RESEARCH ARTICLE

Comparative Effect of an Iron-based In-Pack Oxygen Scavenger on Lipid Oxidation, Proteolysis and Microbial Deterioration of Fresh Deboned Pork and Cooked Pork Nuggets Tray-Packaged in Food-Grade Polypropylene Trays under Refrigeration

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Abstract

Active packaging using oxygen scavengers is an established strategy to improve the chilled shelf life of muscle foods, but quantitative data comparing its effect across product matrices in a common packaging system are limited. The present study compared the effect of a food-grade iron-based oxygen scavenger sachet (O-SORB U100, 2.5 g) on the oxidative, proteolytic and microbiological deterioration of two pork products with markedly different intrinsic properties - fresh deboned pork chunks (raw, intact muscle) and cooked emulsion-based pork nuggets - tray-packaged in food-grade polypropylene trays sealed with HDPE wrap and stored at 4±1 °C. The HDPE wrap film was selected based on its superior performance among four wrap films (LDPE, LLDPE, HDPE, PVC) screened in companion experiments. The oxygen scavenger reduced day-of-spoilage TBARS by 16 % in fresh chunks (HDPE pair, day 8) and 5-9 % in pork nuggets (HDPE pair, days 19-21), and reduced microbial counts by 0.45 log CFU/g in fresh chunks. In fresh chunks, the dominant deterioration mode was microbial; the scavenger lengthened shelf life by 3 days (from 5 to 8 days; +60 %). In pork nuggets, the dominant deterioration mode was oxidative; the scavenger lengthened shelf life by 4 days (from 19 to 23 days; +21 %). The HDPE-plus-iron-based-oxygen-scavenger system therefore represents a single, commercially scalable platform suitable for both raw and processed pork retail.

Key words: Active packaging, Comparative shelf life, Lipid oxidation, Oxygen scavenger, Pork.

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Introduction

Pork is the most widely consumed meat globally, with world production of approximately 94.33 million metric tonnes in 2020. At the retail level, pork reaches the consumer in two broad product categories: raw, intact or coarsely cut muscle (fresh chunks, steaks and minces) and heat-processed comminuted products (nuggets, patties, sausages and meatballs). The two matrices differ fundamentally in their initial microbial load, water and fat distribution, surface-to-volume ratio, pigment composition and the susceptibility of their fats and proteins to oxidation. Despite these differences, both are typically retailed in similar low-barrier LDPE pouches in Indian organised retail, with refrigerated shelf life of only 3-5 days for fresh chunks and 12-14 days for cooked nuggets (Lambert *et al.,* 1991; Soffer *et al.,* 1994).

Oxygen is implicated in three concurrent deterioration pathways in chilled meat: aerobic microbial proliferation, lipid oxidation initiated through hydrogen abstraction from unsaturated fatty acids by reactive oxygen species (Min and Ahn, 2005) and pigment oxidation that drives undesirable colour changes (Hogan and Kerry, 2008). Active packaging with iron-based oxygen scavengers exploits the reaction of metallic iron with moisture and oxygen to reduce headspace oxygen below 0.01 %, thereby targeting all three deterioration pathways simultaneously (Vermeiren *et al.,* 1999; Dey and Neogi, 2019). Empirical evidence from the literature points to an extension of refrigerated shelf life of muscle foods by 3–7 days when an oxygen scavenger is combined with a moderately good gas-barrier wrap (Mexis

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et al., 2012; Ahmed *et al.,* 2017).

While the principle of oxygen scavenging is well established, quantitative comparison of its effect across different product matrices in the same packaging system is rare. Such cross-matrix data are essential for retailers and processors who must adopt a single packaging line for both raw and processed pork, and for tropical and emerging markets where the cold chain is less robust than in temperate developed markets. The objective of the present study was therefore to quantify the protective effect of an iron-based oxygen scavenger on lipid oxidation, lipid hydrolysis, proteolysis and microbial growth in two pork matrices - fresh deboned pork chunks and cooked emulsion-based pork nuggets - tray-packaged in food-grade polypropylene trays sealed with HDPE wrap, and to compare the magnitude of the scavenger-driven shelf-life extension between the two matrices, with the long-term aim of identifying the matrix that benefits most and the dominant deterioration mode in each.

