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Evaluation of fibrous feed ingredients alternatives to oat hulls as a source of feed structure in broiler diets

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ABSTRACT This study aimed to evaluate several fibrous feed ingredients as potential substitutes for oat hulls (**OH**), assessing their efficacy in providing structural integrity to broiler feeds. A total of 4,160 day-old male Ross-308 broilers were allocated to eight dietary treatments, including a control group (**CON**) without additional fiber supplementation and 7 diets where 3% of the wheat content was replaced by either OH, soy hulls (**SH**), beet pulp (**BP**), carob bean (**CB**), wheat straw (**WS**), rice hulls (**RH**), or wheat bran (**WB**). The experimental design followed a complete randomized block design with 10 pens per treatment and 52 birds each. Growth performance and gut development indices were monitored, and the coefficients of total tract apparent retention (**CTTAR**) of nutrients were measured at 28 d. The OH improved feed conversion ratio (**FCR**) during the entire growth period (1−36 d) compared to the CON, SH, CB, WS, RH, and WB ($P < 0.05$). Conversely, BP diets reduced the final BW and ADFI compared to OH ($P < 0.05$) but were not different from the CON ($P > 0.05$). However, the FCR in birds fed with BP was similar to OH but lower than the CON group. In addition, BP-fed birds had higher CTTAR of ether extract and non-starch polysaccharides and relative weight of empty proventriculus and gizzard to BW at 14 and 28 d compared to CON. The WS, RH, and WB yielded similar final BW to OH and CON but higher FCR ($P < 0.05$). The CB, on the other hand, resulted in the highest FCR when contrasted with the other substitutes and CON ($P < 0.05$). Finding an alternative to OH with comparable benefits remains a challenge, with WS, RH, and WB showing similar final BW but inferior FCR to OH, and BP showing similar FCR but lower BW and ADFI.

Key words: fibrous feed ingredient, feed structure, alternative to oat hull, broiler

2024 Poultry Science 103:104297
https://doi.org/10.1016/j.psj.2024.104297

INTRODUCTION

In modern broiler production, approximately 70% of total production costs are attributed to feed (Waller, 2007). The primary portion of these costs is linked to the feed ingredients used in diet formulation (Abdollahi et al., 2013). Consequently, nutritionists have invested considerable effort in exploring more economical alternatives for feed ingredients to enhance productivity while reducing costs.

The adoption of pelleting technology has led to increased voluntary feed consumption by birds, minimizing feed wastage and resulting in improved feed efficiency and decreased costs (Mateos et al., 2012). Pellet quality has become a paramount concern for feed compounders, often addressed through fine grinding strategies to reduce the size of feed particles in pellets (Mateos et al., 2012). This trend highlights the prevalent use of finely ground pelleted feeds in the broiler industry over recent decades.

Traditionally, fine grinding is believed to enhance substrate availability for enzymatic digestion. However, recent studies suggest improved animal performance and feed efficiency with coarse grinding or non-ground fibrous feeds (Amerah et al., 2007). The use of fibrous feed ingredients is a widely adopted strategy to address the deficiency of coarse particles in pelleted feeds, resulting in enhanced feed efficiency and nutrient digestibility (Svihus and Hetland, 2001; Hetland et al., 2002; Hetland et al., 2003; Garçon et al., 2023). The improved performance is attributed to the better grinding activity of the gizzard (Amerah et al., 2007; Abdollahi et al., 2011) and increased production of pepsin and pancreatic enzymes (Svihus,

Received June 29, 2024.
Accepted September 3, 2024.

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2011), contributing to improved starch digestibility (Svihus and Hetland, 2001).

Increased digestibility in birds with well-developed gizzards may compensate for diet dilution when hulls partially replace cereals. Therefore, with a competitive price, cereal hull supplementation could potentially reduce feeding costs. Broilers exhibit the ability to tolerate substantial dilutions of large coarse fiber, up to 15%, displaying improved feed conversion without adverse effects on growth (Sacranie et al., 2012). This resilience underscores their capacity to handle significant coarse fiber dilutions, reinforcing the potential for enhanced feed efficiency in response to strategies such as cereal hull supplementation.

Svihus (2011) proposed that feed particles should exceed 1 mm in size to adequately stimulate gizzard development. Supplementing broiler feeds with various fibrous sources has demonstrated enhanced performance, particularly when using oat hulls (**OH**) compared to other fiber sources such as beet pulp (**BP**) or soy hulls (**SH**) (González-Alvarado et al., 2008; Jiménez-Moreno et al., 2010; Jiménez-Moreno et al., 2011).

While moderate amounts of coarse fibers may contribute to improved broiler performance, the heterogeneous response when supplementing broiler diets with different fiber sources can be attributed to the varied physicochemical characteristics of each source. Thus, not all fiber sources are likely to yield the desired effects in broilers, with certain feed ingredients proving more beneficial than others. Several studies have emphasized OH as a superior fiber source for broiler diets (González-Alvarado et al., 2008; Jiménez-Moreno et al., 2010; Jiménez-Moreno et al., 2011). However, economic and geographical considerations influence the suitability of applying OH. Therefore, this study aims to assess various fibrous feed ingredients as potential alternatives to OH, examining their ability to provide adequate structure to broiler feeds.

MATERIALS AND METHODS

All experimental procedures in this study received approval from the Animal Ethics Committee of the Poultry Research Centre (Trouw Nutrition R&D), complying with Spanish guidelines for the care and use of animals in research (Boletín Oficial del Estado, 2013).

Housing and Management

A total of 4,160 one-day-old male Ross-308 broilers were housed in 80 collective pens (52 chicks per pen, dimensions 2.5 m × 1.6 m; 10 replicates per treatment), evenly distributed across 2 identical rooms at the Trouw Nutrition Poultry Research Centre (El Viso de San Juan, Toledo, Spain). Both rooms were equipped with artificial lighting and an automatic environmentally controlled system for ventilation and temperature maintenance. The arrangement of pens within each room served as the blocking factor, with 10 established blocks (5 blocks per room).

Each pen featured wood shavings litter, a water line with 4 nipples, and a circular feeding hopper. Treatments were randomly assigned to pens within each block. Room temperatures were maintained at 32°C for the initial 2 d, gradually decreasing with age and reaching 20°C by 36 d. The lighting program included 24 h of light for the first 3 d, followed by 16 h of light and 8 h of darkness for the remainder of the experiment. Throughout the entire experimental period, chicks had free access to both feed and water.

