{b}	59.40 ± 0.96^{a}
Ext (mm)	15.67 ± 1.71^{b}	21.75 ± 2.89^{a}	23.37 ± 2.28^{a}	23.84 ± 2.25^{a}	25.11 ± 2.48^{a}
Area	259.10 ± 5.51^{e}	479.61 ± 2.65^{d}	538.98 ± 10.3^{c}	621.95 ± 4.5^{b}	647.15 ± 1.36^{a}
Stickness (g)	28.81 ± 0.03^{c}	31.21 ± 0.38^{a}	29.67 ± 0.82^{b}	28.70 ± 0.09^{c}	24.55 ± 0.05^{d}
Adhesion (g.sn)	4.46 ± 0.65^{a}	4.28 ± 0.10^{a}	4.05 ± 0.13^{a}	3.65 ± 0.04^{b}	3.44 ± 0.23^{b}
Dough strength (mm)	3.40 ± 0.88^{bc}	4.40 ± 0.41^{a}	2.64 ± 0.26^{c}	2.51 ± 0.22^{c}	3.94 ± 0.55^{b}
Wet gluten (%)	30.52 ± 1.21^{a}	23.3 ± 0.98^{c}	24.1 ± 0.99^{c}	23.0±±0.98^{c}	26.10 ± 1.10^{b}
Dry gluten (%)	10.2 ± 0.32^{a}	7.6 ± 0.15^{d}	8.0 ± 0.16^{c}	7.0 ± 0.13^{d}	8.8 ± 0.01^{b}
Gluten index (%)	56.46 ± 0.56^{d}	91.89 ± 0.15^{b}	92.90 ± 0.12^{b}	60.61 ± 0.58^{c}	99.9 ± 0.10^{a}
WBC (%)	20.32 ± 0.15^{a}	15.7 ± 0.55^{c}	16.1 ± 0.11^{c}	16.0 ± 0.12^{c}	17.3 ± 0.13^{b}

The mean values in the same row of the table with differing superscripts and lowercase letters are significantly different at $P < 0.05$.

accumulation of hypochlorite and H_2O_2 generated by PAW, which prevents the expansion and fragmentation of starch molecules (Ershidat et al., 2024). The highest level of dough strength occurred at PAW-30, whereas PAW-60 and PAW-120 had a decrease; conversely, PAW-180 shown an increase. At PAW-30, the breakdown of starch molecules and the formation of hydrophilic components may have led to enhanced water absorption and the establishment of a stronger structure. The continuous application of plasma led to the reconfiguration of starch structures, less water binding, and a decrease in dough strength. At PAW-180, the dough's strength augmented due to gluten polymerisation as highlighted by Niu et al. (2018).

3.4. The wet and dry gluten content, gluten index, and water binding capacity of SDWD

Although the wet and dry gluten and WBC decreased with the PAW application relative to the PAW-0, a partial rise was seen at the PAW-180 (Table 2). The gluten index of the SDWF is typically low. A significant increase in this value was observed with the application of PAW compared to PAW-0. Nevertheless, PAW-30, PAW-60, and PAW-180 shown a notable enhancement, whilst PAW-120 demonstrated a regression towards PAW-0 levels. Ulutürk and Gül (2025) indicated that alterations in hydration capacity could lead to a reduction in wet and dry gluten content, while concurrently enhancing gluten quality and dough characteristics. They attributed these phenomena to the plasma environment rich in reactive species and the modification of protein structures.

3.5. Chemical, physical, phenolic content, antioxidant characteristics, crust and crumb colours of SDWB

Chemical, physical characteristics, phenolic content and antioxidant activities and also crust and crumb color paramaters of SDWB are given in Table 3.

The moisture and a_w of SDWB demonstrated a steady decrease with the usage of PAW. This decrease can be attributed to the reactive species in the applied plasma remove the moisture on the surface, and the water molecules are broken down by the reactive species in the plasma (Thirumdas et al., 2016). The H_2O_2 concentration in PAW-180 was found to be the highest, potentially resulting in a drying effect on SDWD and SDWB. The oxidative effects of H_2O_2 result in a drying effect on dough by diminishing the mobility of water within the dough matrix. H_2O_2 obtained from calcium peroxide or glucose oxidase enhances the elastic modulus (G') and viscous modulus (G'') of the dough, resulting in drier dough (Miller and Hoseney, 1999).

