RESEARCH ARTICLE

Shelf-Life Extension of Refrigerated Pork Nuggets by Active Tray Packaging in Polypropylene Trays with Different Barrier Wrap Films and an Iron-Based Oxygen Scavenger

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Abstract

Pork nuggets are an emulsion-based, cooked, ready-to-eat meat product whose lipid- and protein-rich matrix is highly susceptible to oxidative deterioration and post-process microbial recontamination during chilled retail. The present study evaluated the effect of four food-grade wrap films (LDPE, LLDPE, HDPE and PVC) combined with food-grade polypropylene trays, with or without an iron-based oxygen scavenger sachet (2.5 g O-SORB U100), on the physico-chemical, microbiological and sensory quality of refrigerated pork nuggets. Pork nuggets prepared from a standardised emulsion (70% lean meat, 10% vegetable oil, 10% ice, 3.5% onion-garlic, 2.5% corn flour and curing salts) were heat-processed to a core temperature of ≥82 °C, sliced (13 mm) and tray-packaged (200 g per tray). Eight treatments were stored at 4 ± 1 °C for up to 23 days and sampled on days 0, 5, 10, 13, 16, 19, 21 and 23. Pork nuggets tray-packaged with HDPE wrap and an in-pack oxygen scavenger (THDPE) retained acceptable quality up to 23 days, whereas the same product wrapped in HDPE without scavenger or in LDPE, LLDPE or PVC with scavenger remained acceptable only up to 21 days, and pork nuggets in control LDPE, LLDPE or PVC packs (no scavenger) spoiled by day 19. On day 19, THDPE recorded the lowest values of TBARS (0.403 mg MDA/kg), free fatty acid value (0.464% oleic acid), tyrosine value (0.601 mg/g), total plate count (3.58 log CFU/g), and highest sensory acceptance, in comparison with CLDPE (TBARS 0.480 mg MDA/kg, FFA 0.683%, tyrosine 0.704 mg/g, TPC 4.03 log CFU/g). The HDPE + oxygen scavenger system therefore extended the refrigerated shelf-life of pork nuggets by 4 days (from 19 to 23 days) relative to current LDPE retail practice and represents a practical, cost-effective tray-packaging upgrade for chilled processed-pork retailing.

Keywords: Active packaging, Barrier film, HDPE, Lipid oxidation, Oxygen scavenger, Pork nuggets, Refrigerated storage, Shelf life.

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Introduction

Cooked, comminuted and emulsion-based pork products such as nuggets, patties, meatballs and sausages occupy an expanding share of organised meat retail in emerging economies, driven by urbanisation, rising disposable incomes and the convenience of ready-to-eat formats (Olaoye and Onilude, 2010; McAfee *et al.,* 2010). Pork nuggets, in particular, are popular in urban Indian retail because their bite size, mild spicing and short preparation time align well with home and food-service use. Although heat processing of nuggets (core temperature ≥82 °C) substantially reduces the initial microbial load, the cooled product remains a nutritionally rich substrate (≈18-20% protein, 10-14% fat) susceptible to lipid oxidation, fat hydrolysis, proteolysis, and surface recontamination by psychrotrophic bacteria, yeasts and moulds during chilled retail (Ercolini *et al.,* 2009).

Conventional retail packaging of processed pork products in India is dominated by simple LDPE pouches sealed under air. LDPE wrap films have an oxygen transmission rate (OTR) of 6,500-8,500 cm^3/m^2/24 h and a water vapour transmission rate (WVTR) of 10-20 g/m^2/24 h, which are inadequate to control lipid oxidation in fat-rich emulsion products over the typical 12-14 day refrigerated shelf life of pork nuggets. Vacuum and modified atmosphere packaging (MAP) extend shelf life but require specialised equipment, gas mixtures and tightly controlled cold chain conditions that are not always available in small-to-medium scale processors and retailers (Soffer *et al.,* 1994; Lanari *et al.,* 1995).