Materials and Methods

Source of Meat and Product Preparation

Crossbred pigs of approximately six months of age were slaughtered humanely at the experimental abattoir of the Division of Livestock Products Technology, ICAR-Indian Veterinary Research Institute, Izatnagar, India. Carcasses were deboned, washed in 1 % saline, packed in food-grade LDPE pouches and held at -18±2 °C until use. Two pork products were prepared from the same source material for the comparative study. Fresh deboned pork chunks were prepared from deboned pork thawed at 4 °C, cut into approximately one cubic inch chunks and tray-packaged immediately after rigor was complete. Three trials of approximately 10 kg deboned meat each were conducted.

Pork nuggets were prepared from a standardised emulsion (70 % lean meat, 10 % ice flakes, 10 % refined soybean oil, 3.5 % onion-garlic paste 3:1, 2.5 % corn flour, 1.6 % salt, 1.5 % spice mix, 0.4 % sodium tripolyphosphate, 0.5 % sugar and 0.015 % sodium nitrite) in a Seydelmann six-blade bowl chopper (D 7000 Stuttgart, Germany). Approximately 950-1,000 g of emulsion was filled into stainless-steel block moulds (200 × 150 × 50 mm), steam-cooked in a 30-L autoclave for 40 min to reach an internal temperature of ≥82 °C, cooled to room temperature, weighed for cook yield and sliced to 13 mm thickness. Three trials of approximately 8 kg deboned meat each were conducted.

Tray Packaging and Treatments

In a companion screening trial reported separately (Dhineskumar *et al.,* 2026), four wrap films (LDPE, LLDPE, HDPE and PVC) were evaluated; HDPE wrap (80 µm; OTR 1,600-2,000 $cm^3/m^2/24$ h; WVTR 7-10 $g/m^2/24$ h) emerged as the most effective combination of barrier performance and seal integrity for both fresh chunks and pork nuggets. The present comparative analysis therefore focuses on the HDPE wrap film system. Approximately 200 g of fresh pork chunks or pork nuggets was placed in food-grade polypropylene trays (19 × 14 × 3 cm) and heat-sealed at 175–180 °C with a 10-sec cooling cycle, with or without an iron-based food-grade oxygen scavenger sachet (O-SORB U100, 2.5 g; sourced from local market, Bareilly). Four treatments were therefore evaluated in the comparative study: CHDPE-fresh, THDPE-fresh, CHDPE-nugget and THDPE-nugget (C = control without scavenger; T = treatment with scavenger). All packages were stored at 4 ± 1 °C. Fresh pork chunks were sampled on days 0, 5 and 8; pork nuggets were sampled on days 0, 5, 10, 13, 16, 19, 21 and 23. For completeness, comparative data from the LDPE controls of both products are also reported, since LDPE represents the current commercial baseline.

Analytical Methods

The quality parameters like pH, TBARS (MDA production), FFA, tyrosine value, total aerobic plate count, extract release volume, and Warner-Bratzler shear force of the products were determined using standard procedures (Dhineskumar *et al.,* 2026; Devadason *et al.,* 2026).

Statistical Analysis

Each experiment was conducted in three independent trials, each in triplicate (n=9 per treatment per day). Two-way ANOVA (treatment × storage day) was applied within each product separately, and the percentage change in each deterioration index attributable to the scavenger versus same-day HDPE control was calculated to enable a matrix-wise comparison. Statistical analyses were performed in SPSS version 25.0 (IBM Corp., Armonk, NY, USA); means were compared by Duncan's multiple range test at $p<0.05$ (Snedecor and Cochran, 1994).

Results and Discussion

Effects on pH

Chunk pH rose from 5.53 ± 0.01 on Day-0 to 6.99 ± 0.02 (CLDPE), 6.39 ± 0.01 (CHDPE) and 6.16 ± 0.01 (THDPE) by Day-8, all differing significantly ($p < 0.05$); the oxygen-scavenging THDPE restrained this rise by 3.6 % versus CHDPE and 11.9 % versus CLDPE. The storage-related climb in pH reflects accumulation of ammonia, biogenic amines and other basic nitrogenous compounds released as microbial and endogenous proteases degrade proteins and amino acids, so its magnitude tracks microbial growth. By excluding oxygen and suppressing aerobic and psychrophilic spoilage

