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Utilization of spray-dried raspberry powder as a natural additive to improve oxidative stability, microbial quality and overcome the perception of discoloration in vacuum-packed ground beef during chilled storage

Muhammet İrfan Aksu [a,*], Emre Turan [b], Aysel Gülbandılar [a], Faruk Tamtürk [c]

[a] Eskişehir Osmangazi University, Faculty of Agriculture, Department of Food Engineering, 26160 Eskişehir, Turkey
[b] Ordu University, Faculty of Agriculture, Department of Food Engineering, 52200 Ordu, Turkey
[c] DÖHLER Food and Beverage Ingredients R&D Center, Karaman 70100, Turkey

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ABSTRACT

The present study was conducted to determine the effects of spray-dried raspberry powder (SDRP) (CONTROL, 1.0%, 2.0%, and 3.0%) as a natural antioxidant, antimicrobial, and colorant on physicochemical properties, lipid oxidation, discoloration, and microbial quality of vacuum-packed (VP) ground beef during chilled storage at 2 ± 0.5 °C for 18 days. By incorporating SDRP into VP ground beef pH, lipid oxidation (TBARS), lightness, and hue angle ($h°$) values decreased ($P < .01$), while redness (a^*) and chroma (C^*) values improved ($P < .01$). SDRP treatments had higher redness, more stable color, and lower pH and TBARS values during storage in a dose-dependent manner ($P < .05$), demonstrating that SDRP had a preventive effect on lipid oxidation and discoloration. The combination of vacuum packaging with SDRP generally resulted in lower bacterial growth during storage. These results demonstrated that 2% or 3% SDRP treatment has promising potential as an effective strategy to achieve oxidative and microbial stability and overcome discoloration in VP fresh meats.

1. Introduction

Meat and meat products fall into the perishable food category in terms of oxidative and microbial spoilage due to their nutrient content, high water activity, pH range, and presence of autolytic enzymes (Pellissery, Vinayamohan, Amalaradjou, & Venkitanarayanan, 2020). However, ground beef is more susceptible to oxidative rancidity and microbial spoilage than intact muscle. The process of grinding meat results in disruption of the integrity of the muscle membrane and larger surface area. This increases lipid oxidation and microbial growth by facilitating the exposure of the meat surface to air and microbial contamination (Aksu & Turan, 2022; Alp & Aksu, 2010). In this context, low temperature storage, various packaging techniques and antioxidants are widely used in the meat industry to prolong the shelf life by preventing the adverse effects of these two main destructive mechanisms (Falowo, Fayemi, & Muchenje, 2014; Zhou, Xu, & Liu, 2010).

Although overwrapped/air-permeable and modified atmosphere packaging offer a desirable color originating from oxymyoglobin (Oxy-Mb), overexposure to oxygen results in metmyoglobin (Met-Mb) accumulation and growth of aerobic spoilers resulting in discoloration and shortened shelf life. On the other hand, vacuum-packaging provides a more stable color and extended shelf life by limiting oxidative reactions and aerobic bacteria growth as oxygen is eliminated (McMillin, 2008; Reyes, Wagoner, et al., 2022; Rogers et al., 2014). However, vacuum-packed (VP) beef is misjudged and perceived as unwholesome by consumers due to the purplish red color of deoxymyoglobin (Deox-Mb) and the discoloration associated with low oxygen partial pressure (Mancini & Hunt, 2005; Reyes, Smith, et al., 2022). Since vacuum packaging allows the growth of anaerobic bacteria, the sour/cheesy odor caused by the metabolism of these bacteria is another disadvantage. In addition to the loss of product quality, there are also risks to consumer health caused by the presence of certain foodborne pathogens that can grow in

Abbreviations: SDRP, Spray-dried raspberry powder; VP, Vacuum-packed; TBARS, Thiobarbituric acid reactive substances; AAC, Ascorbic acid content; TAP, Total amount of phenolic; TAC, Total anthocyanin content; FRAP, Ferric reducing antioxidant power; MIC, Minimum inhibitory concentration; AMB, Aerobic mesophilic bacteria; APB, Aerobic psychrotrophic bacteria; M / S, Micrococcus / Staphylococcus; DPPH-RSA, DPPH radical scavenging activity; ABTS-RSA, ABTS radical scavenging activity; Oxy-Mb, Oxymyoglobin; Deox-Mb, Deoxymyoglobin; Met-Mb, Metmyoglobin.

* Corresponding author at: Eskişehir Osmangazi University, Faculty of Agriculture, Department of Food Engineering, Eskişehir, Turkey.
E-mail address: mirfan.aksu@ogu.edu.tr (M.İ. Aksu).

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anaerobic conditions (Aksu & Turan, 2022; Jeong & Claus, 2011). Considering that meat color has a key attribute on consumers' purchasing decisions (Feuz, Norwood, & Ramanathan, 2020), additional/multiple applications are required in VP meats to overcome these disadvantages and increase consumer acceptance (Aksu & Turan, 2022; Calderón-Oliver, Escalona-Buendía, & Ponce-Alquicira, 2020).

In addition to deoxygenating the packaging atmosphere, utilizing antioxidants is a common strategy to minimize oxidative reactions and preserve meat color. The replacement of synthetic-based additives with natural ingredients as a clean-label approach to prevent oxidative reactions in the meat industry is a growing trend due to potential health-threatening concerns (Falowo et al., 2014; Lorenzo et al., 2018). Therefore, phenolic-rich natural extracts and powders from fruits, vegetables and herbs have been successfully tested as a consumer-favor and more reliable technique to delay oxidative reactions, prevent discoloration and microbial spoilage in meat products (Aksu, Alinezhad, & Erdemir, 2015; Aksu & Turan, 2022; Babaoğlu, Unal, Dilek, Poçan, & Karakaya, 2022; Calderón-Oliver et al., 2020; Martín-Mateos et al., 2022; Sadeghinejad, Sarteshnizi, Gavlighi, & Barzegar, 2019; Turan & Şimşek, 2021). Moreover, the concepts of "natural food" and "coloring food with food" are gaining importance in the food industry, and anthocyanins are the primary pigments that come to mind (Gras, Nemetz, Carle, & Schweiggert, 2017) with their pH-dependent color changes, water-soluble and health-beneficial properties (Khoo, Azlan, Tang, & Lim, 2017). In this regard, berries are a source of bioactive compounds such as phenolic compounds, anthocyanins, tannins, and ascorbic acid, and have promising potential to be useful as natural antioxidants and/or colorants in foods (Lorenzo et al., 2018; Skrovankova, Sumczynski, Mlcek, Jurikova, & Sochor, 2015).

Raspberry is a bramble plant variety with its unique flavor and attractive color, as well as bioactive components and health benefits (Chen, Xin, Zhang, & Yuan, 2013; Gagneten et al., 2019). Red raspberries are rich in phenolic compounds, especially anthocyanins and ellagitannins (de Souza et al., 2014; Skrovankova et al., 2015), as well as ascorbic acid, vitamins and minerals. The presence of these phytochemicals offers raspberry antioxidant and antimicrobial properties (Chen et al., 2013; de Souza et al., 2014; Suriyaprom et al., 2022), and also contributes to numerous health benefits (Khoo et al., 2017; Szajdek & Borowska, 2008). However, raspberry fruits have a very short post-harvest market life due to their high perishability. Therefore, raspberries need to be subjected to a rapid processing method following harvest, one of these methods is drying (Franceschinis, Salvatori, Sosa, & Schebor, 2014; Sadowska, Świderski, & Hallmann, 2020). Although convective drying is a widely used method due to low costs, the requirement for a long drying time and significant degradation of bioactive components are disadvantages. On the other hand, the freeze-drying process, which largely preserves the bioactive components and structure of the food, is quite costly (Sadowska et al., 2020). In addition, fruit powders are prone to stickiness and color changes due to their low molecular weight sugars (such as fructose, glucose and sucrose) content and glassy properties. In this context, spray-drying method utilizing a suitable carrier agent is a widely used inexpensive and continuous encapsulation method to overcome operational difficulties, to obtain non-sticky and physically stable powders, and to preserve bioactive components for industrial applications (Fang & Bhandari, 2011; Gagneten et al., 2019; Konar, Durmaz, Genç Polat, & Mert, 2022; Syamaladevi, Insan, Dhawan, Andrews, & Sablani, 2012). Additionally, anthocyanins are responsible for the red color of raspberries, and the main anthocyanin compounds are cyanidin-3-glucoside, cyanidin 3-rutinoside, and cyanidin-3-sophoroside (Chen et al., 2013; Skrovankova et al., 2015). Spray drying is an effective drying method to maintain the stability of anthocyanins throughout storage (Fang & Bhandari, 2011).

Despite its strong antioxidant and coloring potential, studies examining the effects of red raspberry on meat products are quite limited (Aksu, Erdemir, Turan, & Öz, 2022; Kryževičūtė, Jaime, Diez, Rovira, & Venskutonis, 2017). To our knowledge, no data are available regarding the evaluation of the effects of red raspberries on VP ground beef. Therefore, the objectives of this study were: i) to determine the antioxidant and antimicrobial potential of spray-dried raspberry powders (SDRP), ii) to evaluate the effects of SDRP on the physicochemical properties, oxidative stability, discoloration and microbiological quality of VP ground beef during chilled storage (18 days at 2 ± 0.5 °C), and iii) to overcome the perception of discoloration misjudged by consumers in VP fresh beef.