Tray-and overwrap packaging is the dominant retail format for fresh and processed meat in developed markets and is more compatible with the existing Indian retail infrastructure than vacuum or MAP. The thermoformable

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polypropylene (PP) tray provides rigidity, oxygen barrier on the base and dimensional stability under heat-sealing temperatures, while the choice of wrap film determines the package's overall barrier and visual properties. Among commercial wraps, LLDPE (OTR ≈200 cm^3/m^2/24 h), HDPE (OTR 1 600-2000 cm^3/m^2/24 h) and PVC (OTR 8-125 cm^3/m^2/24 h) provide substantially lower oxygen ingress than LDPE (Han *et al.,* 2005; Dhineshkumar *et al.,* 2026).

Active packaging - the deliberate inclusion of in-package functional components such as oxygen scavengers, moisture absorbers, antimicrobial release devices or ethylene scavengers -has emerged as a complementary strategy to improve the storage stability of muscle foods (Ahmed *et al.,* 2017; Bhardwaj *et al.,* 2019). Iron-based oxygen scavenger sachets exploit the oxidation of metallic iron in the presence of moisture to reduce residual headspace oxygen below 0.01% (Vermeiren *et al.,* 1999; Dhineshkumar *et al.,* 2026), thereby limiting fat oxidation and aerobic microbial growth. While the application of oxygen scavengers in MAP and vacuum-packed pork has been documented (Mexis *et al.,* 2012; Busolo and Lagaron, 2012), comparative data on tray-packaged cooked pork products with the four commercial wrap polymers most readily available in tropical retail (LDPE, LLDPE, HDPE, PVC) are scarce. The aim of the present study was therefore to evaluate the effect of four wrap film types (LDPE, LLDPE, HDPE, PVC), with and without an in-pack iron-based oxygen scavenger sachet, on the physico-chemical, microbiological and sensory quality of pork nuggets tray-packaged in food-grade PP trays during refrigerated storage at 4±1 °C for up to 23 days to identify the most suitable wrap film and active-packaging combination for organised retail of pork nuggets in tropical Indian markets.

Materials and Methods

Raw Material and Pork Nugget Preparation

Crossbred male pigs (approximately 6 months old, ~90 kg live weight) reared at the Livestock Production Management unit were slaughtered humanely at the experimental abattoir of the Division of Livestock Products Technology, ICAR-Indian Veterinary Research Institute, Izatnagar, India. Carcasses were deboned and washed in 1% saline, packed in food-grade LDPE pouches and held at –18 ± 2 °C until use. For each of three independent trials, approximately 8 kg of frozen deboned pork was thawed overnight at 4±1 °C, drained and minced (Seydelmann mincer, Germany) through 6-mm and 4-mm plates.

The pork emulsion was prepared in a six-blade bowl chopper (Seydelmann D 7000, Stuttgart, Germany) at low speed in the following sequence (formulation in % w/w of total emulsion): lean meat 70.0; ice flakes 10.0; refined soybean oil 10.0; onion-garlic paste (3:1) 3.5; corn flour 2.5; common salt 1.6; spice mix 1.5; sodium tripolyphosphate 0.4; sugar 0.5; and sodium nitrite 0.015. Salt, nitrite and STPP were added first with the first half of the ice to extract myofibrillar proteins; oil, condiments, spice mix and binder were added sequentially. The remaining ice was added at the end and the bowl chopper was operated until a sticky, homogeneous emulsion was obtained. Approximately 950-1000 g of emulsion was filled by hand without air pockets into stainless-steel block moulds (200 × 150 × 50 mm). Filled moulds were sealed and steam-cooked in a 30-L autoclave for 40 min after first steam to reach a core temperature of ≥82 °C, verified with a glass mercury thermometer. Cooked blocks were cooled to room temperature, demoulded, weighed for cook yield and sliced to 13 mm thickness using an electric meat slicer (Electrolux OMAS, Italy) to yield the final pork nuggets.

Packaging Materials and Treatments

Food-grade PP trays (190 × 140 × 30 mm, 5 mm wall) were used as the primary container. Four food-grade wrap films were procured locally: LDPE (60 µm; OTR 6,500-8,500 cm^3/m^2/24 h; WVTR 10–20 g/m^2/24 h); LLDPE (60 µm; OTR ≈200 cm^3/m^2/24 h; WVTR 15.5-18 g/m^2/24 h); HDPE (80 µm; OTR 1 600-2000 cm^3/m^2/24 h; WVTR 7-10 g/m^2/24 h); and PVC (55 µm; OTR 8-125 cm^3/m^2/24 h; WVTR 1.5-5 g/m^2/24 h). Iron-based food-grade oxygen scavenger sachets (O-SORB U100, 2.5 g per sachet) were used as the active packaging element.