Experimental Design and Diets

The study was conducted as a randomized complete block design with eight dietary treatments. These included a control treatment with no additional fiber supplementation (**CON**) and 7 diets where 30 g/kg of the wheat used in the CON diet was replaced by 1 fibrous feedstuff. The fibrous feed ingredients tested were OH, SH, BP, carob bean (**CB**), wheat straw (**WS**), rice hulls (**RH**), and wheat bran (**WB**).

These feed ingredients were sourced from different suppliers: OH and WS from Nanta (Zaragoza, Spain), SH from Farratges Nabau S.L. (Lleida, Spain), CB from Pedro Pérez Martínez S.L. (Valencia, Spain), BP from Secorcio (Valladolid, Spain), RH from Arrocerías Herba S.A. (Valencia, Spain), and WB from Campotrigal (Toledo, Spain). Most of these materials represent by-products with residual value for the food industry, chosen for their relatively lower cost compared to wheat grain and their particle size larger than 1 mm, promoting gizzard development (Svihus and Zimonja, 2011). The physical and chemical characteristics of the feed ingredients are presented in Table 1.

The birds underwent a 3-phase feeding program: the starter phase from 0 to 14 d, the grower phase from 14 to 28 d, and the finisher phase from 28 to 36 d. For each feeding phase, the CON diet was formulated to meet or exceed the nutritional recommendations for chickens of that age, based on the CVB (1999a,b). The grinding process was performed using a hammer mill at 1,500 rpm with a screen size of 2.5 mm. All diets were pelleted using a 3 mm pellet die with an effective thickness of 70 mm, with the conditioning temperature set at 60°C and the pelleting temperature at 80°C. Starter feeds were produced as crumbles using a 3 mm pellet die with an effective thickness of 70 mm, cutting pellets to 4 mm in length.

Growth Performance

Growth performance traits were evaluated using 52, 45, and 44 birds per pen for the starter, grower, and finisher phases, respectively. A schematic overview of activities in the study is shown in Supplementary Figure 1. The BW of birds and feed disappearance were collectively determined per pen at 14, 28, and 36 d, with

Table 1. Feed formulation and nutritional composition of the control diets of each feeding phase (experimental diets replaced 3% of wheat by the corresponding test fibrous feed ingredients).

Ingredient, %	Starter (0−14 d)	Grower (14−28 d)	Finisher (28−36 d)
Wheat	40.00	45.00	50.00
Soybean meal	32.82	26.53	18.54
Corn	15.85	18.97	16.28
Soybean oil	6.34	6.08	6.17
Soybean protein	–	–	5.26
Corn gluten meal	0.95	0.70	1.43
Monocalcium phosphate	1.21	0.47	0.28
Calcium carbonate	1.12	0.50	0.59
Sodium bicarbonate	0.26	0.24	0.19
Sodium chloride	0.17	0.16	0.19
Premix[1]	0.50	0.50	0.50
L-Lysine	0.24	0.27	0.18
DL-Methionine	0.24	0.23	0.17
L-Threonine	0.05	0.08	0.02
L-Valine	–	0.03	–
NSPase, Axtra XB[2]	0.10	0.10	0.10
Phytase, Phyzyme XP[2]	0.10	0.10	0.10
Coccidiostats, Maxiban[3]	0.06	–	–
Coccidiostats, Elancoban[3]	–	0.05	–
Calculated composition			
AMEn broiler Kcal/kg	2850	2946	3237
Crude Protein	209.7	186.3	190.0
SID Lys	11.50	10.30	9.80
SID Met	5.16	4.80	4.37
SID M+C	8.10	7.50	7.20
SID Thre	6.90	6.40	6.10
SID Trp	2.27	1.99	2.01
Crude Fiber	29.49	28.33	27.55
Crude Fat	83.76	81.20	80.34
Non-starch polysaccharides	151.3	148.5	145.5
Ash	57.54	42.05	40.03
Calcium	9.00	5.1	5
Digestible phosphorous, poultry	4.60	3.2	2.9

[1]Added per kg of final feed: 10,000 IU, vitamin A (trans-retinyl acetate); 2,500 IU, vitamin D3 (cholecalciferol); 50 IU, vitamin E (all-rac-tocopheryl-acetate); 2.0 mg, vitamin B1 (thiamine mononitrate); 6 mg, vitamin B2 (riboflavin); 40 mg, vitamin B3 (niacin); 4.0 mg, vitamin B6 (pyridoxine HCl); 25 μg, vitamin B12 (cyanocobalamin); 2.0 mg, vitamin K3 (bisulfate menadione complex); 10 mg, pantothenic acid (d-Ca pantothenate); 1.0 mg, folic acid; 300 mg, choline (choline chloride); 150 mcg, d-biotin; 0.25 mg, Se (Na2SeO3);1.0 mg, I (KI); 15 mg, Cu (CuSO4·5H2O); 65 mg, Fe (FeCO3); 90 mg, Mn (MnO2); 80 mg, Zn (ZnO); 2.25 mg/kg, butylated hydroxyanisole; 11.25 mg/kg, butylated hydroxytoluene.
[2]Danisco Animal Nutrition, Marlborough, UK.
[3]Elanco, Indianapolis, Indiana.

averages calculated based on the number of chickens present. From these data, the ADG and FCR, corrected for mortality, were calculated for each feeding period and cumulatively for the entire cycle. Subsequently, individual ADFI was determined for each feeding phase and the overall period, based on the ADG and FCR calculations.

Coefficient of Total Tract Apparent Retention

At the conclusion of the starter phase (i.e., 14 d), 6 birds (501 ± 18.4 g) from each experimental unit were selected and allocated to 6 consecutive individual digestibility cages, equipped with water nipples and feeding troughs. Each set of 6 consecutive cages shared the same excreta collection tray, representing one experimental unit. Once transferred, chickens were given a 7 d acclimatization period to individual cages. After reaching 22 d, excreta were collected over 3 consecutive days from each experimental unit. On each collection day, feathers or feed spillages in the trays were removed, and excreta were thoroughly mixed before obtaining a composite sample (approximately 100 g). Pooled excreta were stored at -20°C after completing the digestibility assay. Excreta samples were dried at 70°C for 48 h, then blended and ground through a 0.75 mm sieve (ZM 200 Ultra Centrifugal Mill, Retsch GmbH & Co. KG, Haan, Germany). Subsequently, the samples were stored in plastic containers until analysis.