2. Material and methods

2.1. Chemicals and reagents

Ethanol, hydrochloric acid (HCl), Folin-Ciocalteu reagent, gallic acid, potassium chloride, sodium acetate, ascorbic acid, xylene, Brain heart infusion (BHI) broth, Sabouraud dextrose broth, Mueller-Hinton agar, Potato dextrose agar, commercial buffer solutions (pH 4 and 7), trichloroacetic acid (TCA), thiobarbituric acid (TBA), sodium chloride (NaCl), Plate count agar, Violet red bile dextrose (VRBD) agar, de Man Rogosa Sharpe (MRS) agar, Phenol-red mannitol salt agar, Baird Parker agar, egg yolk tellurite emulsion were purchased from Merck (Darmstadt, Germany).

2,6-dichlorophenol indophenol, 6-hydroxy-2,5,7,8-tetramethylchromane-2-carboxylic acid (Trolox), 2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS), 2,2-diphenyl-1-picryl-hydrazyl (DPPH), thiazolyl blue tetrazolium bromide, ethylenediaminetetraacetic acid disodium salt dihydrate (EDTA), propyl gallate were procured from Sigma-Aldrich Corporation (St. Louis, MO, USA). Pseudomonas agar base (CM 0559) and CFC Selective Agar Supplement (SR 0103) were obtained from Oxoid (Basingstoke, UK).

2.2. Preparation of spray-dried raspberry powder (SDRP)

Fresh raspberries (*Rubus ideaus* L. cv. Heritage) were obtained from local farmers/greengrocer in Karaman/Turkey. SDRP was produced according to the method described by Gagneten et al. (2019) with minor modifications. Briefly, a mixture of 12–16 DE maltodextrin and raspberry juice (40:60 *w/v*, average dry matter content of 30%) was homogenized with a digital homogenizer (IKA T25 Ultra-Turrax, Staufen, Germany) at 10000 rpm at room temperature for 10 min. Afterwards, the homogenized mixture was pulverized using a laboratory-scale spray dryer (Buchi B290, Switzerland) with a nozzle diameter of 1.0 μm. In the spray drying process, the inlet temperature, outlet temperature, feed rate and air flow rate parameters were 160 °C, 90 °C, 8 mL/min and 600 L/h, respectively. The obtained spray-dried raspberry powders were stored at 20 ± 2 °C in locked packages in an environment protected from air and light.

2.3. Physicochemical properties of SDRP

Moisture content was determined according to the method based on heating in a oven (Nüve FN500, Turkey) at 70 °C until constant weight. Water activity (a_w) measurement of SDRP was carried out at 20 °C with a WaterLab Steroglass Dew Point Water Activity Meter instrument that allows temperature-controlled measurements of a_w. For pH measurement of the SPRP-distilled water mixture (1:10 *w/v*), a calibrated digital pH meter (HANNA edge, Woonsocket, RI, USA) was used. Instrumental color values of SDRP were measured on a white background using a chromometer (Konica Minolta CR-400, Osaka, Japan) with a D_{65} illuminant, 11 mm measuring aperture, and 2° standard observer conditions. For instrumental color values, the definitions given by the International Commission on Illumination (CIE) were taken into account; and accordingly L^* ($L^* = 0$, darkness; $L^* = 100$, lightness), a^* ($+a$ = redness; $-a^*$ = greenness), and b^* ($+b^*$ = yellowness; $-b^*$ = blueness).

2.4. Bioactive properties of SDRP

The ascorbic acid content (AAC) of SDRP was determined by the spectrophotometric method based on decolorization of 2,6-dichlorophenol indophenol with ascorbic acid. The color intensity of the excess dye extracted with xylene was measured using a spectrophotometer (Jasco, V-730, Japan) at 500 nm wavelength, and the AAC was calculated from a calibration curve prepared using ascorbic acid solutions (0–25 mg/L) as standards.

Acidified ethanol-distilled water mixture (80:20 *v*/v) containing 1% HCl was used for the extraction of phenolic compounds in SDRP. The total amount of phenolic compounds (TAP) was determined by the Folin-Ciocalteu assay (Singleton, Orthofer, & Lamuela-Raventós, 1999). TAP were calculated as mg gallic acid-equivalents (GAE)/100 g dry-weight (dw) from a standard curve obtained using gallic acid.

The total anthocyanin content (TAC) of SDRP was determined by spectrophotometric monitoring (Jasco, V-730) of the pH-dependent color change resulting from treatment of the extract with 0.025 M potassium chloride (pH 1.0) and 0.4 M sodium acetate (pH 4.5) buffer solutions. TAC were expressed as mg cyanidin-3-glucoside (C3G)/100 g dw (Lee, Durst, & Wrolstad, 2005).

In vitro antioxidant activity of SDRP extract (2 mg/mL) were evaluated by using DPPH scavenging activity, ABTS scavenging activity, and Ferric reducing antioxidant power (FRAP) methods developed by Brand-Williams, Cuvelier, and Berset (1995), Re et al. (1999), and Benzie and Strain (1996), respectively. The results of all three antioxidant activity assays were presented as μg trolox-equivalent (TE)/mg dw.

2.5. Antibacterial and antifungal potential of SDRP

The antimicrobial activity of SDRP was tested on eight bacteria and two fungi using the agar-well diffusion and minimum inhibitory concentration (MIC) assays. The bacterial strains consisted of three Gram-positive (*Staphylococcus aureus*, *Micrococcus luteus*, *Listeria monocytogenes*) and five Gram-negative (*Citrobacter freundii, Pseudomonas aeruginosa*, *Yersinia enterocolitica*, *Klebsiella pneumoniae*, *Escherichia coli*). *Saccharomyces cerevisiae* and *Candida albicans* were used for antifungal activity.

The agar-well diffusion assays were performed according to Al-Zoreky (2009) with some modifications. The reactivation of bacterial and fungal strains was carried out by transferring from stock cultures into appropriate medium (BHI broth for bacteria, Sabouraud dextrose broth for fungus). Subsequently, overnight cultures were prepared in the same broths and suspensions were adjusted to 0.5 McFarland turbidity using sterile 0.85% saline and a densitometer (Biosan Den-1, Riga, Latvia). An aliquot (100 μL) of bacterial and fungal inoculums was spread aseptically with sterile swab over the surface of Mueller-Hinton agar and Potato dextrose agar, respectively. A sterile cork-borer was used to punch round wells (6 mm diameter) on agar in Petri dishes. The wells were loaded with different concentrations (100–400 mg/mL) of SDRP. Gentamicin (Bioanalyse, Turkey) and ampicillin (Bioanalyse, Turkey) were considered positive controls for bacteria, while amphotericin B (Bioanalyse, Turkey) was used for fungi. The inoculed bacteria and fungi plates were incubated for 18 h at 37 °C and 48 h at 25 °C, respectively. Antimicrobial tests were performed in triplicate and the zones of inhibition (mm) were measured using a digital caliper.

For the MIC test, the microdilution technique reported by Demirdoven, Karabiyikli, Tokatli, and Oncul (2015) was followed with some modifications. Primarly, aliquots of BHI broth were added to the wells in sterile 96-well U-based plates. Then, interwell mix transfer was performed to prepare serial dilutions of SDRP (250 mg/mL to 0.24 mg/mL). Test inoculum adjusted to 0.5 Mcfarland added into each wells (except 12th row). The 12th row containing only BHI broth were considered sterility control for the culture medium. The plates prepared in this way were incubated for 18–24 h at 37 °C. After the incubation period, thiazolyl blue tetrazolium bromide (0.2 mg/mL) was added to each cell as a bacterial growth indicator.

2.6. Production and storage conditions of ground beef samples

Beef rounds meats were purchased from a meat producer (NAMSAN Inc., Eskişehir/Turkey) after 24 h postmortem. Muscles were obtained from three different beef carcasses for each of the three replications and cold chain conditions were followed during transfer to the laboratory. The beef muscles were grounded in a meat grinder equipped with 3–5 mm diameter plate under strict hygiene rules. The ground beef samples were kept at 4 °C (approximately 1 h) until treated with spray-dried raspberry powder. For the experiment, ground beef was first randomly divided into 4 batches and each batch was used for one of four treatment groups consisting of CONTROL (0% SDRP), 1.0% SDRP, 2.0% SDRP, and 3.0% SDRP. Then, ground beef samples subdivided into 200 g were treated with different concentrations of SDRP and placed in polystyrene dishes after mixing manually with gloves. In order to ensure that the powders are homogeneously included in the ground beef, they were dissolved in 2 mL of sterile water and an equal volume of distilled water was also added to the CONTROL group without SDRP. Taking into account the storage period (0, 3, 6, 9, 12, 15 and 18 days), a total of 84 ground beef samples (four treatments x seven storage times x three independent replications) were prepared. Preparation of ground beef samples was designed as three independent trials on three separate days. All samples were placed in the polyamide/polyethylene (PA/PE) packaging material (3 seal-bag GB 65; thickness 65 μm; Oxygen Transmission Rate (OTR): $\leq$50 cm^3/m^2/day.bar at 23 °C, 50% RH; CO_2 Transmission Rate (COTR): $\leq$ 200 cm^3/m^2/day.bar at 23 °C, 0% RH; N_2 Transmission Rate (NTR): $\leq$15 cm^3/m^2/day.bar at 23 °C, 0% RH and Water Vapor Transmission Rate (VWTR): $\leq$9 g/m^2/day 38 °C, 90% RH) and vacuum packed using a vacuum packing unit (Germany, Multivac 300/16 Sepp. Haggenmuller D 87787 Wolgertschwenden; Vacuum program, medium mode, 20 s, applied vacuum (up to −0.1 MPa), vacuum pump capacity: 10 m^3/h). Analyzes of treatments stored at 2 ± 0.5 °C for 18 days were performed at three-day intervals. All determinations were performed in triplicate.