Approximately 200 g of pork nuggets were placed in each PP tray. Trays were heat-sealed in a manual MITSUMI tray sealer at 150-155 °C (LDPE), 155-160 °C (LLDPE) or 175-180 °C (HDPE) with a 10-s cooling step; PVC was shrouded manually since the film does not tolerate heat sealing. Eight treatments were prepared: CLDPE, TLDPE, CLLDPE, TLLDPE, CHDPE, THDPE, CPVC and TPVC, where C denotes control (no scavenger) and T denotes treatment (one 2.5 g iron-based oxygen scavenger sachet placed in the package prior to sealing). All packages were stored at 4±1 °C and analysed on days 0, 5, 10, 13, 16, 19, 21 and 23. Spoiled packages were terminated from further sampling.

Laboratory Evaluation of Nuggets

The physico-chemical, microbiological and sensory evaluation of the pork nuggets was carried out using standard procedures as detailed in our earlier publication on pork chunks (Dhineshkumar *et al.,* 2026).

Statistical Analysis

The experiment was conducted in three independent trials, each in triplicate (n=9 per treatment per day). Data were analysed by two-way ANOVA (treatment × storage day) in SPSS version 25.0 (IBM, Armonk, NY, USA). Treatment means were compared by Duncan's multiple range test at $p < 0.05$.

Results and Discussion

pH of Nuggets

The initial pH of pork nuggets was 6.10 ± 0.02, characteristic of cooked, salt-cured emulsion products. pH increased significantly ($p < 0.05$) in all treatments during refrigerated

storage, with the most rapid increase between day 16 and day 19, attributable to protein degradation by surviving and post-process recontaminating bacteria yielding basic nitrogenous metabolites (Jay, 1996). On day 19, control LDPE nuggets recorded the highest pH (6.42 ± 0.01), whereas THDPE recorded the lowest (6.23 ± 0.01) (Table 1). At later sampling points, the rapid pH rise in spoiled samples (e.g., TLDPE reached 6.77 on day 21 and THDPE 6.79 on day 23) signalled the end of acceptable shelf life. The pH pattern is therefore a robust marker of microbial spoilage in this product. We found very similar trend/results with pork chunks packaged and stored in a similar fashion earlier (Dhineshkumar *et al.,* 2026)

Instrumental Colour

L* values rose and a* and b* values declined in all treatments during refrigerated storage. The increase in L* and decrease in a* are attributable to surface desiccation and to the oxidation of nitrosylmyoglobin - the cooked, cured pigment - to brown metmyochromogen, particularly at higher oxygen exposure (Brewer and Wu, 1993; Lavieri and Williams, 2014). PVC-wrapped nuggets showed the smallest changes in L*, a* and b*, consistent with the low OTR of PVC. HDPE-wrapped nuggets were the second most colour-stable. LDPE wraps showed the largest increase in L* and the largest decline in a*. The presence of an oxygen scavenger improved colour retention within each polymer category, as was noticed by Dhineshkumar *et al.* (2026).

TBARS and Free Fatty Acid Value

Lipid oxidation, expressed as TBARS, rose significantly ($p < 0.05$) in all treatments from an initial value of 0.1640 mg MDA/kg. The pattern of TBARS across treatments was consistent throughout the 23-day storage period (Table 1). THDPE consistently recorded the lowest values, while CLDPE recorded the highest within each polymer pairing. On day 19, TBARS values were 0.480 ± 0.001 (CLDPE), 0.418 ± 0.001 (TLDPE), 0.491 ± 0.001 (CLLDPE), 0.452 ± 0.001 (TLLDPE), 0.439 ± 0.001 (CHDPE), 0.403 ± 0.001 (THDPE), 0.456 ± 0.001 (CPVC) and 0.445 ± 0.001 (TPVC) mg MDA/kg. Although day-19 values remained below the 1.0 mg MDA/kg rancidity threshold for all treatments, by day 21 the surviving non-scavenger samples spoiled and TBARS in the scavenger samples rose to 0.65-0.99 mg MDA/kg, indicating that lipid oxidation accelerates rapidly toward end-of-shelf-life. The free fatty acid value followed a similar trend: initial FFA was 0.3041% oleic acid, rising on day 19 to 0.683% (CLDPE) and 0.464% (THDPE) (Table 1). The lower FFA values observed for HDPE-packaged samples reflect lower lipolytic activity, consistent with the lower microbial counts measured with this treatment (Rao *et al.,* 2003; Das *et al.,* 2008; Dhineshkumar *et al.,* 2026).