Excreta samples were analyzed for titanium, starch, nitrogen, ether extract, ash and gross energy to determine the AME, and coefficient of total tract apparent retention (**CTTAR**) for DM, CP (without correction for uric acid in excreta), ether extract, ash, non-starch polysaccharides (**NSP**), and starch. The AME was corrected to zero nitrogen balance, AMEn, according to Hill and Anderson (1958).

For the CTTAR assessment, only a selection of fibrous feed ingredients was chosen based on their global availability as by-products and the performance results obtained in the study. Therefore, excreta samples associated with the CON, OH, BP, and RH were used. After relocating birds to the digestibility room, they received the grower diets with the corresponding fibrous feedstuff (OH, BP, or RH), with the addition of 5 g/kg TiO_2, thoroughly mixed and pelleted to facilitate nutrient digestibility determination.

Passage Rate

At 25 d, 3 birds (out of the 6 birds used for the digestibility assessment) per experimental unit were chosen to determine digesta passage rate. Gelatin capsules containing ferric oxide (Fe_2O_3 200 mg/kg live-weight) were orally administered into esophagus (at least 4 cm deep) following the method described by Iskander and Pym (1987). Excreta trays were examined for signs of red coloration in voided droppings. The whole-tract transit time for each chicken was calculated as the duration (in minutes) from the administration of ferric oxide in a gelatin capsule to the first observation of red coloration in the droppings.

Gizzard and Proventriculus Development

At the conclusion of each feeding phase (i.e., 14, 28, and 36 d), one bird per pen, falling within the ±5% range relative to the average BW in the pen, was selected, weighed, and euthanized by cervical dislocation. The empty weight of the proventriculus and gizzard was determined in absolute grams and expressed relative to BW. This measurement served as an indicator of gizzard development, following established procedures (Barnes et al., 2001).

Digesta Viscosity

On 28 d, the ileum was dissected from the same birds used for proventriculus and gizzard weight determination. Digesta contents from the ileum were collected by gentle squeezing and stored in plastic tubes. Subsequently, the digesta contents were centrifuged at 4,500 rpm 10,000 *g* for 10 min. The supernatant was then collected for measurement of viscosity using a digital viscometer (DV-II +, Brookfield, Stoughton, MA), following the method outlined by Langhout et al. (2000). The water retention of the sediment fraction in digesta was assessed in accordance with the method described by Tan et al. (2017). The difference in weight between the tube with and without the supernatant was determined as an indication of water retention in the digest.

Chemical Analyses

Samples of fibrous feedstuff by-products under evaluation, experimental diets, and excreta underwent comprehensive analyses following AOAC International 18th edition (2005) guidelines. The analyses included determining DM content by oven-drying (method 934.01), total ash (method 942.05), nitrogen by combustion (method 990.03) using a LECO analyzer, and ether extract (method 960.39). Starch content was determined by the α-amylase glucosidase method (method 996.11), while crude fiber was analyzed through sequential extraction with diluted acid and alkali (method 962.09). Total, soluble, and insoluble NSP and their constituent sugars were assessed following the method described by Bach Knudsen (1997), with modifications for treating polysaccharides in ST-free residues.

Additionally, fibrous feed ingredients and feed samples were analyzed for neutral detergent fiber, acid detergent fiber, and acid detergent lignin using a Fibertec System M-1020 lab equipment based on the analytical procedures of Van Soest et al. (1991). Gross energy values were determined in feed and excreta samples using a Parr 6100 adiabatic bomb calorimeter (Parr Instrument Company, Moline, IL). Titanium, originating from the TiO2 marker, was determined by spectrophotometry in feed and excreta post hydrolysis according to Short et al. (1996).

To assess the physical properties of the feedstuff feed ingredients underwent a grinding procedure. The grinding procedure involved a coffee grinder in which 10 g of sample was ground for 30 seconds (2 periods of 15 s). Samples for fibrous feed ingredients were taken before and after grinding for feed particle size determination (ANSI/ASAE) based on dry-sieving methods.

The reduction in feed particle size, measured as geometric mean diameter and the percentage of coarse and fine particles between the original and the ground sample, provided insights into the resulting coarseness of the test materials after the manufacturing process. Additionally, samples of complete pelleted experimental diets were taken to assess their feed particle size using a wet-sieving method according to Amerah et al. (2007a). Briefly, 100 *g* of the feed sample were soaked in water and stirred for 30 min, then passed through sieves connected to running water at a flow rate of 2.5 liters per minute for 3 min. The retained samples were collected from all the sieves, oven-dried overnight at 103°C, and then weighed.

Statistical Analysis

The CTTAR for each of the evaluated nutrients and the AMEn content of the experimental diets were calculated based on the method described by Hill and Anderson (1958). Performance parameters measured in this study were analyzed using the PROC GLM procedures of SAS 9.3 (SAS Institute, 2017) for each feeding period, with the pen as the experimental unit and block as a random effect. Multiple mean comparisons were performed using Tukey tests, and statistical significance was established at $P < 0.05$. Digestibility data were analyzed only for 4 dietary treatments (CON, OH, BP, and RH) following the same procedure used for the performance parameters but using 6 consecutive individual cages as the experimental unit.

RESULTS

Fibrous Feed Ingredients Characteristics

The DM contents of all fibrous feed ingredients exceeded 900 g/kg, with WS exhibiting the highest DM content and CB the lowest (Table 2). The CP levels

Table 2. Chemical composition of the tested fibrous feed ingredients, g/kg.