2.7. Analysis of ground beef

2.7.1. pH

For pH measurements, 10 g of ground beef samples weighed into glass jars were homogenized with an ultra-turrax (IKA T25) by adding 100 mL of distilled water, and pH values were recorded using a desktop pH meter calibrated with commercial buffer solutions (pH 4 and 7) before use.

2.7.2. Instrumental color parameters

Instrumental color values of ground beef samples were measured as indicated in section 2.3. Following the opening of the vacuum packaging for each storage period, the samples were thoroughly mixed by hand. Color measurements were performed immediately after mixing. For each sample, repeated random measurements were taken from different parts of the meat surface and the average values were recorded. In addition to L^*, a^*, and b^* parameters, hue angle (h°) = $\tan^{-1}$[b/a] and chroma (C^*) = $[a^2 + b^2]^{1/2}$ equations were used to calculate h° and C^* values, which express the discoloration and intensity of redness, respectively.

2.7.3. Lipid oxidation

Evaluation of lipid oxidation was carried out according to the thiobarbituric acid reactive substances (TBARS) assay (Lemon, 1975) with some modifications. Immediately after the vacuum package was opened, each ground beef sample was thoroughly mixed by hand and random sampling was performed. Two grams of ground beef were placed in falcon tubes and 12 mL of TCA solution (7.5% TCA, 0.1% EDTA, 0.1% propyl gallate) were added. The mixture was homogenized with ultra-

turrax (IKA T25) at 10000 rpm for 15–30 s and filtered (Whatman No.1). Two mL of filtrate were transferred to a screw cap glass tube and combined with 2 mL of 0.02 M TBA solution. The mixtures were cooled under tap water for 5 min after 40 min of boiling water bath (Daihan Scientific Bath.) exposure and then centrifuged at 2000 xg (Hermle Z 326 K, Germany) for 5 min at 20 °C. Absorbance measurements were performed at 532 nm in a spectrophotometer (Jasco V-730). In addition, the method modified by Aksu and Turan (2021) was followed to overcome the interference and overestimation handicaps of results caused by the natural color of SDRP. Calculation of TBARS values was done as mg malondialdehyde (MDA)/kg ground beef.

2.7.4. Microbiological analysis

Ground beef meat weighed 25 g aseptically into sterile sample bags was homogenized for 1 min using a stomacher (VWR, Star-Blender LB400, France) after adding 225 mL of saline solution (NaCl 0.85%). Ten-fold serial dilutions of the homogenates were prepared and the spread plate technique was used for microbiological counts. After spreading on Plate count agar from appropriate dilutions for aerobic mesophilic bacteria (AMB) and aerobic psychrotrophic bacteria (APB) counts, incubation was carried out under aerobic conditions for 48 h at 30 °C and 7 days at 10 °C, respectively. VRBD (Violet red bile dextrose, Merck) agar was used for *Enterobacteriaceae* counts. After 48 h of incubation at 30 °C under anaerobic conditions (Anaerocult A, Merck), red colonies with a diameter larger than 1 mm were considered for the enumeration *Enterobacteriaceae*. *Micrococcus / Staphylococcus (M / S)* counts were determined by considering catalase (+) cocci after inoculation of appropriate sample dilutions on Phenol-red mannitol salt agar and aerobic incubation at 30 °C for 48 h. CFC Agar (*Pseudomonas* agar base) medium prepared by adding CFC Selective Agar Supplement was used for counting *Pseudomonas*. *Pseudomonas* counts were performed by enumerating oxidase (+) colonies after 48 h of incubation of inoculated petri dishes at 25 °C under aerobic conditions. *Staphylococcus aureus* was counted on Baird Parker Agar supplemented with 5% egg yolk tellurite emulsion. After incubation for 30–48 h at 37 °C, colonies with a clear zone and gray-black shiny were considered as possible staphylococci. Then, coagulase test was applied to these colonies and coagulase (+) colonies were taken into consideration.

2.8. Statistical analysis

The research was carried out by designing according to the randomized plots factorial design, by applying 4 different treatments to the ground beef meat, in 7 different storage periods, with an average of 3 parallels and 3 indepentent replications. In the current statistical model of the study, treatment (CONTROL, 1.0% SDRP, 2.0% SDRP, and 3.0% SDRP) and storage periods (0, 3, 6, 9, 12, 15, and 18 days) were fixed factors. It was investigated whether there is a statistical difference between the treatment and storage period averages and the existence of interaction between these factor levels. All experimental (pH, TBARS, color values and microbial counts) data of the ground beef samples were analyzed by two-way analysis of variance (Two-way ANOVA). In addition, data on the antimicrobial activity of SDRP were subjected to one-way ANOVA. All SDRP and ground beef analyzes were performed in triplicate. The difference between treatment and storage time averages and the existence of interaction has been revealed the Duncan multiple comparison test at a 5% significance level. SPSS 25.0 software (IBM SPSS Inc., Chicago, USA) was used for all statistical analyses. The mathematical model used in the study was given in eq. 1 below.

$$y_{ij} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \varepsilon_{ijk} \quad (1)$$

μ: Overall mean.τ_i: fix effect of ith level of treatment.β_j: fix effect of jth level of storage period.$(\tau\beta)_{ijk}$: effect of interaction between $\tau_i$and β_j.ε_{ijk}: Random error terms

3. Results and discussion

3.1. Physicochemical properties

Characteristics, bioactive content and antioxidant capacity of SDRP are shown in Table 1. The moisture, water activity (a_w) and pH of raspberry powders obtained after spray drying were 4.50%, 0.2829 and 3.30, respectively, and these values were consistent with the literature data (Sadowska et al., 2020). L^*, a^*, and b^* instrumental color parameters of SDRP were 45.70, +46.40 and + 14.12, respectively, and especially high redness value was remarkable. The color values of SDRP were similar to the L^*, a^*, and b^* color values reported by Syamaladevi et al. (2012) for spray-dried red raspberry powders with gum arabic as 43.7, +45.1 and + 11.3, respectively.

3.2. Antioxidant potential of SDRP

Berries are rich in bioactive compounds such as monomeric anthocyanins, polyphenols, ascorbic acid, and flavonols that contribute to antioxidant activity and many biological functions (Gagneten et al., 2019; Skrovankova et al., 2015). The bioactive compound content of raspberries varies depending on geographical conditions, variety, fruit maturity degree, storage/processing conditions, and drying method (Sadowska et al., 2020; Skrovankova et al., 2015). The AAC of SDRP was lower than the amount reported for raspberry fruit and powders in previous studies (Vulić et al., 2014; Sadowska et al., 2020). The SDRP had a TAC of 108.82 mg in C3G equivalents per 100 g dw (Table 1). TAP (541.92 mg GAE/100 g dw) was similar to the content reported by Syamaladevi et al. (2012) for spray-dried raspberry powders, and higher than the values reported by Gagneten et al. (2019) and Sadowska et al. (2020). Vasco, Ruales, and Kamal-Eldin (2008) classified phenolic contents as low (<100 mg GAE/100 g), moderate (100–500 mg GAE/100 g), and high (>500 mg GAE/100 g). Accordingly, SDRP can be categorized as a good source of phenolics. On the other hand, the TAP and TAC contents reported for freeze-dried raspberry powders by Aksu, Turan, Şat, and Erdemir (2021) were considerably higher than those of SDRP. These differences can be attributed to the presence of carrier agents used in the spray drying process and hence the lower juice content in the spray-dried powders. In addition, differences in applied drying method, drying temperature, and extraction method may have caused changes in the content of bioactive components (Gagneten et al., 2019; Sadowska et al., 2020). Similar results have been reported for freeze-dried and spray-dried powders of blackberry (Franceschinis et al., 2014).

The antioxidant capacity of SDRP was evaluated in three different assays as DPPH-RSA, ABTS-RSA and FRAP, and the values were 11.16, 14.69 and 259.67 μg TE/mg, respectively (Table 1). Besides ascorbic acid and phenolic compounds (anthocyanins, especially *p*-coumaric acid or ellagic acid and their esters) are considered to be responsible for the antioxidant capacity of raspberries (Skrovankova et al., 2015). Chen et al. (2013) determined that the antioxidant capacity of 15 commercial raspberries was strongly correlated with total phenolic, flavonoid and anthocyanin contents. Phenolic compounds and ascorbic acid are natural compounds that are effective in inhibiting oxidative processes by chelating metal ions, quenching singlet oxygen, and scavenging reactive species that initiate peroxidation. In addition, combining of anthocyanins, a group within the phenolic compounds, with ascorbic acid provides a synergistic effect and increases antioxidant capacity. Moreover, the antioxidant capacity of anthocyanin depends on the number and location of $^{-}$OH groups, the pH of the surrounding environment, and other components of the system such as metals and the continuous phase (Brewer, 2011). On the other hand, anthocyanins offer a red and more stable color under acidic pH conditions (Khoo et al., 2017). Accordingly, SDRP has promising potential to be incorporated into meat products with its rich bioactive content and antioxidant capacity as well as high redness and acidic pH values.