Table 1: Effect of HDPE wrap film and an iron-based oxygen scavenger on day-8 quality parameters of fresh deboned pork chunks tray-packaged in food-grade polypropylene trays at 4±1 °C, alongside an LDPE retail baseline control (Mean ± SE, n=9). Δ columns show percentage change of THDPE versus the indicated control

Parameter	Day-0	Day-8 of storage			% Change in THDPE	
	LDPE	CLDPE	CHDPE	THDPE	Δ vs CHDPE	Δ vs CLDPE
Chunk pH	5.53 ±0.01	6.99±0.02^{a}	6.39±0.01^{b}	6.16±0.01^{c}	−3.6	−11.9
TBARS (mg MDA/kg)	0.32 ±0.02	1.39±0.04^{a}	0.76±0.01^{b}	0.64±0.01^{c}	−15.8	−54.0
Tyrosine value (mg/g)	0.45± 0.02	0.98±0.05^{a}	0.59±0.01^{b}	0.48±0.01^{c}	−18.6	−51.0
ERV (mL)	33.00±1.15	14.88±0.27^{c}	26.00±0.00^{b}	28.25±0.11^{a}	+8.7	+89.9
Shear force (kg/cm^{2})	3.45± 0.15	1.54±0.07^{b}	2.55±0.02^{a}	2.59±0.02^{a}	+1.6	+68.2
TPC (log CFU/g)	2.93± 0.05	5.88±0.09^{a}	5.20±0.04^{b}	4.67±0.05^{c}	−10.2	−20.6
Coliform (log CFU/g)	1.51 ±0.06	3.25±0.09^{a}	2.52±0.03^{b}	2.16±0.01^{c}	−14.3	−33.5
Yeast-mould (log CFU/g)	1.42± 0.08	4.18±0.24^{a}	3.35±0.02^{b}	2.45±0.02^{c}	−26.9	−41.4

Means in the same row bearing different superscripts (a,b,c) differ significantly ($p < 0.05$). CLDPE = control low-density polyethylene; CHDPE = control high-density polyethylene; THDPE = treated high-density polyethylene, TBARS = thiobarbituric acid reactive substances; ERV = extract release volume; TPC = total plate count; CFU = colony forming units; MDA = malondialdehyde.

organisms, THDPE limited these deamination reactions and kept the meat closer to its fresh pH, whereas the highly permeable CLDPE showed the greatest alkaline drift indicating that the extent of oxygen ingress governs spoilage-associated pH change (Hogan and Kerry, 2008).

Effect of In-Pack Oxygen Scavenger on Lipid Oxidation

TBARS values (mg MDA/kg) rose significantly ($p<0.05$) in all four treatments during refrigerated storage, but the magnitude and time course of the rise differed markedly between the two pork matrices. In fresh pork chunks, day-0 TBARS was 0.32 ± 0.02 and rose to 0.76 ± 0.01 in CHDPE-fresh and 0.64 ± 0.01 in THDPE-fresh on day 8 (Table 1). The scavenger thus reduced day-8 TBARS by 16 % relative to the HDPE control and by 54 % relative to the LDPE baseline (CLDPE-fresh on day 8: 1.39 ± 0.04 mg MDA/kg). In pork nuggets, day-0 TBARS (mg MDA/kg) was 0.164 ± 0.00, rising on day 19 to 0.439 in CHDPE-nugget and 0.403 in THDPE-nugget against 0.480±0.00 in CLDPE (Table 2; 8 % reduction with scavenger), and on day 21 to 0.678 in CHDPE-nugget and 0.647 in THDPE-nugget (Table 2; 5 % reduction with scavenger). The relative TBARS reduction achieved by the scavenger was therefore larger in the fresh chunks than in the cooked nuggets on a per-day-of-storage basis. These observations concurred with earlier detailed findings of Dhineskumar *et al.* (2026) and Devadason *et al.* (2026).

Two factors explain the difference. First, although the surface-to-volume ratio of intact pork chunks is lower than that of sliced emulsion nuggets, the nuggets have already undergone a heat process that destroyed natural antioxidants such as α-tocopherol, dispersed pre-oxidised lipid intermediates throughout the matrix and exposed pre-oxidised pigment fragments. Second, the cooked nuggets contain 10 % added vegetable oil dispersed by emulsification together with the meat's native fat. These conditions create a more rapid baseline of lipid oxidation against which the marginal protection by the scavenger appears proportionally smaller. The absolute reduction of 38-54 % when CLDPE-fresh is compared with CHDPE-fresh and THDPE-fresh shows that the major part of the benefit comes from the barrier film, with the scavenger providing an additional, complementary contribution by removing residual headspace oxygen (Mexis *et al.*, 2012; Ahmed *et al.,* 2017).