Items	Oat Hulls	Soybean hulls	Carob bean	Beet pulp	Wheat straw	Rice hulls	Wheat bran
Dry matter	931.4	926.1	920.8	940.3	943.5	938.6	924.1
Crude protein[1]	27.2	117.5	38.1	78.8	36.9	23.8	147.1
Ash	41.7	49.3	29.5	64.9	63.3	142.2	53.9
Crude fiber	323.9	192.9	365.5	514.7	365.5	514.7	101
Starch	89.5	1.7	5.0	0.5	7.3	16.0	147.9
Neutral detergent fiber	710.5	593.7	319.8	465.7	710.5	730	475.4
Acid detergent fiber	432.1	434.8	236	260.5	446.3	704.5	120.9
Acid detergent fiber corrected by ash	407.7	434.2	236.9	240.9	424.9	576.2	126.8
Acid detergent lignin	89.2	38.2	130.1	22.3	63	205.7	37.7
Ether extract	11.5	27	3.0	4.5	15.5	3.0	25.5
Soluble non-starch polysaccharides	52.7	138.6	30.7	241.1	23.8	14.1	67.7
Insoluble non-starch polysaccharides	572.8	496.6	78.0	365.7	532.4	476.8	420.3
Soluble non-starch: Insoluble non-starch polysaccharides	0.09	0.28	0.39	0.66	0.04	0.03	0.16
Total non-starch polysaccharides	625.5	635.3	108.7	606.9	556.1	490.9	488.1
Uronic Acid	13.6	107.5	29.7	167.9	25.0	15.4	15.5
Rhamnose	1.6	6.9	1.3	9.8	1.9	1.7	1.4
Fucose	0.0	3.2	0.0	1.4	0.0	0.0	0.0
Arabinose	29.9	46.5	8.9	169.5	30.4	17.9	80.1
Xylose	198.7	66.4	12.5	10.5	178.5	123.0	128.4
Mannose	0.0	52.4	5.9	9.3	0.0	0.0	2.2
Galactose	9.2	27.8	7.2	48.1	8.7	8.1	6.8
Glucose	372.7	324.6	43.2	190.3	311.6	324.8	253.6

[1]Dumas method, total combustion.

varied, with WB having the highest CP content and RH the lowest. RH also stood out for having the highest ash content, while CB had the lowest. The greatest differences among the measured nutrients were in starch content, where BP had the lowest and WB had the highest. Concerning fiber content, RH and BP had the highest crude fiber content, whereas WB had the lowest. The RH had the highest content of acid detergent fiber, neutral detergent fiber, acid detergent fiber corrected by ash, and acid detergent lignin among the fibrous feed ingredients. The CB had the lowest neutral detergent fiber, WB had the lowest acid detergent fiber, and acid detergent fiber corrected by ash, and BP had the lowest acid detergent lignin. Ether extract levels varied, with CB and RH having the lowest, and SH having the highest ether extract level.

The analysis of NSP across various fibrous feed ingredients revealed discrepancies in both soluble and insoluble fractions (Table 2). BP exhibited the highest levels of soluble NSP (241.1 g/kg), followed by SH (138.6 g/kg), whereas RH and WS displayed the lowest soluble NSP concentrations, registering 14.1 and 23.8 g/kg, respectively. Regarding insoluble NSP, OH and WS recorded the highest levels at 572.8 and 532.4 g/kg, respectively, with CB showing the lowest value at 78.0 g/kg.

The profile of monosaccharides exhibited variations in uronic acid, arabinose, xylose, mannose, galactose, and glucose across the feed ingredients. Glucose predominated as the main monosaccharide. BP and SH showcased the highest uronic acid content at 167.9 and 107.5 g/kg, respectively, whereas other ingredients exhibited values below 30.0 g/kg. Arabinose content peaked in BP at 169.5 g/kg, followed by 80.1 g/kg in WB, with other fibrous feed ingredients registering values lower than 50 g/kg. Xylose content was notably high in OH at 198.7 g/kg, followed by 178.5 g/kg in WB, whereas CB and BP displayed the lowest concentrations at 12.5 and 10.5 g/kg, respectively. SH recorded the highest mannose content at 52.4 g/kg, whereas BP, CB, and WB contained 9.3, 5.9, and 2.2 g/kg, respectively, with the remaining feed ingredients devoid of mannose. Galactose content was highest in BP (48.1 g/kg), followed by SH (27.8 g/kg), with other fibrous feed ingredients exhibiting values below 10 g/kg.

The results of geometric mean diameter, the percentage of particles size of the fibrous feed ingredients are shown in Table 3. Initially, all fibrous feed ingredients had a geometric mean diameter above 1,000 μm, with CB having the highest (3,434 μm) and SB the lowest (1,061 μm), while the rest exhibited intermediate values (1,562−2,176 μm). This was consistent with the presence of particles coarser than 2,000 μm but inversely related to the presence of fine particles (710−1,400 μm) in the original feedstuff presentation.

After grinding, the resultant geometric mean diameter and coarseness shifted in ranking compared to the original material. CB exhibited the lowest geometric mean diameter (390 μm), while OH had the highest (760 μm), indicating variations in the capacity of feedstuff to preserve particle size. The reduction in geometric mean diameter relative to the original material ranked as follows: CB (89%), WS (74%), BP (71%), RH (62%), SH (59%), WB (58%), and OH (57%).

Feed Characteristics

Nutritional composition analysis and wet sieving was conducted on all the experimental feeds examined in this study, as detailed in Table 4. Overall, the geometric mean diameter exhibited relatively similar characteristics between treatments within each feeding phase. The geometric mean diameter ranged from 448 to 474 μm for the starter phase, 421 to 480 μm for the grower phase,

Table 3. The geometric mean diameter and percentage of particles of tested fibrous feed ingredients (assessed by dry sieving) before and after grinding.[1]

Items	Oat hulls	Soybean Hulls	Carob bean	Beet pulp	Wheat straw	Rice hulls	Wheat bran
Geometric mean diameter, μm							
Original	1787	1061	3434	2176	2007	1805	1562
Ground	760	437	390	630	526	683	659
Geometric standard deviation, μm							
Original	1.9	2.1	1.7	1.6	2.7	1.8	1.6
Ground	2.0	1.7	1.9	2.0	2.0	1.8	1.9
Percentage of particles, %							
≥2,000 μm[2]							
Original	58.9	20.6	90.6	65.7	56.7	54.6	30.7
Ground	8.0	0.2	3.4	2.7	0.7	0.8	0.4
1,400−2,000 μm[3]							
Original	19.6	21.4	4.5	21.0	11.5	19.2	37.9
Ground	17.4	0.7	3.0	12.7	11.2	11.1	10.3
710−1,400 μm[4]							
Original	11.7	30.4	2.6	10.0	14.2	18.4	27.7
Ground	28.7	17.9	12.8	32.5	23.7	40.7	42.0

[1]Samples were analyzed in duplicate.
[2]Percentage of feed particles equal or coarser than 2,000 μm.
[3]Percentage of feed particles equal or coarser than 1400 μm but finer than 2,000 μm.
[4]Percentage of feed particles equal or coarser than 710 μm but finer than 1,400 μm.