Table 1
Characteristics, antioxidant capacity and antimicrobial activity of spray-dried raspberry powders (SDRP).

Moisture (%)	Water activity (a_w)	pH	Color values			AAC[a] (mg/kg)	TAC[b] (mg C3G/ 100 g)	TAP[c] (mg GAE/ 100 g)	*In vitro* antioxidant activity (μg TE/mg)		
			L^*	a^*	b^*				DPPH-RSA[d]	ABTS-RSA[e]	FRAP[f]
4.50 ± 0.03	0.2829 ± 0.03	3.30 ± 0.02	45.70 ± 0.38	+46.40 ± 0.11	+14.12 ± 0.13	300.87 ± 4.53	108.82 ± 2.91	541.92 ± 6.68	11.16 ± 0.81	14.69 ± 0.37	259.87 ± 2.85

Microorganism	Zone of inhibition (mm)							MIC (mg/mL)
	SDRP (100 mg/mL)	SDRP (200 mg/mL)	SDRP (300 mg/mL)	SDRP (400 mg/mL)	Gentamicin (10 μg/disc)	Ampicillin (10 μg/disc)	Amphotericin B (100 μg/disc)	
Gram-negative bacteria								
Y. enterocolitica ATCC®27,729	8.20 ± 1.20e	11.85 ± 0.10d	14.60 ± 1.00c	17.10 ± 0.30b	20.88 ± 0.38a	8.50 ± 0.50e	NT	≥ 31.25
K. pneumoniae ATCC®13,883	0.00 ± 0.00d	7.10 ± 0.10c	7.35 ± 0.15c	8.90 ± 0.50b	26.50 ± 0.70a	0.00 ± 0.00	NT	≥ 125
E. coli ATCC®25,922	7.00 ± 0.10e	10.25 ± 0.05d	11.90 ± 0.40 cd	13.15 ± 0.35c	25.88 ± 1.33a	16.45 ± 0.95b	NT	≥ 62.5
C. freundii ATCC®43,864	8.85 ± 1.75c	12.05 ± 0.75b	13.60 ± 0.80b	14.80 ± 1.00b	20.63 ± 0.73a	0.00 ± 0.00d	NT	≥ 62.5
P. aeruginosa ATCC®27,853	8.55 ± 1.35c	11.05 ± 1.05bc	12.35 ± 0.75c	13.55 ± 0.95b	23.28 ± 0.83a	11.15 ± 0.75bc	NT	≥ 125
Gram-positive bacteria								
M. luteus NRRL B-1018	0.00 ± 0.00f	10.57 ± 0.90e	12.80 ± 0.70d	14.45 ± 0.15c	24.90 ± 0.20b	49.15 ± 0.25a	NT	≥ 62,5
L. monocytogenes ATCC®7644	7.05 ± 0.10e	10.75 ± 0.10d	12.25 ± 0.55c	13.55 ± 0.10b	19.61 ± 0.11a	0.00 ± 0.00f	NT	≥ 125
S. aureus ATCC®6538	0.00 ± 0.00e	9.60 ± 1.40d	11.95 ± 0.45 cd	12.75 ± 0.15c	28.50 ± 0.70b	35.45 ± 1.05a	NT	≥ 125
Fungus								
S. cerevisiae ATCC®9763	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	NT	NT	24.38 ± 0.18a	NT
C. albicans ATCC®10,231	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	NT	NT	18.65 ± 0.25a	NT

All values are expressed as mean ± SE of three replicates.
Different lowercase letters (a-f) represent significant differences between zones of inhibition in the same row ($P < .05$, Duncan's test).
[a]Ascorbic acid content; [b]Total anthocyanin content; [c]Total amount of phenolics; [d]DPPH radical scavenging activity; [e]ABTS radical scavenging activity; [f]Ferric reducing antioxidant power; NT: Not treated.

3.3. Antimicrobial activity of SDRP

The antimicrobial activity results of SDRP against selected bacterial and fungal strains are presented in Table 1 and Fig. 1. SDRP showed potential inhibitory activity against both Gram-positive and Gram-negative bacteria, but no inhibitory effect was observed on *S. cerevisiae* and *C. albicans* fungi at all concentrations tested. Increasing SDRP concentration resulted in larger inhibition zones on all test bacteria. SDRP exhibited maximum antibacterial activity against Gram (−) *Y. enterocolitica* (17.10 mm) and Gram (+) *M. luteus* (14.45 mm). These results are consistent with Demirbas, Yilmaz, Ildiz, Baldemir, and Ocsoy (2017), who reported that raspberry extracts were more effective on Gram-negative bacteria (*E. coli*) than Gram-positive (*S. aureus*, *B. cereus*) bacteria and no effect was observed on *C. albicans*. Inhibition zones and

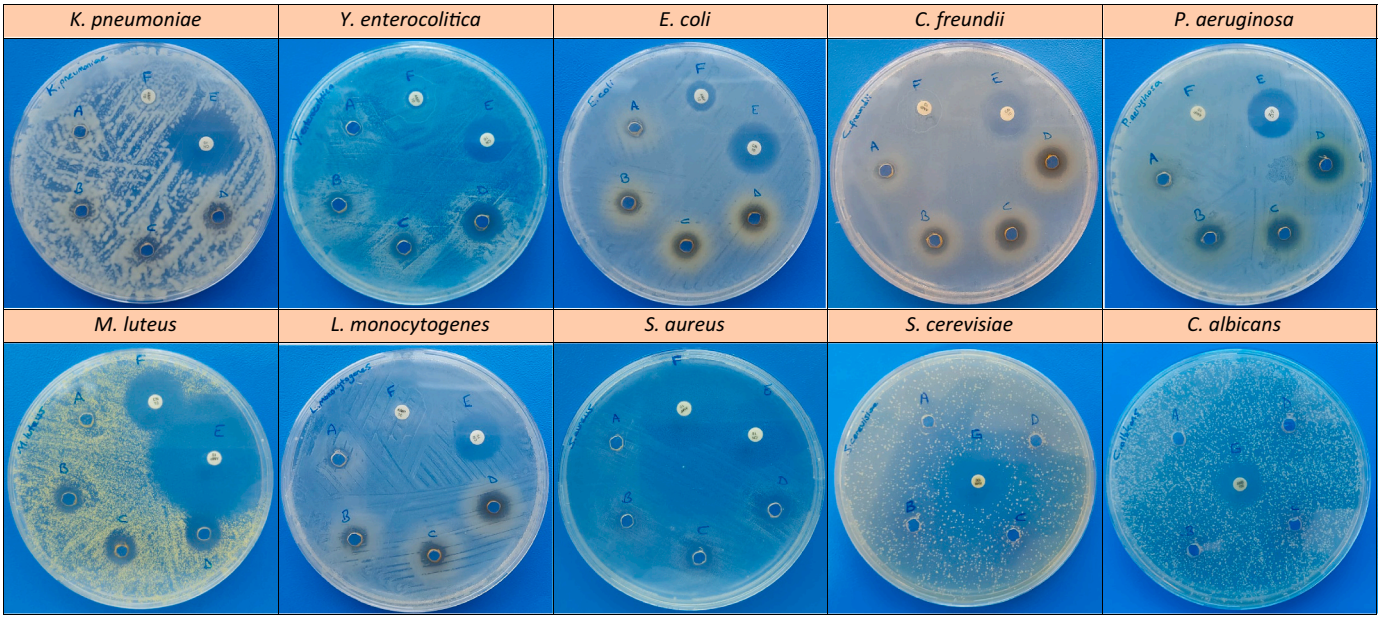

Fig. 1. Images of antibacterial and antifungal activity results of spray-dried red raspberry powders (SDRP).
(A) 100 mg/mL SDRP, (B) 200 mg/mL SDRP, (C) 300 mg/mL SDRP, (D) 400 mg/mL SDRP, (E) Ampicillin (10 μg/disc), (F) Gentamicin (10 μg/disc), (G) Amphotericin B (100 μg/disc) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

MIC values indicated that *Y. enterocolitica* was the most sensitive bacteria to the inhibition of SDRP. Similar results have been reported for black mulberry fruit and pomegranate peel extracts (Al-Zoreky, 2009; Turan & Şimşek, 2021). SDRP had a weaker ($P < .05$) inhibitory effect on the tested bacteria than gentamicin used as the reference antibiotic. On the other hand, the antibiotic ampicillin had no antibacterial effect on *K. pneumoniae* and *C. freundii*, while SDRP formed zones of inhibition on these bacteria (Table 1, Fig. 1). Previous studies have revealed that raspberry fruit extracts have antimicrobial activity on pathogenic bacteria (Demirbas et al., 2017; Nohynek et al., 2006; Vulić et al., 2014). In addition, Nohynek et al. (2006) determined the antifungal effect of lyophilized raspberry extracts on *C. albicans*. The lack of antifungal effect of SDRP on the fungi tested in the present study can be attributed to the decrease in the bioactive content of raspberry powders due to the use of carrier agents and heat treatment in the drying process. The potent antibacterial activity of raspberry phenolic extracts rich in ellagitannins and anthocyanins has been associated with outer membrane disruption, lipopolysaccharide release, increased cytoplasmic membrane permeability and induction of cell damage by demolishing cellular structures (Khoo et al., 2017; Nohynek et al., 2006; Suriyaprom et al., 2022). In addition, low pH inhibits microbial growth by damaging the membrane and leading loss of (H^+)-ATPases (Mattos, Tonon, Furtado, & Cabral, 2017), and contributes to the antimicrobial activity of berries (Suriyaprom et al., 2022). Accordingly, the bioactive component content and acidic pH of SDRP can be attributed as responsible for the antimicrobial effect. The obtained findings indicated that SDRP has strong potential to be utilized as a natural antibacterial in delaying microbial growth in foods.