PAW led to notable variations in the protein levels of SDWB. PAW-180 exhibited the highest protein content, whereas PAW-60 and PAW-120 shown no statistically significant difference. The rise can be attributed to the elevated levels of H_2O_2 and water alkalinity following the application of 180-s argon plasma. Gujral and Rosell (2004) indicated that H_2O_2 enhanced the formation of disulphide bonds in gluten proteins and facilitated the gelation of water-soluble pentozans. The rise of protein at PAW-180 SDWB is may also be attributed to the enhanced solubility of proteins with prolonged plasma application duration. Hydrophobic-hydrophilic equilibrium and charged groups of protein fragments are the primary determinants of protein solubility (Mirzaee et al., 2022). Abarghoei et al. (2023) established that protein solubility increases at elevated pH levels. This may be linked to PAW-180, which demonstrates the highest pH.

The phenolic content of the SDWB consistently increased after PAW treatment, but the antioxidant activity decreased and stayed at the same level after PAW-30. The increase in pH value confirms that argon gas has a high value in terms of OH^- ion. The decrease in the antioxidant value may be related to the fact that argon gas contains reducing species such as OH^- (Rezaei et al., 2018), which is the most destructive and reactive radical component in biological systems. This free radical can react strongly with biomolecules such as proteins, carbohydrates, and lipids and cause serious damage to cells (Al-Mamary and Moussa, 2021).

SDWB weight exhibited a reduction at PAW-30, PAW-60, and PAW-120 in comparison PAW-0. The reduction in bread weight can be attributed to starch degradation; excessive degradation leads to increased water absorption by the flour during kneading. This impacts the weight of the bread and its shelf life derived from a unit of flour (Ma et al., 2019). The elevated stickiness and adhesion values at 30 and 60 s support this explanation. A notable rise of 6.6 % was seen in the weight of PWA-180 SDWB. This phenomenon can be attributed to the elevation of H_2O_2 during this period, which facilitates the creation of disulphide bonds in gluten proteins, enhances gas retention, and promotes the gelation of water-soluble pentosans (Gujral and Rosell, 2004).

Compared to PAW-0, the loaf volume of SDWB exhibited a decrease at PAW-30 and PAW-60, followed by an increase at PAW-120 and PAW-180. The application of PAW-120 and PAW-180 in bread preparation markedly enhanced the specific volume of SDWB. PAW-180 produced the most favourable results for, loaf volume, specific volume, width, length and height values for SDWB. This may also correlate with the increase in H_2O_2 levels with PAW. H_2O_2 enhanced dough permeability and resulted in an increase in pore and gas cell formation within the dough. Hasan and Altaee (2021) reported comparable findings in their research. With an increase in water plasma activation time, there was a corresponding increase in the concentration of plasma reactive species. During dough formation, the oxidation of cysteine molecules within the protein network led to an increase in loaf volume and specific volume, correlating with the development of high-molecular-weight polymeric proteins. Research indicates that the specific volume rises in direct correlation with the duration of water activation (Pivovarov et al., 2018; Ershidat et al., 2024).

The crust and crumb L* and b* of the SDWB increased with the PAW and simultaneously with the extended application duration. This situation can be ascribed to the active species in plasma, particularly H_2O_2 and O_3, which oxidise the pigment responsible for the yellow colour, resulting in a whiter colour (Li et al., 2013). The a* of the crust exhibited no variation compared to the control at 30 s of PAW treatment, but revealed a substantial reduction with prolonged treatment duration. Similarly, the a*of SDWB crumb decreased after uasge of PAW. This reduction in a* could be attributed to the oxidative effects of the PAW, which likely enhances the degradation of certain pigments responsible for the red coloration. Consequently, longer exposure times may lead to a more pronounced whitening effect, aligning with prior observations regarding the impact of plasma treatments on colorimetric properties in various food products.

3.6. TPA of SDWB

The properties of TPA, including hardness, springiness, cohesiveness, gumminess and chewiness of SDWB are presented in Table 3. The hardness of the bread produced by application of the PAW-30, PAW-60, and PAW-120 SDWB significantly increased relative to the PAW-0. However, the hardness of the bread produced by application of the PAW-180 decreased considerably, falling even below that of the PAW-0. There is an inverse relationship between the volume and hardness of the breads. In particular, the PAW-180 SDWB exhibits higher volume, specific volume, width, length, and height, and its hardness is the lowest among the SDWB, indicating a softer texture that may appeal to some consumers. Bread made with PAW exhibits prolonged freshness, with studies indicating an extension of up to two days in freshness during storage (Pivovarov et al., 2018). These results emphasise the potential of PAW to markedly enhance SDWB quality and provide important insights for future baking methodologies from SDWF.