Tyrosine Value and Shear Force

Tyrosine value, an indicator of proteolysis, rose from 0.1801 mg/g on day 0 to 0.704 mg/g (CLDPE) and 0.601 mg/g (THDPE) on day 19, reflecting both endogenous and microbial enzymatic action (Strange *et al.,* 1977). The lower tyrosine value in HDPE-packaged nuggets is consistent with their lower microbial load. Warner-Bratzler shear force decreased from an initial 0.23 kg/cm^2 to lower values during storage; on day 19, THDPE retained the highest shear force among treatments while CLDPE recorded the lowest, paralleling the tyrosine value data (Table 1). A very similar trend with pork chunks packaged and stored in a similar fashion was found in our earlier study (Dhineshkumar *et al.,* 2026).

Microbiological Quality

Total aerobic plate count, coliform, psychrotrophic and yeast–mould counts all increased significantly ($p < 0.05$) during refrigerated storage (Table 2). Initial TPC was 1.54 ± 0.01 log CFU/g, reflecting the residual microbial load after cooking. On day 19, control LDPE nuggets recorded 4.03 ± 0.00 log CFU/g and THDPE recorded the lowest TPC (3.58 ± 0.02 log CFU/g). Adopting 5.0 log CFU/g as the practical upper acceptable limit for cooked emulsion products, THDPE remained microbiologically acceptable up to day 21 (TPC 4.05 log CFU/g) and was the only treatment to remain within acceptable range on day 23 (TPC 4.99 log CFU/g). Coliform counts in HDPE-packaged samples were significantly lower than in LDPE, LLDPE and PVC samples on day 19. The yeast-mould load was lowest in HDPE-packaged nuggets and highest in PVC-packaged nuggets, consistent with the higher CO_2 retention of PVC, which can selectively favour CO_2-tolerant yeast species (Babic *et al.,* 1992). Recently we found very similar trend/ results with pork chunks packaged and stored in a similar fashion (Dhineshkumar *et al.,* 2026).

Sensory Acceptance

Mean sensory scores for appearance and colour, flavour, texture, juiciness and overall acceptability declined progressively in all treatments (Table 2). THDPE pork nuggets consistently received the highest sensory scores from day 5 to day 21 in all attributes except odour, where PVC was comparable to HDPE. The better sensory performance of HDPE-packaged nuggets reflects their lower TBARS, FFA, tyrosine value and microbial load, and higher shear force. Pork nuggets in CLDPE, CLLDPE and CPVC packages were rejected by the panel on day 19; samples in TLDPE, TLLDPE, CHDPE and TPVC packages were rejected on day 21; only THDPE remained sensorially acceptable on day 23, after which the panel scored the product below 5 on the 8-point hedonic scale and the trial was terminated. Similar results were obtained by Dhineshkumar *et al.* (2026)

Practical Implications for Retail

The combined data indicate that the HDPE + oxygen-scavenger active tray-packaging system extended the refrigerated shelf life of pork nuggets to 23 days, compared with 19 days for the conventional LDPE control. This

Table 1: Pattern of pH changes, free fatty acids, TBARS (mg MDA/kg) and tyrosine value (mg/g) in pork nuggets tray-packaged in food-grade polypropylene trays sealed with LDPE, LLDPE, HDPE and PVC wrap films and stored for 23 days at 4 ± 1 °C with and without iron-based oxygen scavenger (Mean ± SE, n=9)