Table 4. The nutritional composition and physical characteristics in the final pelleted diets determined by wet sieving for each of the 3 feeding phases.[1]

Items	Control	Oat hulls	Soybean hulls	Carob bean	Beet pulp	Wheat straw	Rice hulls	Wheat bran
Starter (0-14 d)								
Protein[2], g/kg	209.5	214.6	213.4	213.4	214.5	214.3	209.4	217.6
Ash. g/kg	56.1	58.3	57.6	58.1	58.5	59.5	61.4	59.5
Crude fiber, g/kg	132.8	136.5	135.5	135.7	136.5	136.9	135.4	138.6
GMD[3], μm	454	462	449	476	467	475	456	458
GSD[4], μm	2	2	2	2	2	2	2	2
≥2000 μm[5], %	3.0	3.1	2.7	3.8	4.3	3.9	2.7	2.7
1,400−2,000 μm[6], %	6.8	8.7	9.2	8.6	8.2	7.7	6.8	7.7
710−1,400 μm[7], %	20.8	19.2	17.7	20.9	18.4	20.2	21.2	20.5
Grower (14−28 d)								
Protein[2], g/kg	190.6	184.9	192.7	188.0	188.3	187.0	189.4	189.9
Ash. g/kg	43.7	44.3	44.9	44.6	45.3	45.4	47.3	45.0
Crude fiber, g/kg	28.7	36.3	38.0	30.3	34.2	38.2	44.8	31.4
GMD[3], μm	429	481	433	421	458	451	459	436
GSD[4], μm	2	2	2	2	2	2	2	2
≥2,000 μm[5], %	2.1	3.7	2.2	2.3	4.0	2.0	3.6	2.0
1,400−2,000 μm[6], %	5.9	6.9	6.4	6.9	6.2	8.7	8.1	6.2
710−1,400 μm[7], %	20.1	23.4	19.7	17.0	20.2	19.2	19.2	20.3
Starch, g/kg	418.3	371.5	372.4	386.6	374.4	375.9	385.9	400.6
Soluble NSP[8], g/kg	23.6	4.5	16.6	21.9	20.3	20.0	12.7	13.4
Insoluble NSP[8], g/kg	76.3	104.3	98.2	76.9	95.0	90.4	94.2	89.5
Total NSP[8], g/kg	99.9	108.8	114.7	98.8	115.3	110.4	106.8	102.9
Uronic Acid, g/kg	10.6	9.6	13.1	11.0	14.1	10.9	9.9	11.7
Rhamnose, g/kg	0.4	0.0	0.0	0.0	1.3	1.1	0.3	0.0
Fucose, g/kg	0.3	0.0	0.0	0.0	0.4	0.0	0.4	0.6
Arabinose, g/kg	20.2	20.7	20.9	19.3	24.5	20.6	19.1	20.1
Xylose, g/kg	22.3	28.0	24.1	21.8	21.4	25.4	23.7	22.2
Mannose, g/kg	4.7	4.2	5.3	4.2	5.0	4.2	4.6	5.0
Galactose, g/kg	13.2	12.1	13.6	12.6	14.1	12.7	11.9	12.9
Glucose, g/kg	28.3	34.2	37.7	30.0	34.5	35.6	36.8	30.5
Finisher (28−36 d)								
Protein[2], g/kg	194.9	195.7	192.6	192.6	193.5	197.2	190.0	194.0
Ash. g/kg	42.7	42.7	42.7	41.9	43.5	43.1	45.8	43.1
Crude fiber, g/kg	31.0	35.3	38.2	30.3	33.2	37.7	42.1	30.8
GMD[3], μm	438	444	447	490	511	437	470	441
GSD[4], μm	2	2	2	2	2	2	2	2
≥2,000 μm[5], %	2.1	2.1	2.8	4.2	5.0	2.6	2.3	2.0
1,400−2,000 μm[6], %	5.6	7.1	5.7	5.9	8.9	5.6	6.1	5.7
710−1,400 μm[7], %	20.6	18.8	20.2	23.7	22.1	18.8	24.3	21.8

[1]Samples were analyzed in duplicate.
[2]Dumas method, total combustion.
[3]Geometric mean diameter of feed particles in pelleted feeds determined by wet sieving (ANSI/ASAE, 2008).
[4]Log SD of feed particles in pelleted feeds determined by wet sieving.
[5]Percentage of feed particles equal or coarser than 2,000 μm.
[6]Percentage of feed particles equal or coarser than 1400 μm but finer than 2,000 μm.
[7]Percentage of feed particles equal or coarser than 710 μm but finer than 1400 μm.
[8]Non-starch polysaccharides.

Table 5. The effect of fibrous feed ingredients on the growth performance of Ross 308 male birds.

Items	Starter (0–14 d)			Grower (14–28 d)			Finisher (28–36 d)			Overall (0–36 d)		
	ADG[1], g	ADFI[2], g	FCR[3], g/g	ADG[1], g	ADFI[2], g	FCR[3], g/g	ADG[1], g	ADFI[2], g	FCR[3], g/g	BW[4], g	ADFI[2], g	FCR[3], g/g
Control	32.7[ab]	39.9[a]	1.221[ab]	97.0[ab]	137.2[a]	1.414[bcd]	126.0	204.5	1.623[ab]	2,858[abc]	118.7[a]	1.520[bc]
Oat hulls	33.4[a]	39.8[a]	1.193[d]	98.4[a]	138.8[a]	1.410[cd]	127.1	205.4	1.616[b]	2,898[a]	119.3[a]	1.506[d]
Soybean Hulls	32.9[ab]	39.4[a]	1.198[d]	97.4[ab]	139.5[a]	1.433[ab]	125.9	207.9	1.656[a]	2,869[ab]	120.2[a]	1.529[ab]
Carob bean	32.0[b]	39.2[a]	1.225[a]	95.4[bc]	137.7[a]	1.443[a]	125.2	207.1	1.654[a]	2,827[bc]	119.2[a]	1.543[a]
Beet pulp	30.6[c]	37.2[b]	1.220[abc]	94.1[c]	132.5[b]	1.408[d]	126.3	204.5	1.619[b]	2,799[c]	115.7[b]	1.513[cd]
Wheat straw	32.8[ab]	39.5[a]	1.204[cd]	96.7[abc]	138.0[a]	1.428[abc]	126.5	205.3	1.630[ab]	2,874[ab]	119.1[a]	1.520[bc]
Rice hulls	33.2[ab]	39.8[a]	1.199[d]	96.7[abc]	138.3[a]	1.429[ab]	128.3	210.1	1.638[ab]	2,888[ab]	120.3[a]	1.524[bc]
Wheat bran	32.7[ab]	39.4[a]	1.205[bcd]	97.1[ab]	138.6[a]	1.428[abc]	126.4	206.5	1.634[ab]	2,872[ab]	119.5[a]	1.522[bc]
SEM (n=10)[5]	0.30	0.34	0.0039	0.61	0.85	0.0041	0.99	1.39	0.0069	15.32	0.62	0.0031
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.564	0.087	<0.001	<0.001	<0.001	<0.001