Adhesiveness is reduced with the use of PAW. As with hardness, PAW-180 SDWB have the lowest adhesion. This result was consistent with the SMS/Chen-Hoseney dough stickiness test results of SDWD, which we found that a PAW-180 was the most effective treatment to

decrease the stickiness of SDWD. This result is significant since PAW shows potential in reducing the stickiness of the SDWB, a critical issue associated with SDWB derived from SDWF. As previously stated, sunn-pest, which secretes proteolytic enzymes that break down gluten proteins, not only causes an increase in dough stickiness but also complicates shaping and processing and compromises the overall quality of the finished product. Consequently, there is a critical need for effective solutions to maintain the quality of SDWF and ensure optimum baking results. We propose utilising 180 s of PAW-treated water in damaged dough as a possible solution to reduce stickiness and enhance the quality of both dough and bread.

The springiness, which indicates the percentage recovery, of PAW-30, PAW-60, and PAW-120 decreased with PAW treatment; however, at PAW-180, it returned equal to the value of the untreated counterpart. The cohesiveness, an essential parameter for SDWB, decreased in the PAW-120 and PAW-180 SDWBs, respectively. The chewiness/toughness parameter is usually characterised by the total positive area under the curve during the test and reflects the cumulative 'work' required to chew a product until is ready to be swallowed. Higher area values indicate a higher energy expenditure, which in turn results in a harder product for consumers to bite into and chew. Table 3 shows that PAW-0 SDWB has the highest chewability while it decreased with the PAW application. However, while the chewability of the SDWB was higher at a short application time of 30 s, this value decreased as the duration increased. The chewability value of the PAW-180 SDWB was found to be the lowest, which indicates that this bread is easy to bite. Moreover, these data align with the characteristics of PAW-180 SDWB, which exhibited the greatest loaf volume and the least firmness. The gumminess value exhibited a similar tendency to the chewability value; specifically, a short (30 s) application of PAW resulted in an increase in this value, but prolonged PAW application led to a drop, ultimately reaching its minimum at 120 s. This suggests that the optimum application duration for PAW to improve gumminess and chewability of SDWB is about 180 s.

3.7. FTIR spectrum characteristics of SDWB

Fig. 2 shows the FTIR spectra of the SDWB prepared with PAW.

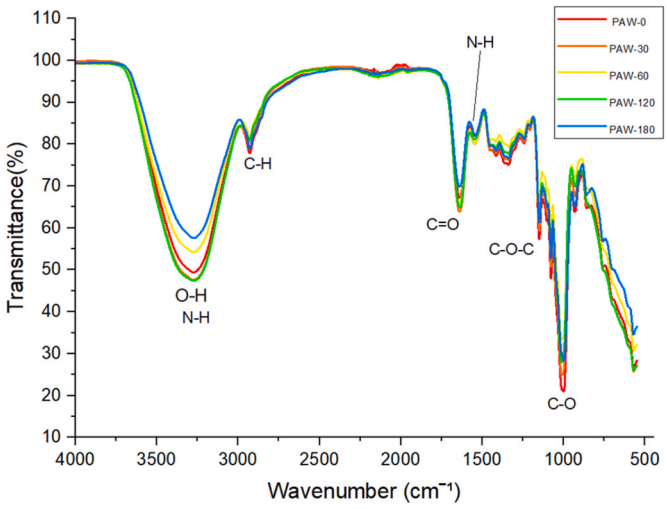


Fig. 2. FTIR spectrums of SDWB prepeared with PAW.