Parameter	Packaging	Days of storage at 4±1 °C							
		0	5	10	13	16	19	21	23
pH	CLDPE	6.10±0.02^{aA}	6.20±0.01^{bE}	6.23±0.00^{cD}	6.26±0.00^{dD}	6.36±0.02^{eD}	6.42±0.01^{fE}	*Sp*	*Sp*
	TLDPE	6.10±0.02^{aA}	6.20±0.01^{cE}	6.13±0.01^{bA}	6.23±0.01^{dC}	6.27±0.01^{eB}	6.34±0.01^{fC}	6.77±0.01^{gE}	*Sp*
	CLLDPE	6.10±0.02^{aA}	6.15±0.00^{bD}	6.17±0.01^{cB}	6.23±0.01^{dC}	6.29±0.02^{eC}	6.40±0.05^{fD}	*Sp*	*Sp*
	TLLDPE	6.10±0.02^{aA}	6.15±0.01^{bD}	6.21±0.01^{cC}	6.20±0.01^{cB}	6.33±0.02^{dD}	6.36±0.02^{dC}	6.58±0.02^{eC}	*Sp*
	CHDPE	6.10±0.02^{aA}	6.12±0.01^{aC}	6.16±0.01^{bB}	6.20±0.01^{cB}	6.25±0.01^{dB}	6.29±0.01^{eB}	6.48±0.02^{fB}	*Sp*
	THDPE	6.10±0.02^{bA}	6.07±0.00^{aA}	6.14±0.01^{cA}	6.18±0.00^{dA}	6.19±0.01^{eA}	6.23±0.01^{fA}	6.40±0.01^{gA}	6.79±0.02^{hA}
	CPVC	6.10±0.02^{aA}	6.12±0.00^{bC}	6.16±0.00^{cB}	6.21±0.00^{dB}	6.24±0.02^{eB}	6.41±0.04^{fD}	*Sp*	*Sp*
	TPVC	6.10±0.02^{aA}	6.09±0.00^{aB}	6.14±0.01^{bA}	6.19±0.02^{cA}	6.19±0.02^{cA}	6.37±0.01^{dD}	6.66±0.02^{eD}	*Sp*
Free fatty acids (% oleic acid)	CLDPE	0.304±0.01^{aA}	0.440±0.00^{bE}	0.532±0.00^{cG}	0.631±0.00^{dG}	0.651±0.00^{eF}	0.740±0.00^{fE}	*Sp*	*Sp*
	TLDPE	0.304±0.01^{aA}	0.443±0.00^{bF}	0.524±0.00^{cE}	0.626±0.00^{dF}	0.636±0.00^{eE}	0.718±0.00^{fD}	0.895±0.00^{gC}	*Sp*
	CLLDPE	0.304±0.01^{aA}	0.455±0.00^{bH}	0.538±0.00^{cH}	0.637±0.00^{dH}	0.655±0.00^{eG}	0.773±0.00^{fF}	*Sp*	*Sp*
	TLLDPE	0.304±0.01^{aA}	0.451±0.00^{bG}	0.527±0.00^{cF}	0.625±0.00^{dE}	0.631±0.00^{eD}	0.872±0.00^{fG}	1.209±0.00^{gE}	*Sp*
	CHDPE	0.304±0.01^{aA}	0.386±0.00^{bB}	0.512±0.01^{cD}	0.579±0.00^{dB}	0.594±0.00^{eA}	0.687±0.00^{fB}	0.872±0.01^{gB}	*Sp*
	THDPE	0.304±0.01^{aA}	0.380±0.00^{bA}	0.480±0.00^{cA}	0.569±0.00^{dA}	0.594±0.00^{eA}	0.658±0.00^{fA}	0.773±0.00^{gA}	0.988±0.00^{hA}
	CPVC	0.304±0.01^{aA}	0.419±0.00^{bD}	0.501±0.00^{cC}	0.606±0.00^{dD}	0.617±0.00^{eC}	1.111±0.01^{fH}	*Sp*	*Sp*
	TPVC	0.304±0.01^{aA}	0.404±0.00^{bC}	0.491±0.00^{cB}	0.597±0.00^{dC}	0.607±0.00^{eB}	0.707±0.00^{fC}	1.016±0.00^{gD}	*Sp*