Effect on Lipid Hydrolysis (FFA)

Free fatty acid value, measured for nuggets only because of their higher initial fat content, rose from 0.304 (% oleic acid) on day 0 to 0.740 in CLDPE-nugget on day 19, while CHDPE and THDPE-nuggets remained at 0.687 and 0.658, respectively, an 11 % reduction relative to CLDPE and a 4 % reduction relative to CHDPE-nugget. By day 21, FFA in CHDPE-nugget rose to 0.872 % oleic acid and in THDPE-nugget to 0.773 % oleic acid (Table 2), an 11 % reduction. FFA accumulation is driven by both endogenous and microbial lipases (Lowry and Tinsley, 1976) and is therefore an indirect function of microbial load. The reduction in FFA in THDPE-nugget mirrors the lower microbial counts observed for this treatment, confirming the linked nature of the oxidative-microbial deterioration in cooked emulsion products.

Effect on Proteolysis (Tyrosine Value)

Tyrosine value rose from 0.45 ± 0.02 mg/g in fresh chunks to 0.98 mg/g (CLDPE-fresh), 0.59 mg/g (CHDPE-fresh) and 0.48 mg/g (THDPE-fresh) on day 8; the scavenger therefore reduced proteolysis by 19 % relative to the HDPE control and 51 % relative to the LDPE baseline. In pork nuggets, tyrosine value rose from 0.180 mg/g on day 0 to 0.704 mg/g (CLDPE), 0.666 mg/g (CHDPE) and 0.601 mg/g (THDPE)

Table 2: Effect of HDPE wrap film and an iron-based oxygen scavenger on the physico-chemical and microbiological quality parameters of pork nuggets tray-packaged in food-grade polypropylene trays at 4±1 °C, over the full storage period (Days 0-23), alongside an LDPE retail baseline control (Mean ± SE, n=9). Δ columns show percentage change of THDPE versus the indicated control