3.4. pH values of SDRP-treated ground beef

SDRP treatment and storage period had a significant ($P < .01$) effect on pH values of vacuum-packed ground beef samples, but no significant interaction effect between these parameters was observed ($P > .05$). Increasing SDRP concentration gradually decreased the pH values of ground beef ($P < .05$). The greatest pH decline (from 5.57 to 5.22 on average) was found in samples treated with 3% SDRP (Table 2), and the lowest values during storage period were determined in these samples (Table 3). The acidic pH of SDRP can be expressed as responsible for this decrease. Similarly, previous studies have reported that besides the potential microbial effect, the pH of the extracts can have a significant effect on the final pH in meat products (Bouarab-Chibane et al., 2017; Martín-Mateos et al., 2022; Zamuz et al., 2018). On the other hand, mean pH values were similar ($P > .05$) up to day 9 of storage. The decreasing pH values on Day 9 increased in the following days and reached the highest value (5.45) at the end of storage ($P < .05$). A similar trend was observed in a previous study, indicating that the pH values of VP ground beef decreased up to day 8 during refrigerated storage and increased on the following days (Calderón-Oliver et al., 2020). The decrease in pH values during storage can generally be associated with the formation of lactic acid as a result of the activity of lactic acid bacteria, which is the dominant flora in meat stored under vacuum conditions. *Pseudomonas* and *Enterobacteriaceae* play a role in the increase of pH values after the 12th day of storage. Especially *Pseudomonas* are effective in spoiling fresh meat stored in refrigerator conditions due to their high proteolytic activities. As a result of microbial and enzymatic activity, formation of microbial metabolites, decomposition of proteins, and accumulation of basic components such as ammonia and amines can be associated with pH increase (Danowska-Oziewicz & Kurp, 2017; Liu et al., 2019). These results showed that the antimicrobial effect of SDRP and the pH stability of SDRP-containing groups at the end of storage delayed the spoilage of vacuum-packed ground meat.

3.5. Lipid oxidation (TBARS) values of SDRP-treated ground beef

In the present study, it was determined that the SDRP treatment ($P <$

Table 2
Main and interaction effects of SDRP treatment and storage period on pH, TBARS, instrumental color values and microbial counts of vacuum-packed ground beef samples.

	pH	TBARS	Color values					Microbial counts (log CFU/g)					
			*L**	*+a**	*+b**	*C**	*h°*	AMB	APB	*Pseudomonas*	*M/S*	*S. aureus*	*Enterobacteriaceae*
Treatment (T)													
Control	5.57^{a}	1.12^{a}	47.63^{a}	15.05^{c}	13.74^{a}	20.58^{b}	43.14^{a}	5.68^{a}	5.75^{a}	5.38^{a}	3.49^{a}	3.32^{a}	3.15^{a}
SDRP 1%	5.43^{b}	0.38^{b}	45.94^{b}	19.66^{b}	13.87^{a}	23.95^{a}	35.60^{bc}	5.22^{b}	5.15^{b}	4.92^{b}	3.27^{b}	2.94^{b}	2.55^{b}
SDRP 2%	5.34^{c}	0.28^{c}	44.86^{bc}	19.74^{ab}	14.27^{a}	24.32^{a}	36.10^{b}	4.97^{c}	4.88^{c}	4.68^{c}	3.25^{b}	2.92^{b}	2.36^{c}
SDRP 3%	5.22^{d}	0.22^{d}	43.54^{c}	20.60^{a}	13.96^{a}	24.50^{a}	34.48^{c}	4.84^{c}	4.75^{c}	4.52^{d}	3.06^{c}	2.86^{b}	2.26^{c}
SEM	0.007	0.016	0.490	0.309	0.213	0.320	0.438	0.051	0.056	0.048	0.051	0.057	0.053
P	**	**	**	**	NS	**	**	**	**	**	**	**	**
Eta Square	0.964	0.975	0.400	0.779	0.057	0.643	0.812	0.739	0.770	0.761	0.390	0.417	0.752
Storage period (days) (SP)													
0	5.38^{c}	0.13^{f}	44.10^{cd}	20.45^{a}	12.26^{c}	23.88^{b}	31.03^{e}	4.05^{f}	4.20^{e}	3.53^{f}	3.36^{b}	3.46^{a}	2.16^{c}
3	5.38^{c}	0.28^{e}	44.51^{bcd}	18.39^{b}	12.36^{c}	21.29^{c}	35.65^{cd}	3.97^{f}	3.94^{f}	3.55^{f}	3.59^{a}	3.48^{a}	2.01^{c}
6	5.37^{c}	0.28^{e}	46.79^{a}	20.67^{a}	14.09^{b}	25.09^{ab}	34.50^{d}	4.45^{e}	4.36^{e}	3.96^{e}	3.52^{ab}	2.67^{c}	2.42^{b}
9	5.35^{d}	0.42^{d}	43.98^{d}	20.31^{a}	14.98^{a}	25.20^{a}	36.85^{bc}	5.04^{d}	5.01^{d}	4.84^{d}	2.69^{d}	2.53^{cd}	2.55^{b}
12	5.38^{c}	0.49^{c}	46.30^{ab}	18.90^{b}	14.80^{ab}	24.06^{ab}	38.37^{b}	5.76^{c}	5.65^{c}	5.51^{c}	3.49^{ab}	3.01^{b}	2.55^{b}
15	5.43^{b}	0.87^{b}	46.00^{abc}	16.34^{c}	14.81^{ab}	21.95^{c}	42.61^{a}	6.12^{b}	5.93^{b}	6.07^{b}	3.07^{c}	2.36^{d}	3.16^{a}
18	5.45^{a}	1.02^{a}	46.79^{a}	16.28^{c}	14.41^{ab}	21.89^{c}	42.29^{a}	6.83^{a}	6.82^{a}	6.64^{a}	3.15^{c}	3.59^{a}	3.22^{a}
SEM	0.009	0.021	0.648	0.409	0.282	0.423	0.579	0.067	0.074	0.064	0.067	0.076	0.070
P	**	**	**	**	**	**	**	**	**	**	**	**	**
Eta Square	0.628	0.965	0.287	0.692	0.646	0.609	0.847	0.966	0.955	0.976	0.709	0.826	0.823
Interactions													
T x SP	NS	**	NS	**	*	**	**	**	**	**	NS	*	**
Eta Square	0.330	0.966	0.199	0.504	0.371	0.476	0.633	0.681	0.616	0.693	0.117	0.395	0.570

SDRP: Spray-dried raspberry powders; TBARS: Thiobarbituric acid reactive substances (mg MDA/kg); *L**: Lightness; *+a**: Redness; *+b**; Yellowness.
AMB:Aerobic mesophilic bacteria; APB: Aerobic psychrotrophic bacteria; *M / S*: *Micrococcus/Staphylococcus;* SEM: standard error of mean.
Within column, different lowercase letters (a-d) indicate significant differences ($P < .05$, Duncan's test) between treatments.
Within column, different lowercase letters (a-f) indicate significant differences ($P < .05$, Duncan's test) between storage periods.
NS: not significant ($P > .05$), * $P < .05$, ** $P < .01$.

Table 3
pH and instrumental color values of vacuum-packed ground beef samples treated with different concentrations of spray-dried raspberry powders (SDRP) during 18 days of chilled storage.