The area of OH group activity is indicated by the 3280 cm^{-1} region. The OH group was detected at the lowest at PAW-30 and PAW-120 s and the highest at PAW-180. Absorbance values (R 1600–1700) in the amide I region were determined as PAW-0 (72.06 ± 0.01a), PAW-30 (73.73 ± 0.25a), PAW-60 (73.47 ± 0.52a), PAW-120 (72.70 ± 0.45a) and PAW-180 (74.71 ± 3.25b). PAW-180 was more effective in reducing the vibration on C=O bonds compared to other samples. Absorbance value in the amide II region (R 1500–1600) increased in PAW-0 (81.87 ± 0.02a), PAW-30 (82.59 ± 0.51a), PAW-60 (82.49 ± 0.53a), PAW-120 (83.55 ± 0.12a) and PAW-180 (84.51 ± 1.86b). In the amide I region, PAW-180 was more effective in reducing the vibration on C = O bonds compared to other samples. Which means, there is an increase in the α-helix structure. PAW-180 increased the concentration of C-O-C, C-O and C-O-H groups compared to other times. The increase in the concentration of these functional groups resulted in the improvement of the gluten structure of the dough and the change in the secondary structure. Analysis of all spectra revealed that the PAW-180 outperformed the

Table 3
Chemical, physical, phenolic content, antioxidant, color and TPA characteristics of SDWB.

	PAW-0	PAW-30	PAW-60	PAW-120	PAW-180
Moisture (%)	38 ± 0.01^{a}	36 ± 0.05^{b}	35 ± 0.02^{c}	33 ± 0.12^{d}	30 ± 0.22^{e}
Water activity (a_w)	0.98 ± 0.34^{a}	0.97 ± 0.02^{b}	0.96 ± 0.22^{c}	0.96 ± 0.20^{c}	0.94 ± 0.13^{d}
Protein (%)	7.46 ± 0.04^{d}	7.66 ± 0.02^{c}	7.87 ± 0.02^{b}	7.82 ± 0.02^{b}	8.11 ± 0.01^{a}
Total phenolic compounds (mg GAE/g)	14.32 ± 0.16^{d}	16.62 ± 0.86^{c}	18.33 ± 0.28^{b}	17.26 ± 0.66^{bc}	19.61 ± 1.49^{a}
Antioxidant activities (% DPPH inhibition)	2.81 ± 0.50^{a}	2.10 ± 0.12^{b}	0.88 ± 0.06^{c}	0.70 ± 0.06^{c}	0.77 ± 0.06^{c}
Weight (g)	127 ± 0.72^{b}	119 ± 0.64^{d}	124 ± 0.77^{c}	125 ± 0.78^{c}	132 ± 0.87^{a}
Volume (cm^3)	210 ± 0.74^{c}	198 ± 2.09^{d}	201 ± 0.72^{d}	221 ± 4.04^{b}	290 ± 1.79^{a}
Specific volume (cm^3/g)	1.65 ± 0.01^{c}	1.66 ± 0.19^{c}	1.62 ± 0.01^{c}	1.76 ± 0.02^{b}	2.19 ± 0.02^{a}
Width (mm)	71.93 ± 0.47^{c}	72.63 ± 0.15^{bc}	72.60 ± 0.07^{bc}	73.23 ± 0.68^{b}	74.80 ± 0.17^{a}
Length (mm)	131.86 ± 1.22^{a}	130.20 ± 2.33^{a}	131.00 ± 0.43^{a}	132.10 ± 0.30^{a}	132.16 ± 2.66^{a}
Height (mm)	41.96 ± 2.06^{c}	42.90 ± 0.10^{bc}	44.43 ± 0.87^{b}	44.23 ± 1.18^{b}	46.70 ± 0.30^{a}
Crust colour					
L *	54.04 ± 0.22^{c}	55.08 ± 0.34^{c}	61.66 ± 1.61^{b}	62.04 ± 0.14^{b}	64.17 ± 0.11^{a}
a *	12.57 ± 0.12^{a}	12.84 ± 0.43^{a}	8.90 ± 0.92^{b}	7.29 ± 0.28^{c}	6.73 ± 0.05^{c}
b *	32.20 ± 0.11^{b}	31.74 ± 0.58^{b}	31.77 ± 0.99^{b}	33.41 ± 0.17^{a}	33.05 ± 0.55^{a}
Crumb colour					
L *	70.90 ± 0.57^{e}	72.94 ± 0.09^{d}	74.51 ± 0.05^{c}	77.14 ± 1.72^{b}	79.72 ± 0.40^{a}
a *	1.57 ± 0.03^{a}	0.60 ± 0.00^{d}	0.67 ± 0.03^{c}	0.71 ± 0.01b^{c}	0.74 ± 0.01^{b}
b *	14.88 ± 0.30^{a}	18.33 ± 0.15^{b}	18.59 ± 0.09^{b}	19.43 ± 0.27^{a}	19.58 ± 0.16^{a}
TPA					
Hardness (g)	2337 ± 0.63^{d}	2601 ± 1.69^{c}	2681 ± 1.84^{b}	2783 ± 1.07^{a}	2181 ± 1.10^{e}
Adhesiveness (g. sec)	4.23 ± 0.05^{a}	2.28 ± 0.04^{b}	1.62 ± 0.02^{c}	1.69 ± 0.08^{c}	1.52 ± 0.01^{d}
Springiness	0.94 ± 0.02^{a}	0.88 ± 0.06^{b}	0.90 ± 0.01^{b}	0.88 ± 0.01^{b}	0.94 ± 0.03^{a}
Cohesiveness	0.60 ± 0.01^{b}	0.69 ± 0.08^{a}	0.68 ± 0.00^{a}	0.53 ± 0.01^{c}	0.45 ± 0.11^{d}
Gumminess	1373 ± 5.32^{b}	1666 ± 8.29^{a}	1313 ± 6.36^{b}	1201 ± 2.15^{c}	1190 ± 7.32^{d}
Chewiness	1341 ± 10.41^{b}	1479 ± 16.49^{a}	1276 ± 13.5^{ab}	1096 ± 59.16^{b}	1107 ± 82.94^{b}