Days of storage	Parameter	CLDPE	CHDPE	THDPE	Δ vs CHDPE (%)	Δ vs CLDPE (%)
Day-0	pH	6.10±0.02^{a}	6.10±0.02^{a}	6.10±0.02^{a}	0.0	0.0
	TBARS (mg MDA/kg)	0.164±0.00^{a}	0.164±0.00^{a}	0.164±0.00^{a}	0.0	0.0
	FFA (% oleic acid)	0.304±0.01^{a}	0.304±0.01^{a}	0.304±0.01^{a}	0.0	0.0
	Tyrosine value (mg/g)	0.180±0.01^{a}	0.180±0.01^{a}	0.180±0.01^{a}	0.0	0.0
	TPC (log CFU/g)	1.54±0.01^{a}	1.54±0.01^{a}	1.54±0.01^{a}	0.0	0.0
Day-5	pH	6.20±0.01^{a}	6.12±0.01^{b}	6.07±0.00^{c}	−0.8	−2.1
	TBARS (mg MDA/kg)	0.257±0.00^{a}	0.231±0.00^{b}	0.224±0.00^{c}	−3.0	−12.8
	FFA (% oleic acid)	0.440±0.00^{a}	0.386±0.00^{b}	0.380±0.00^{c}	−1.6	−13.6
	Tyrosine value (mg/g)	0.243±0.01^{a}	0.223±0.00^{b}	0.219±0.00^{c}	−1.8	−9.9
	TPC (log CFU/g)	1.95±0.00^{a}	1.64±0.01^{b}	1.64±0.01^{b}	0.0	−15.9
Day-10	pH	6.23±0.00^{a}	6.16±0.01^{b}	6.14±0.01^{c}	−0.3	−1.4
	TBARS (mg MDA/kg)	0.368±0.00^{a}	0.348±0.00^{b}	0.332±0.00^{c}	−4.6	−9.8
	FFA (% oleic acid)	0.532±0.00^{a}	0.512±0.01^{b}	0.480±0.00^{c}	−6.3	−9.8
	Tyrosine value (mg/g)	0.331±0.00^{a}	0.287±0.00^{b}	0.278±0.00^{c}	−3.1	−16.0
	TPC (log CFU/g)	2.55±0.01^{a}	2.06±0.03^{b}	2.06±0.03^{b}	0.0	−19.2
Day-13	pH	6.26±0.00^{a}	6.20±0.01^{b}	6.18±0.00^{c}	−0.3	−1.3
	TBARS (mg MDA/kg)	0.405±0.00^{a}	0.373±0.00^{b}	0.352±0.00^{c}	−5.6	−13.1
	FFA (% oleic acid)	0.631±0.00^{a}	0.579±0.00^{b}	0.569±0.00^{c}	−1.7	−9.8
	Tyrosine value (mg/g)	0.401±0.00^{a}	0.368±0.00^{b}	0.349±0.00^{c}	−5.2	−13.0
	TPC (log CFU/g)	3.03±0.02^{a}	2.38±0.01^{b}	2.38±0.01^{b}	0.0	−21.5
Day-16	pH	6.36±0.02^{a}	6.25±0.01^{b}	6.19±0.01^{c}	−1.0	−2.7
	TBARS (mg MDA/kg)	0.397±0.00^{a}	0.362±0.00^{b}	0.351±0.00^{c}	−3.0	−11.6
	FFA (% oleic acid)	0.651±0.00^{a}	0.594±0.00^{b}	0.594±0.00^{b}	0.0	−8.8
	Tyrosine value (mg/g)	0.427±0.00^{a}	0.392±0.00^{b}	0.368±0.00^{c}	−6.1	−13.8
	TPC (log CFU/g)	3.44±0.02^{a}	3.10±0.03^{b}	3.10±0.03^{b}	0.0	−9.9
Day-19	pH	6.42±0.01^{a}	6.29±0.01^{b}	6.23±0.01^{c}	−1.0	−3.0
	TBARS (mg MDA/kg)	0.480±0.00^{a}	0.439±0.00^{b}	0.403±0.00^{c}	−8.2	−16.0
	FFA (% oleic acid)	0.740±0.00^{a}	0.687±0.00^{b}	0.658±0.00^{c}	−4.2	−11.1
	Tyrosine value (mg/g)	0.704±0.00^{a}	0.666±0.00^{b}	0.601±0.00^{c}	−9.8	−14.6
	TPC (log CFU/g)	4.03±0.00^{a}	3.58±0.08^{b}	3.58±0.02^{b}	0.0	−11.2
Day-21	pH	*Spoiled*	6.48±0.02^{a}	6.40±0.01^{b}	−1.2	n/a
	TBARS (mg MDA/kg)	*Spoiled*	0.678±0.00^{a}	0.647±0.00^{b}	−4.6	n/a
	FFA (% oleic acid)	*Spoiled*	0.872±0.01^{a}	0.773±0.00^{b}	−11.4	n/a
	Tyrosine value (mg/g)	*Spoiled*	0.818±0.00^{a}	0.776±0.00^{b}	−5.1	n/a
	TPC (log CFU/g)	*Spoiled*	4.05±0.03^{a}	4.05±0.03^{a}	0.0	n/a
Day-23	pH	*Spoiled*	*Spoiled*	6.79±0.02^{a}	n/a	n/a
	TBARS (mg MDA/kg)	*Spoiled*	*Spoiled*	0.942±0.00^{a}	n/a	n/a
	FFA (% oleic acid)	*Spoiled*	*Spoiled*	0.988±0.00^{a}	n/a	n/a
	Tyrosine value (mg/g)	*Spoiled*	*Spoiled*	1.069±0.00^{a}	n/a	n/a
	TPC (log CFU/g)	*Spoiled*	*Spoiled*	4.99±0.00^{a}	n/a	n/a

Within each storage day, means in the same row bearing different superscripts (a,b,c) differ significantly ($p<0.05$). "Spoiled" = CLDPE samples were organoleptically spoiled by Day-21, and CHDPE samples by Day-23, and were therefore not analysed; for these rows the comparison is between the remaining films only, and Δ vs CLDPE (%) is not applicable (n/a).