	Treatment (*T*)	Storage period (days) (*SP*)							SEM
		0	3	6	9	12	15	18	
pH	Control	5.52	5.58	5.53	5.51	5.55	5.64	5.67	0.017
	SDRP 1%	5.45	5.42	5.43	5.40	5.43	5.45	5.47	
	SDRP 2%	5.32	5.33	5.33	5.32	5.32	5.36	5.40	
	SDRP 3%	5.23	5.21	5.21	5.17	5.20	5.26	5.28	
Lightness (L)*	Control	46.46	45.11	47.96	45.84	50.06	48.54	49.43	1.297
	SDRP 1%	45.65	45.46	47.39	44.58	45.05	45.83	47.64	
	SDRP 2%	42.98	44.55	47.10	44.52	44.89	45.87	44.13	
	SDRP 3%	41.30	42.90	44.72	40.97	45.19	43.75	45.97	
Redness (+a)*	Control	19.83^{aA}	16.91^{bB}	16.59^{bB}	15.17^{bB}	15.44^{bB}	11.06^{cB}	10.36^{cB}	0.818
	SDRP 1%	21.56^{aA}	17.91^{bB}	21.41^{aA}	22.13^{aA}	19.44^{abA}	17.91^{bA}	17.29^{bA}	
	SDRP 2%	20.34^{abA}	18.39^{bB}	21.91^{aA}	21.95^{aA}	19.70^{abA}	17.77^{bA}	18.10^{bA}	
	SDRP 3%	20.06^{abcA}	20.33^{abcA}	22.77^{aA}	22.01^{abA}	21.00^{abcA}	18.64^{cA}	19.38^{bcA}	
Yellowness (+b)*	Control	12.91^{abcA}	12.61^{cA}	13.57^{abcA}	13.77^{abcA}	14.85^{aAB}	14.36^{abA}	14.11^{abcA}	0.565
	SDRP 1%	12.89^{abA}	11.88^{bA}	14.35^{aA}	14.72^{aA}	14.28^{aB}	14.65^{aA}	14.31^{aA}	
	SDRP 2%	11.91^{bAB}	12.63^{bA}	15.71^{aA}	15.73^{aA}	14.47^{aAB}	15.23^{aA}	14.22^{aA}	
	SDRP 3%	11.33^{bB}	12.32^{bA}	12.72^{bA}	15.70^{aA}	15.60^{aA}	15.01^{aA}	15.01^{aA}	
Chroma (*C**)	Control	23.70^{aA}	21.13^{bA}	21.46^{bB}	20.56^{bB}	21.50^{bB}	18.15^{cB}	17.55^{cB}	0.846
	SDRP 1%	25.14^{abA}	20.88^{cA}	25.81^{aA}	26.11^{aA}	24.13^{abA}	23.14^{abcA}	22.46^{bcA}	
	SDRP 2%	23.61^{bA}	21.95^{bA}	26.93^{aA}	27.01^{aA}	24.45^{abA}	23.29^{bA}	23.02^{bA}	
	SDRP 3%	23.07^{bcA}	21.19^{cA}	26.18^{aA}	27.12^{aA}	26.17^{aA}	23.23^{bcA}	24.54^{abA}	
Hue angle (h^o)	Control	33.38^{eA}	36.72^{deA}	39.33^{cdA}	42.36^{bcA}	44.14^{bA}	52.41^{aA}	53.66^{aA}	1.159
	SDRP 1%	30.91^{dB}	35.00^{cA}	33.70^{cdAB}	34.48^{cB}	36.36^{bcB}	39.19^{abB}	39.58^{aB}	
	SDRP 2%	30.37^{cB}	35.52^{bA}	35.74^{bA}	35.74^{bB}	36.35^{bB}	40.77^{aB}	38.16^{bB}	
	SDRP 3%	29.47^{bB}	35.36^{aA}	29.24^{bB}	34.83^{aB}	36.63^{aB}	38.08^{aB}	37.75^{aB}	

Within line, different lowercase letters (a-e) indicate significant differences ($P < .05$, Duncan's test) between storage periods for the same treatment.
Within column, different capital letters (A-B) indicate significant differences ($P < .05$, Duncan's test) between treatments for the same storage period.

.01), storage period ($P < .01$) and treatment x storage time interaction ($P < .01$) (Fig. 2) had a significant effects on lipid oxidation in vacuum packed ground meat samples (Table 2). The combination of vacuum packaging with SDRP significantly retarded lipid oxidation of ground beef compared with the VP CONTROL alone. The mean TBARS values decreased depending on the amount of SDRP added to the ground meat, and the lowest mean values were determined in the samples with 3% added (Table 2). The antioxidant potential of SDRP can be related to the phytochemical (phenolics, anthocyanins within the phenolic compounds and ascorbic acid) content and *in vitro* antioxidant ability shown in Table 1, as well as the *p*-coumaric acid, ellagitannins, and ellagic acid compounds reported for raspberry in previous studies (Chen et al., 2013; Skrovankova et al., 2015). The antioxidant properties of these highlighted compounds are due to their ability to chelate metal ions, high reactivity as electron or hydrogen donors, and stabilization/delocalization of unpaired electrons (Brewer, 2011).

As shown in Fig. 2, the treatment x storage time interaction is given, TBARS values were initially (on Day 0) similar in all treatments ($P > .05$). However, from day 3 of storage, treatment groups with SDRP had lower MDA content compared to CONTROL samples ($P < .05$). During storage, a progressive increase in TBARS values was noticed in all treatments ($P < .05$), but the increase in CONTROL samples was dramatic compared to SDRP-formulated groups. These findings were in agreement with Sadeghinejad et al. (2019) and Elhadef et al. (2020),

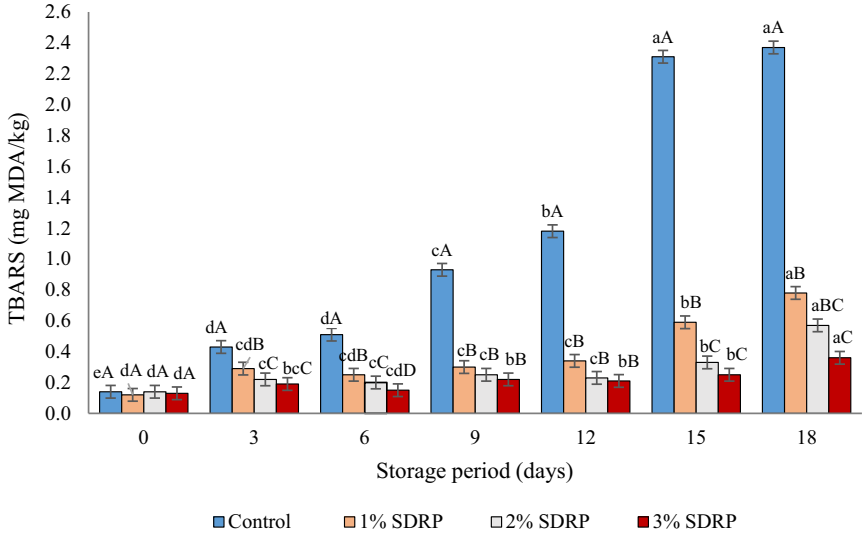

Fig. 2. TBARS values of vacuum-packed ground beef samples treated with different concentrations of SDRP during 18 days of chilled storage (SEM = 0.041). Lowercase and uppercase letters in bar graphs represent significant differences between storage days per treatment and between treatments per storage day, respectively ($P < .05$, Duncan test).

who reported that TBARS values gradually increased as the storage period progressed. At the end of storage, VP ground beef samples enriched with 1%, 2% and 3% SDRP had 67.09%, 75.95% and 84.81% lower MDA contents compared to CONTROL, respectively. Regarding all storage days, the lowest TBARS values were seen in ground beef samples treated with 3% SDRP, while non-significant ($P > .05$) changes (except on Day 6) were detected between the groups containing 2% and 3% SDRP. These results showed that SDRP has a strong effect on delaying lipid oxidation by maintaining its *in vitro* antioxidant capacity in the actual meat structure. Similar findings have been reported in some studies using antioxidant extracts and powders from natural sources such as plants, fruits and vegetables to reduce lipid oxidation in fresh meat products (Aksu & Turan, 2022; Babaoğlu et al., 2022; Elhadef et al., 2020; Kryževičūtė et al., 2017; Martín-Mateos et al., 2022). Considering the tolerable MDA threshold (1 mg/kg) for oxidative rancidity and sensory acceptability in beef (McKenna et al., 2005), the CONTROL sample was unacceptable at Day 12. In contrast, the MDA content of SDRP-containing groups were consistently within the acceptable limits during 18 days of chilled storage. On the other hand, although processes such as vacuum packaging that exclude or reduce the oxygen concentration are applied as an effective way to extend the shelf life of meat by preventing lipid oxidation (Calderón-Oliver et al., 2020; Reyes, Wagoner, et al., 2022; Rogers et al., 2014; Turan & Şimşek, 2021), it can create some problems in terms of color and adversely affect consumer preferences. When the results related to oxidation and color are evaluated together in the current study, it is understood that this negativity arising from vacuum packaging is limited with the addition of SDRP.

3.6. Instrumental color parameters of SDRP-treated ground beef

Meat color is a key factor affecting the visual appeal of consumers. Because of the decisive effect of color on meat purchasing decisions, it is important to provide the desired redness and maintain stability in fresh meat products. The reduction in redness negatively affects meat product in terms of consumer acceptance, so studies on meat color mostly focused on a^* values. Especially considering their water-soluble properties (Khoo et al., 2017), anthocyanin-rich natural extracts and powders are utilized as natural red colorants instead of synthetic or insect-based dyes in meat products (Aksu et al., 2022; Aksu & Turan, 2022; Babaoğlu et al., 2022; Baldin et al., 2016; Ekici et al., 2015). The changes in instrumental color parameters of VP ground beef samples fortified with different levels of SDRP during chilled storage are shown in Table 3. L^* values were significantly affected by SDRP treatment ($P < .01$) and storage time ($P < .01$), but no significant interaction was observed for L^* values ($P > .05$). The incorporation of SDRP into ground beef resulted in a decrease in mean lightness values compared with CONTROL ($P < .05$) (Table 2). The mean L^* values of the 1% SDRP, 2% SDRP, and 3% SDRP groups were 1.69, 2.77, and 4.09 units lower, respectively, compared to the CONTROL group. The reduced lightness may be the result of water being bound by the raspberry powders. Similarly, Martín-Mateos et al. (2022) reported that L^* values associated with water content in cherry-treated beef burgers decreased with increasing cherry concentration. A fluctuating increase in L^* values was observed during the storage period ($P < .05$). The lowest mean L^* values were detected on day 9, while L^* values at the end of storage were approximately 2,5 units higher than the initial values. Changes in L^* values during storage may be due to greater light scattering and increased lightness as a result of changes in meat structure, including protein denaturation (Chikwanha et al., 2019).