[a,b,c,d]Means within a column not sharing a common superscript are different at $P < 0.05$.
[1]Average daily gain, g/d
[2]Average daily feed intake, g/d
[3]Feed conversion ratio, g/g
[4]Body weight, g
[5]Ten replications per treatment with 52 birds each.

and 437 to 511 μm for the finisher phase. The geometric standard deviation of dietary treatments was 2 μm in all the phases. Similarly, the percentage of particles larger than 2,000 μm showed slight variations, ranging from 2.7 to 4.3% in the starter phase, 2.0 to 4.0% in the grower phase, and 2.0 to 5.0% in the finisher phase.

Growth Performance

Throughout the starter (0−14d), grower (14−28d), and overall period (0−36d), dietary treatments significantly influenced ADG, ADFI, and FCR ($P < 0.001$; Table 5). In the starter period, BP exhibited the lowest ADG and ADFI. Additionally, OH demonstrated higher ADG than CB, while no significant differences were observed among the other treatments in terms of ADG and ADFI. OH, SH, WS and RH displayed similar FCR among them but lower FCR compared to CON. FCR of CB, BP, and WB treatments did not differ from CON.

During the grower period, BP showed the lower ADG compared to WB, SH, OH, and CON groups. The OH maintained higher ADG compared to CB. Similar to the starter period, ADFI was lower in BP compared to the other treatments, and FCR was higher in CB compared to OH, BP, and CON. During the finisher period (28−36d), ADG and ADFI did not differ among the treatments ($P > 0.05$), although there was a tendency for RH and BP among the fibrous feed ingredients to maintain the highest and lowest ADFI, respectively. The FCR of SH and CB was higher than OH and BP, whereas the rest of the treatments did not differ significantly.

Over the entire period (0−36d), the BP treatment exhibited lower BW compared to OH, SH, WS, RH, and WB ($P < 0.001$). BW was also lower in CB compared to OH. Consistent with the starter and grower periods, BP treatment had lower ADFI compared to the other treatments ($P < 0.001$). FCR of CB was higher compared to all other treatments ($P < 0.001$) except for SH ($P > 0.05$). Furthermore, FCR in OH was lower compared to CON, WS, RH, and WB.

Table 6. The effect of fibrous feed ingredients on the relative weight of empty proventriculus and gizzard (g/100 g BW) at 14, 28, or 36 d of age.

Items	14 d	28 d	36 d
Control	2.53[bc]	1.27[b]	0.99
Oat hulls	2.99[ab]	1.61[ab]	1.29
Soybean Hulls	2.46[c]	1.50[ab]	1.07
Carob bean	2.64[bc]	1.59[ab]	1.07
Beet pulp	3.16[a]	1.73[a]	1.30
Wheat straw	2.91[abc]	1.45[ab]	1.12
Rice hulls	2.75[abc]	1.53[ab]	1.14
Wheat bran	2.59[bc]	1.48[ab]	1.09
SEM (n = 10)[1]	0.090	0.084	0.069
P-value	<0.001	0.0141	<0.10

[a,b,c,d]Means within a column not sharing a common superscript are different at $P < 0.05$.
[1]One bird per pen (10 birds per treatment) was euthanized for sampling.

Proventriculus and Gizzard Development

The relative weight of the gizzard and proventriculus (g/100g BW) was measured at 14, 28, and 36 d (Table 6). At 14 d, the BP group exhibited significantly higher gizzard and proventriculus weights compared to the CON, SH, CB and WB groups ($P < 0.05$). Similarly, at 28-d, the BP group maintained a higher value for this parameter compared to CON, with the other dietary treatments falling in an intermediate range, not significantly different from the former 2. By 36 d, the difference became less pronounced, and only a trend ($P < 0.1$) was observed, where BP and CON had the highest and lowest gizzard and proventriculus weights/BW values, respectively.

Digesta Viscosity and Transit Time

The digesta water retention and viscosity were not affected by the dietary treatments ($P > 0.05$; Table 7). Nonetheless, the viscosity of birds fed BP tended to be greater than those fed CON (P = 0.075). Digesta transit time was longer in CON birds compared to OH, while the other treatments remained within an intermediate

Table 7. The effect of fibrous feed ingredients supplementation on digesta water retention and viscosity.

Items	Digesta water retention, w/w[1]	Viscosity, cp[2]	Transit time, min[3]
Control	80.07	1.95	242[a]
Oat hulls	72.97	3.49	197[b]
Soybean Hulls	73.29	2.75	229[ab]
Carob bean	80.28	3.06	240[ab]
Beet pulp	81.87	3.67	210[ab]
Wheat straw	74.30	2.01	225[ab]
Rice hulls	75.60	2.59	236[ab]
Wheat bran	79.65	2.38	220[ab]
SEM[4]	4.155	0.607	9.4
P-value	0.1890	0.0747	0.0282

[1]Water retention in ileal digesta content.
[2]Viscosity in ileal digesta content (centipoise).
[3]Elapsed time between the oral administration of ferric oxide and the presence of red colour in the excreta for each fibrous feedstuff.
[4]One bird at 28d per pen was euthanized for digesta water retention, whereas for measuring the transit time 3 birds at 25d per pen were used.

range, without significant differences from the former 2 (Table 6).

Coefficient of Total Tract Apparent Retention

There were no differences of AME, AMEn and CTTAR of CP among the treatments ($P > 0.05$; Table 8). Notably, the CTTAR of DM was higher in OH compared to RH. Additionally, the CTTAR ash was higher in both OH and BP, than in RH ($P < 0.001$). In comparison to CON and RH, the CTTAR of fat exhibited an increase in BP. Moreover, the CTTAR of NSP showed an increase in OH and BP compared to CON ($P < 0.01$). Furthermore, OH presented a higher CTTAR of starch than the CON ($P < 0.05$).