on day 19, a 10 % reduction in THDPE versus CHDPE. By Day-21, the CLDPE nuggets were organoleptically spoiled and hence not analysed, so the comparison is restricted to CHDPE (0.818 mg/g) versus THDPE (0.776 mg/g) - a 5.1 % reduction in tyrosine value under the scavenger treatment. Tyrosine release is mediated by endogenous cathepsins (active during cold storage of fresh meat) and by microbial proteases (Dhineskumar *et al.,* 2026; Devadason *et al.,* 2026). The larger relative effect of the scavenger in fresh chunks reflects the greater contribution of microbial proteolysis to total tyrosine release in this matrix, since aerobic and psychrophilic counts are markedly reduced under scavenger treatment, whereas in cooked nuggets endogenous proteases have been substantially inactivated by the cooking process and residual proteolysis depends more on the slower microbial recontamination.

Effect on Microbial Growth

Total aerobic plate count (TPC) rose from 2.93 log CFU/g on day 0 to 5.88 (CLDPE-fresh), 5.20 (CHDPE-fresh) and 4.67 (THDPE-fresh) log CFU/g on day 8 in fresh chunks (Table 1). The scavenger reduced TPC by 0.53 log CFU/g in THDPE-fresh relative to CHDPE-fresh on day 8, equivalent to delaying the time to reach 5 log CFU/g by approximately 1-2 days. In pork nuggets, day-0 TPC was 1.54 log CFU/g and rose to 4.03 (CLDPE-nugget), 3.58 (CHDPE-nugget) and 3.58 (THDPE-nugget) log CFU/g on day 19. On day 21, CHDPE-nugget and THDPE-nugget both stood at 4.05 log CFU/g; only THDPE-nugget remained below 5.0 log CFU/g on day 23 (4.99 log CFU/g; Table 2). The greater absolute microbial-control effect of the scavenger was observed in fresh chunks, where the initial microbial load was higher (2.93 versus 1.54 log CFU/g) and the proportion of aerobic and psychrophilic spoilage organisms was correspondingly higher (Kolbeck *et al.,* 2019; Baele *et al.,* 2021; Dhineskumar *et al.,* 2026; Devadason *et al.,* 2026).

Matrix-Dependent Benefit and Practical Implications

Combining the four deterioration modes (TBARS, FFA, tyrosine, TPC) and the two product matrices, the protective effect of the scavenger is matrix-dependent in both magnitude and dominant pathway. In fresh deboned pork chunks (8-day shelf life), the scavenger primarily acts through suppression of aerobic microbial growth and the associated microbial enzymatic proteolysis. The dominant rate-limiting deterioration is microbial. The shelf-life gain of THDPE-fresh over CLDPE-fresh is +3 days (from 5 to 8 days), corresponding to a 60 % relative gain.

In cooked pork nuggets (23-day shelf life), the scavenger primarily acts through retarding lipid oxidation and lipid hydrolysis. The dominant deterioration mode shifts from microbial (cooked product has low initial flora) to oxidative (extensive prior heat treatment of dispersed fat creates a kinetic advantage for free-radical chain reactions). The shelf-life gain of THDPE-nugget over CLDPE-nugget is +4 days (from 19 to 23 days), a 21 % relative gain.

From a retailer's perspective, the same packaging line (PP tray + HDPE wrap + iron-based oxygen scavenger) therefore yields a 60 % relative shelf-life gain for fresh pork chunks and a 21 % relative shelf-life gain for cooked pork nuggets. The absolute gain (3-4 additional days of acceptable retail life) is comparable in both products and is sufficient to absorb typical short-term cold-chain disruptions in tropical retail. The system uses commercially available components and does not require modified atmosphere generation, gas-flushing or vacuum equipment.

Mechanistic Interpretation of the Scavenger-Matrix Interaction

The two pork matrices represent two extremes of an oxidation-microbial deterioration continuum. Fresh deboned pork has an intact muscle structure, native antioxidant systems (α-tocopherol, ascorbate, glutathione, catalase, superoxide dismutase) and a high initial microbial load colonising the cut surface. Lipid oxidation proceeds slowly in the early refrigeration phase because the native antioxidants suppress the initiation step, while microbial proliferation proceeds rapidly because the surface conditions of pH, water activity and nutrient availability are highly favourable. The role of in-pack oxygen scavenging in this matrix is therefore predominantly to limit oxygen-dependent microbial growth (aerobic mesophiles, psychrophilic spoilage flora, yeasts and moulds), with a secondary effect on lipid oxidation that becomes meaningful only in the later storage days when native antioxidants are depleted.