Two-way interactions between SDRP treatment and storage period were observed on a^* ($P < .01$), b^* ($P < .05$), C^* ($P < .01$) and h° ($P < .01$) values (Table 2). Regarding redness (a^*) values, initial (Day 0) values showed no difference between all treatments ($P > .05$). However, SDRP-treated groups had more stable redness from Day 6 to the end of the storage period compared to CONTROL ($P < .05$). A similar trend was observed for C^* values. In general, the greatest redness and color intensity were determined in the ground beef samples enriched with 3% SDRP, while there was no significant difference ($P > .05$) in a^* (except for Day 3) and C^* values of the SDRP-treated groups during the storage period. At the end of the storage period, a decrease in redness was observed in all treatment groups compared to initial values, but the loss of redness was significant in the CONTROL and 1% SDRP treatments ($P < .05$). The a^* values of the groups treated with 2% and 3% SDRP on the last day of storage were similar to those at initial ($P > .05$), indicating that these SDRP concentrations were more effective for maintaining the desired redness in VP ground beef. The notable reduction in a^* values of the CONTROL without SDRP indicated greater pigment oxidation in this group than the SDRP treatments. On the other hand, Eta Square values show that the effect of treatment on the a* value is greater than that of the storage period (Table 2). There was no difference between CONTROL and SDRP treatments in terms of b^* values during the storage period ($P > .05$). However, the yellowness of all treatments increased over the initial values during the storage period. A gradual increase in h° values indicating decoloration from red to yellow was observed in all groups with and without SDRP during storage ($P < .05$), but this increase was more pronounced in the CONTROL group. The highest h° values were in the CONTROL samples during storage ($P < .05$).

The decrease in a^* and C^* values and the increase in h° values can be attributed to Met-Mb formation resulting in discoloration (Faustman, Sun, Mancini, & Suman, 2010; Reyes, Wagoner, et al., 2022; Yang et al., 2016). Many factors such as temperature, pH, Met-Mb reducing activity, lipid oxidation, residual oxygen level and oxygen partial pressure are effective in oxidation of Ox-Mb, and Met-Mb formation is promoted by low oxygen partial pressure (Faustman et al., 2010). Considering that oxygen levels of 0.15–2.0% make fresh beef prone to browning (McMillin, 2008), oxidative reactions and discoloration continue even in a vacuum packaging environment with <1% residual oxygen (Smiddy et al., 2002). A recent study reported that vacuum packaging of ground beef with packaging films with different oxygen permeability caused significant changes in Deox-Mb, Met-Mb and Oxy-Mb content and instrumental color values (Reyes, Smith, et al., 2022). Accordingly, the fact that the barrier properties of the packaging material used in the present study are not sufficient to prevent O_2 leakage during storage may be responsible for the increase in discoloration towards the end of storage. In addition to oxidative reactions, microbial spoilage can also cause discoloration of meat (Pellissery et al., 2020). The existence of a strong relationship between MetMb formation, TBARS values and redness loss has been reported in previous studies (Aksu & Turan, 2021; Sadeghinejad et al., 2019). Reyes, Smith, et al. (2022) determined that the MetMb content of vacum-packaged ground beef increased approximately two-fold (from 20.81% to 41.14%) during 14 days of storage, resulting in a decrease in a^* (from 22.05 to 16.03) and C^* (from 25.86 to 21.64) values. In the present study, instrumental redness ($r = -0.821$, $P < .01$) and C^* ($r = -0.644$, $P < .01$) values were strongly negatively correlated with TBARS values, while a positive correlation was observed between h° and TBARS values ($r = 0.879$, $P < .01$, data not shown). Considering Day 12, when the oxidative rancidity threshold was exceeded for the CONTROL sample without SDRP, the a^* values of the VP ground beef samples containing 1%, 2%, and 3% SDRP were 25.91%, 27.59%, and 36.01% higher, respectively, than those of the CONTROL group. On the following days 15 and 18, treatments containing 1%, 2%, and 3% SDRP had 66.89%, 74.71%, and 87.06% higher redness values compared to CONTROL. Higher color stability as a result of reduced oxidative reactions attributed to the absence of oxygen in VP samples compared to air-permeable or modified atmosphere packaging has been reported in previous studies (Reyes, Wagoner, et al., 2022; Turan & Şimşek, 2021; Yang et al., 2016). However, the purplish-red color from Deox-Mb in VP meats is perceived as unwholesome by consumers who are known to prefer a bright cherry-red color for beef (Feuz et al., 2020; Rogers et al., 2014). (Holman, van de Ven, Mao, Coombs, & Hopkins, 2017) stated that stated that the color of beef with redness (a^*) values

below +14.5 is perceived as unacceptable by consumers. Accordingly, the CONTROL group without SDRP was unacceptable from Day 15, but the redness of all treatments with SDRP was above the critical threshold for beef acceptability.

The available findings in the present study showed that SDRP made a remarkable contribution to providing the desired color in VP ground beef and maintaining color stability during storage. In other words, SDRP retarded oxidative reactions and prevented discoloration of ground beef during chilled storage under vacuum conditions. This can be attributed to the ability of its bioactive components such as phenolics, anthocyanins and ascorbic acid to donate hydrogen, quench reactive oxygen species and chelate metals (Brewer, 2011). In addition, the color (especially the high a^* value) of the powders contributed greatly to the maintenance of redness. Similarly, Turan and Şimşek (2021) determined that the inclusion of freeze-dried black mulberry water extract in raw beef patties stored in both air-permeable and vacuum packaging significantly reduced redness loss compared to the control without extract by reducing lipid oxidation and Met-Mb formation.

3.7. Microbial quality of SDRP-treated ground beef

Aerobic mesophilic bacteria (AMB) and aerobic psychrotrophic bacteria (APB) counts were significantly affected by treatment ($P < .01$), storage period ($P < .01$) and SDRP treatment × storage period ($P < .01$) interaction. Addition of SDRP to vacuum packed ground meat decreased both AMB and APB counts, and the highest counts were determined in the control samples (Table 2). Ground processing of meat increases the risk of microbiological spoilage and chemical changes during storage (Aksu & Alp, 2012). Therefore, the addition of antimicrobials such as SDRP due to inhibit growth of spoilage microorganisms is important to extend the shelf life and to preserve the quality properties of ground meat. According to Table 4, which was given changes in microbial counts of VP ground beef samples treated with different concentrations of SDRP during chilled storage, initial AMB counts ranging from 3.80 to 4.33 log cfu/g were consistent with counts reported for ground beef in the literature (Babaoğlu et al., 2022; Calderón-Oliver et al., 2020). AMB counts decreased insignificantly ($P > .05$) on Day 3 excluding 2% SDRP treatment, but increased steadily for all treatments in the following days ($P < .05$). A similar trend was observed for APB counts. During storage, APB proliferation was noticeably weaker in SDRP-treated samples than in CONTROL ($P < .05$). The difference in APB counts of CONTROL and 3% SDRP-treated samples at Day 18 of storage is approximately 2 log cycles ($P < .05$). Although lower ($P < .05$) counts were recorded in the 2% and 3% SDRP groups at the end of storage, all groups containing SDRP had similar ($P > .05$) APB counts throughout the storage period (except Day 6). Enrichment of VP ground beef with SDRP, particularly at 2% and 3% concentrations, resulted in generally lower AMB and APB counts than CONTROL during the storage period. AMB counts of the CONTOL and 1% SDRP groups exceeded the critical level (7 log cfu/g) for microbiological spoilage on days 15 and 18 of storage, respectively. However, those of the 2% and 3% SDRP treatments were within acceptable levels during the entire storage period. These results showed that 2% and 3% concentrations of SDRP delayed microbial spoilage in VP ground beef and extended shelf life by at least 3 days compared to CONTROL. Similar results were reported for VP raw beef patties treated with freeze-dried black mulberry extract (Turan & Şimşek, 2021).

SDRP treatment, storage period and SDRP treatment × storage period interaction had a significant ($P < .01$) effect on *Pseudomonas* counts. The lowest *Pseudomonas* counts counts in all treatment groups were observed in the 3% SDRP group (Table 2). Regarding *Pseudomonas* counts, similar increase in AMB and APB counts for all treatments from day 6 was faster in the CONTROL sample than in the SDRP-containing groups. SDRP treatment of VP ground beef resulted in lower ($P < .05$) *Pseudomonas* counts than CONTROL, with 2% and 3% SDRP treatments being more effective in all days of storage (Table 4). Similar findings on the reducing effect of *Pseudomonas* counts by plant and fruit extracts in beef products stored in different atmospheric environments have been reported in previous studies (Aksu et al., 2015; Alp & Aksu, 2010; Kryževičūtė et al., 2017).

Micrococcus/Staphylococcus (*M/S*) counts were significantly affected by treatment ($P < .01$) and storage period ($P < .01$) parameters, but no significant ($P > .05$) interaction effect was observed. The mean *M / S* counts of SDRP-treated samples were lower ($P < .05$) than CONTROL, and this reduction was most pronounced in the 3% SDRP group

Table 4
Changes in microbial counts (log CFU/g) of vacuum-packed ground beef samples treated with different concentrations of spray-dried raspberry powders (SDRP) during 18 days of chilled storage.