DISCUSSION

Our findings revealed that although all fibrous feed ingredients provided coarse particles, their influence on broiler performance and nutrient utilization differed significantly. The addition of 3% OH to broiler diets resulted in similar (during grower and finisher periods) or even improved (during the starter and overall periods) broiler performance compared to the CON group. These findings are consistent with previous studies that have highlighted the benefits of OH for broiler production (González-Alvarado et al., 2010; Jiménez-Moreno et al., 2013a).

The positive effects of OH inclusion on broiler performance are typically attributed to improved digestibility, primarily through an increase in gizzard size and enhanced retention of digesta in the gizzard (González-Alvarado et al., 2010). In our study, any significant differences were not observed in the relative weights of the empty proventriculus and gizzard to BW at any age, and the total tract transit time of digesta in birds fed OH was shorter than in the CON group. This seemingly contradictory difference in total tract transit, however, does not exclude the potential for prolonged retention time of coarse OH in the gizzard. In addition, the observed reduction in the transit time of digesta in birds fed the OH diet compared to the CON group might be attributed to the higher concentration of insoluble NSP in the OH diet, which contained 104.3 g/kg compared to 76.3 g/kg in the CON diet.

The average predicted mean retention time of the solid phase of digesta in the gizzard has been reported to be approximately 5 min longer than the liquid phase in 30-day-old broilers (Garçon et al., 2023). Coarse particles greater than 0.6 mm are preferentially retained in the gizzard (Hetland et al., 2002). Thus, the application of fine-particle markers to measure transit time, such as ferric oxide in the current study, might not accurately represent the transit time of coarse particles (Garçon et al., 2023).

Furthermore, it is important to note that variations in the relative weight of the proventriculus-gizzard complex do not inherently correlate with improved performance. For example, in our study, birds fed with BP exhibited higher relative weights of the empty proventriculus and gizzard compared to BW compared to those in the CON group at both 14 and 28 d. However, they maintained lower BW and ADFI compared to the CON group. The high pectin content in feed ingredients like BP has been linked to physical dilation of the gastrointestinal tract, resulting in increased size of digestive organs, improved gut fill, and reduced ADFI (Jiménez-Moreno et al., 2011).

Broilers fed BP diets exhibited reduced ADG and ADFI, particularly during the starter and grower phases, consistent with previous research (Jiménez-Moreno et al., 2013a). BP contained the highest amount of soluble NSP, rich in uronic acid and arabinose residues from pectic polysaccharides. These soluble NSP have a high water-holding capacity, which can increase digesta viscosity within the gastrointestinal tract (Jørgensen et

Table 8. Effect of oat hulls, beet pulp and rice hulls on coefficient of total tract apparent retention.

Items	AME, kcal/kg	AME_n, kcal/kg	Dry matter	Crude protein[1]	Ether extract	Ash	Non-starch polysaccharides	Starch
Control	3688	3488	0.753[ab]	0.853	0.864[b]	0.396[ab]	0.094[c]	0.981[c]
Oat hulls	3764	3567	0.764[a]	0.862	0.914[ab]	0.426[a]	0.207[ab]	0.991[ab]
Beet pulp	3748	3545	0.761[ab]	0.858	0.929[a]	0.436[a]	0.234[a]	0.990[abc]
Rice hulls	3684	3492	0.742[b]	0.848	0.908[b]	0.361[b]	0.141[bc]	0.988[bc]
SEM[2]	34.73	34.63	0.0052	0.0073	0.0158	0.0118	0.0233	0.0023
P-value	0.260	0.296	0.026	0.569	0.051	<0.001	<0.01	<0.05

[a,b,c,d]Means within a column not sharing a common superscript are different at $P < 0.05$.
[1]Without correction for uric acid in excreta.
[2]Ten replications per treatment each with 6 birds (60 birds per treatment in total).

al., 1996; Jiménez-Moreno et al., 2013a). This viscous environment may hinder nutrient movement across the intestinal wall, potentially reducing nutrient absorption and utilization by broilers (Jørgensen et al., 1996; Jiménez-Moreno et al., 2013a). Additionally, the viscous properties of pectin can stimulate pancreatic secretions and potentially increase organ weight (Ikegami et al., 1991). Increased digesta bulk and viscosity may limit nutrient interaction with the intestinal mucosa, further compromising nutrient absorption (Jiménez-Moreno et al., 2013b).

However, an alternative hypothesis that should be considered is that the negative impact of BP on broiler performance could be related to its effect on ADFI rather than solely on digestion and nutrient absorption. Additionally, one reason for the differences in FCR between OH and WS, despite their similar chemical compositions, could be the variation in soluble NSP content between these ingredients. The high water-holding capacity of BP, due to its soluble NSP and high viscosity, may lead to increased bulk in the gizzard, potentially reducing ADFI (Jiménez-Moreno et al., 2011). Despite the higher viscosity in the BP group, AME, AMEn, and CTTAR of nutrients were not adversely impacted, suggesting that the primary issue may be related to reduced ADFI rather than impaired nutrient absorption.

Similarly, to BP, the inclusion of CB led to a reduction in BW compared to the OH group. CB contained the lowest amount of insoluble NSP and total NSP. However, compared to BP, CB contained a different fiber profile. The adverse impact of CB might be attributed to its galactomannans, known to increase viscosity (Vilà et al., 2012), and high quantity of tannins, which have the potential to create sediment with proteins and reduce digestibility (Kotrotsios et al., 2011).

Categorizing the fibrous feed ingredients based on their soluble-to-insoluble NSP ratio offers an alternative perspective on their distinct impacts on broiler performance. Ingredients such as OH, SH, WS, RH, and WB, with soluble-to-insoluble NSP ratios of 0.09, 0.28, 0.04, 0.03, and 0.16 respectively, primarily consist of hard, resistant fibers that enhance gizzard function through mechanical breakdown. In contrast, ingredients like BP and CB, which have higher soluble-to-insoluble NSP ratios of 0.66 and 0.39 respectively, contain a higher percentage of soluble fibers relative to total NSP. This characteristic increases digesta viscosity and may hinder nutrient absorption, potentially explaining why BP and CB exhibit similar performance effects by reducing ADG and ADFI.