The mean values in the same row of the table with differing superscripts and lowercase letters are significantly different at $P < 0.05$.

other samples. This finding is consistent with the results obtained from Kieffer dough and gluten extensibility, gluten index and SEM analyses.

3.8. SEM of SDWB prepeared with PAW

SEM images of SDWB were illustrated in Fig. 3, which clearly indicates that both the PAW application and varying durations significantly influenced the SEM images of SDWB.

Comparison of the SEM image of white wheat bread with the SDWB image indicates that damage from the sunn pest has led to the degradation of proteins and starch molecules by protease and amylase enzymes, inhibiting the formation of a continuous gluten network. It was concluded that lack of a specified gluten network resulted in inadequate gas cell retention, while starch breakdown contributed to increased stickiness of the bread. The low volume and high stickiness of the SDWB confirm the SEM images. As the argon plasma treatment was increased from 30 s to 120 s, the effect on the depolymerization of the gluten network and especially starch increased. Active species such as ozone and hydroxyl radicals produced by argon plasma can corrode the surface of wheat starch granules; there may be different degrees of cracks, voids, and fragmentation on the surface. During the PAW process, the starch chain decomposes or depolymerises, leading to an increase in amylose content similar result was described by Ji et al. (2024). As can be seen in the PAW-120, as the argon plasma treatment time increased, the etching intensity also increased, causes granule disintegration and subsequent aggregation, resulting in more prominent starch granules. However, the most interesting result in SEM images was seen in PAW-180 in which, compared to other times, starch particles were homogeneously distributed, i.e. a well-developed gluten network was detected. The prolongation of the plasma treatment led to the production of sufficient