	Treatment (T)	Storage period (days) (SP)							SEM
		0	3	6	9	12	15	18	
Aerobic mesophilic bacteria (AMB)	Control	4.33^{efA}	3.99^{fA}	4.55^{eAB}	5.19^{dA}	6.55^{cA}	7.26^{bA}	7.87^{aA}	0.134
	SDRP 1%	4.12^{fAB}	3.91^{fA}	4.72^{eA}	5.14^{dA}	5.59^{cB}	5.96^{bB}	7.07^{aB}	
	SDRP 2%	3.94^{eAB}	4.07^{deA}	4.37^{dBC}	4.95^{cA}	5.51^{bB}	5.75^{bB}	6.20^{aC}	
	SDRP 3%	3.80^{dB}	3.92^{dA}	4.18^{dC}	4.88^{cA}	5.37^{bB}	5.52^{bB}	6.17^{aC}	
Aerobic psychrotrophic bacteria (APB)	Control	4.45^{eA}	4.31^{eA}	4.72^{eA}	5.46^{dA}	6.31^{cA}	7.00^{bA}	7.99^{aA}	0.149
	SDRP 1%	4.23^{dAB}	3.71^{eB}	4.86^{cA}	4.73^{cB}	5.63^{bAB}	5.84^{bB}	7.04^{aB}	
	SDRP 2%	4.15^{dAB}	3.93^{dB}	4.01^{dB}	4.95^{cAB}	5.22^{bcB}	5.55^{bB}	6.33^{aC}	
	SDRP 3%	3.96^{dB}	3.81^{dB}	3.86^{dB}	4.90^{cAB}	5.43^{bB}	5.35^{bB}	5.92^{aC}	
Pseudomonas	Control	3.82^{efA}	3.63^{fA}	4.07^{eAB}	5.07^{dA}	6.15^{cA}	7.11^{bA}	7.77^{aA}	0.128
	SDRP 1%	3.57^{fAB}	3.74^{efA}	4.21^{deA}	4.57^{dB}	5.46^{cB}	6.11^{bB}	6.74^{aB}	
	SDRP 2%	3.47^{dAB}	3.69^{dA}	3.86^{dBC}	4.83^{cAB}	5.30^{bBC}	5.62^{abBC}	6.00^{aC}	
	SDRP 3%	3.27^{eB}	3.15^{eA}	3.69^{dC}	4.89^{cAB}	5.13^{cC}	5.43^{bC}	6.06^{aC}	
Micrococcus/Staphylococcus (M / S)	Control	3.47	3.81	3.85	3.08	3.69	3.28	3.24	0.135
	SDRP 1%	3.37	3.66	3.53	2.61	3.61	2.92	3.20	
	SDRP 2%	3.39	3.54	3.31	2.66	3.50	3.12	3.24	
	SDRP 3%	3.23	3.36	3.40	2.41	3.15	2.93	2.93	
S. aureus	Control	3.57^{bA}	3.53^{bA}	2.88^{cA}	2.95^{cA}	3.44^{bA}	2.48^{dA}	4.40^{aA}	0.152
	SDRP 1%	3.52^{aA}	3.49^{aA}	2.66^{bcA}	2.36^{cB}	3.06^{abAB}	2.38^{cA}	3.12^{abB}	
	SDRP 2%	3.48^{aA}	3.52^{aA}	2.40^{cA}	2.39^{cB}	2.94^{bAB}	2.25^{cA}	3.46^{aB}	
	SDRP 3%	3.27^{aA}	3.37^{aA}	2.74^{bA}	2.40^{bcB}	2.61^{bcB}	2.31^{cA}	3.36^{aB}	
Enterobacteriaceae	Control	2.52^{cdA}	2.05^{dA}	2.83^{bcA}	3.05^{bcA}	3.19^{bA}	4.34^{aA}	4.09^{aA}	0.140
	SDRP 1%	2.05^{cdB}	2.00^{dA}	2.27^{bcdB}	2.72^{abAB}	2.51^{bcB}	3.14^{aB}	3.19^{aB}	
	SDRP 2%	2.00^{cB}	2.00^{cA}	2.26^{cB}	2.33^{bcBC}	2.30^{bcB}	2.62^{bB}	3.03^{aB}	
	SDRP 3%	2.08^{bB}	2.00^{bA}	2.32^{abB}	2.10^{bC}	2.22^{abB}	2.53^{aB}	2.59^{aB}	

Within line, different lowercase letters (a-f) indicate significant differences ($P < .05$, Duncan's test) between storage periods for the same treatment.
Within column, different capital letters (A-C) indicate significant differences ($P < .05$, Duncan's test) between treatments for the same storage period.

(Table 2). On the other hand, 2% and 3% SDRP-added groups had similar *M / S* counts ($P > .05$). *M / S* counts fluctuated during storage and were lowest at Day 9 ($P < .05$). Although *M / S* counts increased after Day 9, they were lower than the counts at the beginning of storage on days 15 and 18 (Table 4). The mean *M / S* counts of 3.49 log cfu/g in CONTROL without SDRP were consistent with Aksu and Turan (2022), but lower than Bedir and Kuleaşan (2021).

SDRP exhibited a concentration-independent inhibitory effect on *S. aureus* growth during the storage period (Table 2). There was no difference in *S. aureus* counts up to day 9 between the CONTROL and all SDRP treatments ($P > .05$). At Day 9, *S. aureus* counts in the CONTROL were higher ($P < .05$) than in SDRP-containing groups with similar counts among themselves (Table 4). On the other hand, *S. aureus* counts generally decreased by day 15, similar to Yu et al. (2020) who reported that *S. aureus* growth in vacuum skin-packed beef was reduced during refrigerated storage. However, an increase was observed on day 18, with the highest ($P < .05$) counts recorded for CONTROL compared to SDRP treatments. Based on initial counts, the *S. aureus* counts determined at the end of storage were significant only for the CONTROL group, with counts approximately 1 log units higher. Similar observations have been reported that pistachio green hull water extract significantly reduced the growth of *S. aureus* in beef patties during chilled storage (Sadeghinejad et al., 2019).

The presence of *Enterobacteriaceae* is an important indicator to evaluate the general hygienic condition of meat products, and their growth is high under vacuum conditions. In this study, the highest *Enterobacteriaceae* counts were in the CONTROL samples and the lowest in the samples with 2% and 3% SDRP treatments ($P < .05$). Storage period and SDRP treatment × storage period interaction had very significant effects ($P < .01$) on the *Enterobacteriaceae* counts (Table 2). Incorporation of SDRP into VP ground beef resulted in lower ($P < .05$) *Enterobacteriaceae* enumerations during storage (except Day 3). The beneficial effect of treatment with SDRP on the proliferation of *Enterobacteriaceae* was quite evident with differences up to 1.81 log cycles (Day 15) compared to CONTROL samples (Table 4). The *Enterobacteriaceae* count of all treatments with and without SDRP increased significantly ($P < .05$) in the storage period after Day 3, this increase was more pronounced in the CONTROL. Overall, the lowest *Enterobacteriaceae* counts during storage were counted in the 3% SDRP treatments, but the difference between SDRP treatments was only significant ($P < .05$) at Day 9 (Table 4). Consistent with our findings, previous studies have indicated the antimicrobial effect of various natural extracts on *Enterobacteriaceae* in fresh meat products (Aksu & Turan, 2022; Elhadef et al., 2020).

Microbial spoilage in raw meats during chilled storage is mainly caused by psychrotrophic lactic acid bacteria, *B. thermosphacta*, *Pseudomonas, Carnobacterium*, *Clostridium* and *Enterobacteriaceae* species (Doulgeraki, Ercolini, Villani, & Nychas, 2012). Vacuum packaging film acts as a barrier between the outer and microenvironments, minimizing oxygen diffusion to the meat. Although vacuum packaging limits the proliferation of aerobic microorganisms, facultative and obligate anaerobes can survive in this environment, leading to meat spoilage as the predominant microflora (Pellissery et al., 2020). Microbial enumerations in the present study showed that the antimicrobial properties of SDRP, as revealed by zones of inhibition and MIC values on the tested bacteria (Table 1), were also reflected in the VP ground beef during chilled storage. The antimicrobial potential offered by SDRP in the present study can be attributed to possible mechanisms associated with the presence of bioactive compounds and acidic pH, as described in Section 3.3.

4. Conclusions

SDRP had antioxidant, antimicrobial and coloring properties related to its rich bioactive content, and these properties provided substantial advantages in providing the desired color as well as oxidative and microbial stability in VP ground beef. The incorporation of SDRP into VP ground beef contributed substantially to the prevention of discoloration and extending shelf life by delaying oxidative and microbial deterioration and maintaining redness during storage. Regardless of the extract level, SDRP-containing groups displayed a redder and more stable color over the entire storage period compared with CONTROL. On the other hand, the addition of SDRP reduced microbial counts in VP ground beef meat effectively. Considering AMB counts and redness thresholds, SDRP had the potential to extend the shelf life of VP ground beef by at least 3 days compared to CONTROL and by at least 6 days based on oxidative rancidity. In general, the most promising results were obtained with SDRP concentrations of 2% and 3%. More importantly, SDRP could be a good option to overcome the perception of discoloration misinterpreted by consumers in fresh meat stored under limited oxygen conditions such as vacuum-packaging. Therefore, future studies with detailed sensory testing are needed to evaluate consumer acceptability of VP fresh meat products fortified with SDRP.

Author statement

The paper has not been published, nor is under consideration for publication or in press elsewhere.

CRediT authorship contribution statement

Muhammet İrfan Aksu: Conceptualization, Data curation, Methodology, Investigation, Funding acquisition, Project administration, Writing – review & editing. **Emre Turan:** Resources, Visualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Aysel Gülbandılar:** Formal analysis, Methodology. **Faruk Tamtürk:** Formal analysis, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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