The effects of other fibrous feedstuff alternatives to OH varied across different ages. None of the alternatives resulted in differences in final BW compared to the CON group, indicating that the primary factor for comparison was FCR. While some alternatives, including SH, WS, RH, and WB, showed similar FCR to OH during the starter phase, differences emerged during the grower and finisher phases, with only BP, WS, and WB maintaining FCR not significantly different from OH. Among the alternatives, BP exhibited a comparable FCR to OH but at the cost of lower BW (99g) and ADFI (3.6 g/d). The use of other alternatives for OH, including WS, RH, and WB, led to similar final BW; however, they exhibited higher FCR compared to OH.

The initial divergence in growth metrics, particularly noticeable during the starter and grower phases, implies that the influence of dietary fiber might be more pronounced in the earlier stages of development. However, the diminishing significance observed in the finisher phase suggests the potential presence of adaptability or compensatory mechanisms within the digestive system, as noted in previous studies (Jiménez-Moreno et al., 2013a). In their research, Jiménez-Moreno et al. (2013a) noted the impact of dietary fiber sources and levels on ADG during the first 6 d of life. However, this effect did not persist throughout the remainder of the experimental period, which extended up to 18 d. In addition, dietary fibrous ingredients affected the weight of the empty proventriculus and gizzard up to 28 d, which might extend to other gastrointestinal tract segments. This could contribute to a more pronounced effect during the starter and grower phases compared to the finisher period, as the relative weight of the GIT to body weight gradually decreases as broilers age (Juanchich et al., 2021).

Furthermore, it is essential to acknowledge that the assessment of particle size through sieving provides a simplified representation, potentially overlooking nuanced aspects of particle morphology and mechanical properties. For instance, OH particles may exhibit longitudinal splitting, resulting in thin but elongated fragments, which may not be fully captured by traditional sieving methods. This highlights the multidimensional nature of particle characteristics, which warrants comprehensive exploration beyond GMD.

Beyond particle size reduction, the response of fibrous feed ingredients to grinding can offer insights into their mechanical properties and suitability for processing. The observed variation in particle size reduction among feed ingredients, as indicated by changes in GMD, may reflect differences in characteristics such as hardness and elasticity. For instance, OH exhibited a relatively lower reduction in GMD (57%) post-grinding, suggesting greater resistance to size reduction and possibly higher hardness compared to other materials. However, it is important to note that the example of OH may not be ideal due to its multidimensional nature, which allows particles to escape from the sieving method as well as from the grinding process. Conversely, CB displayed a higher reduction in GMD (89%), indicating lower grinding resistance and potentially lower hardness or greater elasticity.

These characteristics not only influence particle size distribution but also may have implications for processing in the gizzard, where mechanical breakdown plays a crucial role in feed digestion. Understanding the interplay between particle dimensions, mechanical properties, and their impact on grinding resistance can provide valuable insights into feed processing efficiency and digestive performance, offering opportunities for optimization in feed formulation and processing strategies.

Moreover, the dietary inclusion of OH and BP resulted in improved CTTAR of NSP, starch, and ether extract compared to the CON group. This is consistent with previous findings by González-Alvarado et al. (2010), who reported that the addition of 3% of OH or BP increased CTTAR in 32 d broilers attributed to higher HCl production, increased pepsin activity, and bile salt secretion (González-Alvarado et al., 2010; Jiménez-Moreno et al., 2011).

Additionally, the increase in CTTAR of NSP may be elucidated by 2 factors: firstly, the greater degradability of NSP originating from the supplemented fiber-source origins in comparison to the substituted NSP from the basal diet; and secondly, the improved breakdown of NSP originating from wheat, corn, and soybean meal in the basal diet, owing to indirect effects on digestive processes, including muscular activity and grinding efficacy within the gizzard, alongside digesta retention (Garçon et al., 2023).

The noted increase in CTTAR of NSP with the inclusion of fiber-based diets surpassed the anticipated increase solely from the additional NSP content introduced by OH and BP. Even under the presumption of complete degradation of these sources, such as the 8.9 and 15.4 g/kg of supplementary NSP in the OH and BP diets, respectively, compared to the control diet, an additional 11.3 and 14 g/kg of NSP respectively underwent degradation. Hence, it is plausible to infer that the supplementation of OH and BP also facilitated the degradation of NSP originally inherent in the control diet (Garçon et al., 2023).

It is important to note that in our study, the substitution of wheat with fibrous ingredients may have resulted in slight changes to the overall diet composition. Although these changes were minor and unlikely to significantly affect the main outcomes, the differences in nutrient density could have contributed to variations in AME values. Previous studies have approached fiber inclusion by diluting the diet with fiber (Jiménez-Moreno et al., 2011; Jiménez-Moreno et al., 2013a,b) or by adding fiber sources at the expense of filler ingredients such as sand or sepiolite (González-Alvarado et al., 2010), rather than directly replacing a nutrient-dense ingredient like wheat, to maintain a consistent nutrient profile across treatments.

The observed phenomenon whereby the inclusion of RH did not significantly alter nutrient retention compared to the control treatment devoid of fibrous ingredients suggests that RH may possess characteristics that do not substantially impact nutrient utilization in broiler chickens under the conditions of this study. There is a lack of information explaining the lower CTTAR of DM, ether extract, and ash in RH birds compared to OH or BP, especially because there were no differences in the relative weight of the proventriculus and gizzard and digesta viscosity and transit time among RH, OH, and BP.

In conclusion, our study confirmed that the addition of OH at 3% is a promising approach to improving feed efficiency and nutrient utilization in broilers. Our study highlighted the difficulty of finding a replacement for OH that results in similar growth performance. Although certain alternatives, including WS, RH, and WB, resulted in comparable final BW, they fell short of OH in terms of FCR. The BP, on the other hand, achieved a similar FCR to OH, but this came at the expense of lower BW and ADFI. Therefore, future research should prioritize identifying cost-effective fibrous feed ingredients that mimic the positive impact of OH on growth performance while maintaining feed efficiency.

ACKNOWLEDGMENTS

The authors appreciate the assistance of members of the Poultry Research Centre of Trouw Nutrition (El Viso de San Juan, Toledo, Spain) in performing the animal trial. The authors would like to thank Erika Martin Chaves for her support during the execution of this study. Reza Akbari Moghaddam Kakhki is a recipient of Torres Quevedo Fellowship by The Ministry of Science and Innovation of Spain.

DISCLOSURES

The authors declare no conflicts of interest.

SUPPLEMENTARY MATERIALS

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.psj.2024.104297.

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