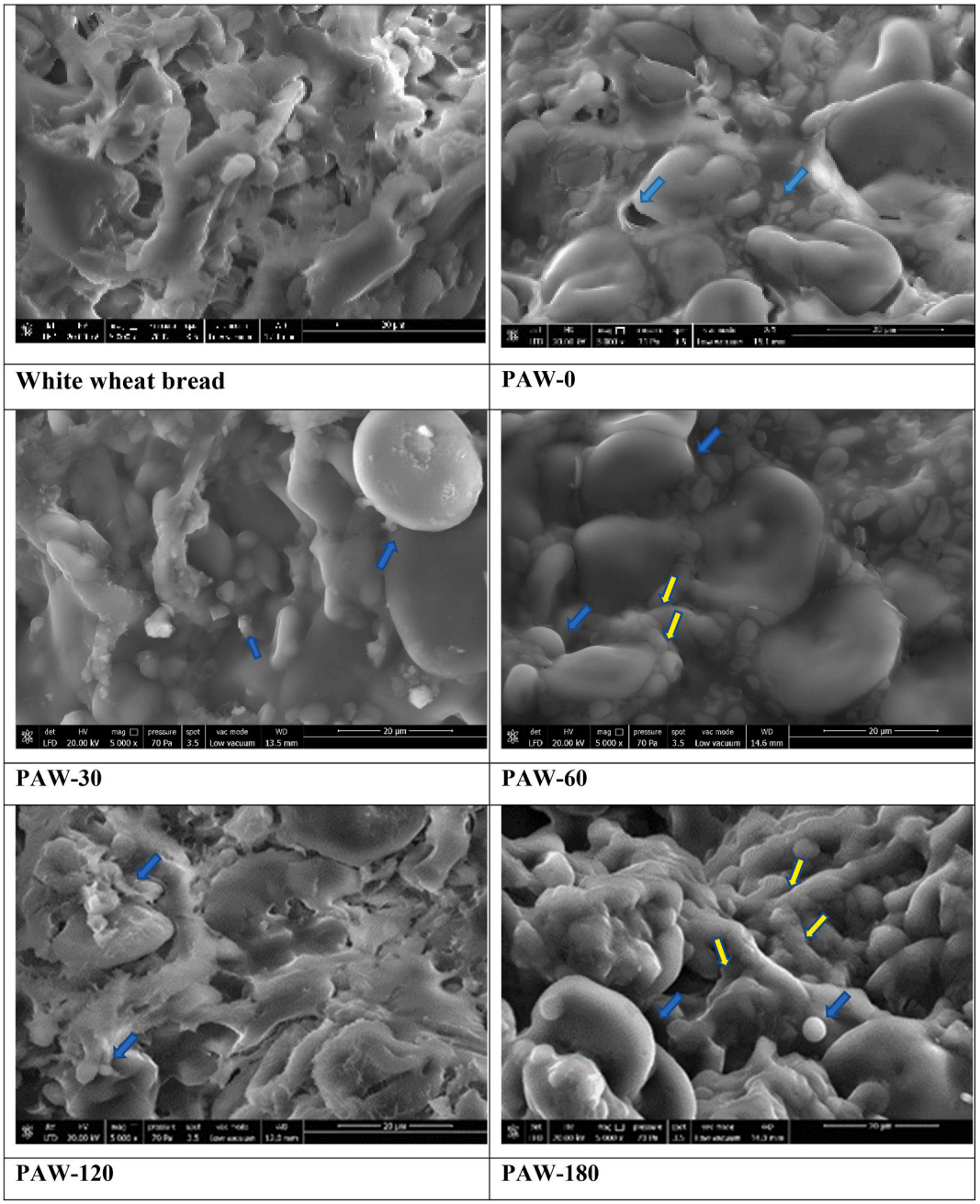


Fig. 3. SEM images of sunn pest-damaged wheat flour bread samples under 5000x magnifications Yellow arrows: gluten network; blue arrows: conversion of starch particles. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

reactive species and free radicals to decompose air and water molecules, contributing to the sufficient interaction of plasma species with protein and starch (Sarkar et al., 2023). This result is in line with the better results of PAW-180 sample in all rheological and bread analysis.

4. Conclusions

This study shows that PAW significantly influences the technological characteristics of doughs and breads made from SDWF. Because of their increased biological activity, the reactive species produced by PAW cause significant changes in both protein and starch components, providing a way to lessen the damaging effects of sun pest damage. Given the concentration of these reactive species, the findings of the Kieffer dough test, the analyses of the gluten index, dough stickiness, and SDWB characteristics, the PAW-180 treatment successfully enhanced the rheological characteristics and general bread quality of SDWB. The presence of reducing species, like OH, in argon gas resulted in a reduction in antioxidant value, although the concentration of phenolic compounds peaked in PAW-180. In conclusion, the application of PAW in the production of bread from SDWF offers a promising method to improve the rheology of the dough and optimise its chemical, physical, and textural properties. Additionally, it enhances loaf volume (as demonstrated by SEM imagery) and reduces bread hardness and dough stickiness. These results point to possible wider uses for PAW in food processing as well as its function in reducing quality problems associated with other kinds of damaged or low-quality flours. Moreover, adding PAW to wheat flour may inspire new leads to innovative approaches in the baking sector, especially in areas where crops are damaged by pests. Future studies could examine how different discharge power levels of argon plasma and other plasma parameters affect reactive species concentrations and the rheological characteristics of dough and bread made from SDWF, while exploring ways to further minimise quality losses in SDWF by combining PAW with other dough enhancers or milling techniques. Such studies could strengthen PAW's position as a versatile tool for enhancing the functional and nutritional qualities of various cereal-based products, in addition to serving as a remedy for flour damaged by sun pests.

CRediT authorship contribution statement

Şeyma Ulutürk: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hülya Gül:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

The authors have declared no conflicts of interest for this article.

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Data availability

Data will be made available on request.

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