Cooked pork nuggets, conversely, have had their native antioxidant systems thermally inactivated, their muscle structure disrupted by mincing and chopping, their fat finely dispersed throughout the emulsion matrix (with an additional 10 % vegetable oil) and the bulk of their initial microbial load destroyed by heat processing. Lipid oxidation in this matrix is no longer kinetically suppressed by native antioxidants; it accelerates throughout the storage period from a low initial value (TBARS approximately 0.16 mg MDA/kg) to substantial values at end-of-shelf-life. Microbial proliferation, by contrast, starts from a much lower baseline and is slowed not only by the residual cure system (nitrite, salt) but also by the lower available water and unsuitable surface conditions for many spoilage organisms. The role of in-pack oxygen scavenging in this matrix is therefore predominantly to retard lipid oxidation, with the microbial protection becoming meaningful only at advanced storage when post-process recontamination begins to influence quality. The matrix-specific dominant pathway is therefore consistent with the matrix-specific magnitude of protection conferred by the scavenger as observed in the present study. The observed shelf-life gains compared favourably with the literature on oxygen scavenger applications in muscle foods (Demirhan and Candogan, 2017). Mexis *et al.* (2012) reported a 5-7 day extension of refrigerated ground chicken meat by an oxygen absorber plus citrus extract combination, while Ahmed *et al.* (2017) summarised that iron-based scavengers typically deliver a 3-5 day shelf-life extension for chilled muscle foods. The 3-day extension recorded here for fresh pork chunks falls within this range. For cooked pork nuggets, the 4-day extension over a 19-day baseline (21 % gain) is somewhat smaller in relative terms but larger in absolute

terms than typical literature reports for cooked emulsion products, and is achieved in a simpler tray-pack format that avoids the high capital cost of MAP and vacuum systems (Soffer *et al*., 1994; Lanari *et al.,* 1995). The performance therefore positions HDPE-plus-scavenger as a commercially attractive entry-level upgrade for organised retailers transitioning from open-pouch displays to retail-ready packaging.

Limitations and Recommendations for Further Research

The present comparative study has three limitations that should be addressed in future work. First, the scavenger sachet mass (2.5 g) was selected based on the commercial pack size of O-SORB U100 rather than on a dose–response optimisation; the marginal benefit of larger or smaller sachet doses against the headspace volume of the 19 × 14 × 3 cm PP tray (approximately 800 mL gross volume; ~600 mL effective headspace after product loading) remains uncharacterised. Second, the storage was conducted at a constant 4 ± 1 °C, whereas real-world Indian retail experiences temperature fluctuations up to 8 °C that would accelerate both oxidative and microbial deterioration; the temperature sensitivity of the HDPE-plus-scavenger performance should be quantified. Third, the comparative analysis here used a single barrier polymer (HDPE) and a single scavenger chemistry (iron-based); evaluation against alternative oxygen scavengers (e.g., enzymatic systems, palladium-catalysed systems) and alternative barrier polymers (e.g., EVOH-laminated films) under the same protocol would clarify whether HDPE plus iron-based scavenger is the global optimum for both pork matrices or whether matrix-specific optima exist. A factorial designed experiment with three temperatures, three scavenger doses and two product matrices would provide the design space needed for these recommendations.

Conclusions

An iron-based oxygen scavenger sachet incorporated in food-grade polypropylene trays sealed with HDPE wrap improved the chilled shelf life of both fresh pork chunks (from 5 to 8 days; 60 % gain) and cooked pork nuggets (from 19 to 23 days; 21 % gain) at 4±1 °C. The protective effect is matrix-dependent: in fresh raw pork, the scavenger primarily suppresses aerobic and psychrophilic microbial growth and microbial proteolysis; in cooked emulsion-based pork nuggets, it primarily retards lipid oxidation and hydrolysis. The HDPE-plus-oxygen-scavenger active tray-packaging system therefore represents a single, commercially scalable platform suitable for both raw and processed pork retail formats, with documented quantitative shelf-life benefits in both matrices. Future work should evaluate the system under fluctuating retail-display temperatures, consumer-handling abuse and against vacuum and MAP alternatives, and should map the dose–response relationship between scavenger sachet mass and shelf-life gain to enable cost-optimised commercial deployment.

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