TBARS (mg MDA/kg)	CLDPE	0.164±0.00^{aA}	0.257±0.00^{bG}	0.368±0.00^{cE}	0.405±0.00^{eH}	0.397±0.00^{dD}	0.480±0.00^{fG}	*Sp*	*Sp*
	TLDPE	0.164±0.00^{aA}	0.242±0.00^{bE}	0.348±0.00^{cC}	0.388±0.00^{dF}	0.323±0.06^{cA}	0.418±0.00^{eB}	0.971±0.00^{fD}	*Sp*
	CLLDPE	0.164±0.00^{aA}	0.260±0.00^{bH}	0.355±0.00^{cD}	0.393±0.00^{eG}	0.388±0.00^{dC}	0.491±0.00^{fH}	*Sp*	*Sp*
	TLLDPE	0.164±0.00^{aA}	0.239±0.00^{bD}	0.348±0.00^{cC}	0.379±0.00^{eE}	0.377±0.00^{dA}	0.452±0.00^{fE}	0.991±0.00^{gE}	*Sp*
	CHDPE	0.164±0.00^{aA}	0.231±0.00^{bB}	0.348±0.00^{cC}	0.373±0.00^{eC}	0.362±0.00^{dA}	0.439±0.00^{fC}	0.678±0.00^{gB}	*Sp*
	THDPE	0.164±0.00^{aA}	0.224±0.00^{bA}	0.332±0.00^{cA}	0.352±0.00^{eA}	0.351±0.00^{dA}	0.403±0.00^{fA}	0.647±0.00^{gA}	0.942±0.00^{hA}
	CPVC	0.164±0.00^{aA}	0.243±0.00^{bF}	0.352±0.01^{cC}	0.377±0.00^{dD}	0.387±0.00^{eB}	0.456±0.00^{fF}	*Sp*	*Sp*
	TPVC	0.164±0.00^{aA}	0.235±0.00^{bC}	0.335±0.00^{cB}	0.366±0.00^{dB}	0.377±0.00^{eA}	0.445±0.00^{fD}	0.902±0.00^{gC}	*Sp*
Tyrosine value (mg/g)	CLDPE	0.180±0.01^{aA}	0.244±0.01^{bF}	0.331±0.00^{cH}	0.401±0.00^{dG}	0.427±0.00^{eF}	0.704±0.00^{fH}	*Sp*	*Sp*
	TLDPE	0.180±0.01^{aA}	0.234±0.00^{bF}	0.324±0.00^{cG}	0.369±0.00^{dD}	0.384±0.01^{eB}	0.633±0.00^{fC}	1.230±0.01^{gD}	*Sp*
	CLLDPE	0.180±0.01^{aA}	0.247±0.00^{bG}	0.321±0.00^{cF}	0.406±0.00^{dH}	0.422±0.00^{eE}	0.703±0.00^{fG}	*Sp*	*Sp*
	TLLDPE	0.180±0.01^{aA}	0.231±0.00^{bD}	0.306±0.00^{cE}	0.372±0.00^{dE}	0.392±0.00^{eD}	0.638±0.00^{fD}	1.280±0.00^{gE}	*Sp*
	CHDPE	0.180±0.01^{aA}	0.223±0.00^{bC}	0.288±0.00^{cB}	0.368±0.00^{dC}	0.392±0.00^{eD}	0.666±0.00^{fF}	0.818±0.00^{gB}	*Sp*
	THDPE	0.180±0.01^{aA}	0.219±0.00^{bA}	0.278±0.00^{cA}	0.349±0.00^{dA}	0.368±0.00^{eA}	0.601±0.00^{fA}	0.776±0.00^{gA}	1.069±0.00^{hA}
	CPVC	0.180±0.01^{aA}	0.233±0.00^{bE}	0.302±0.00^{cD}	0.376±0.00^{dF}	0.390±0.00^{eC}	0.649±0.00^{fE}	*Sp*	*Sp*
	TPVC	0.180±0.01^{aA}	0.220±0.00^{bB}	0.294±0.00^{cC}	0.364±0.00^{dB}	0.380±0.00^{eB}	0.612±0.00^{fB}	1.162±0.00^{gC}	*Sp*

"Sp" indicates spoiled and removed from analysis. C = control (no oxygen scavenger); T = oxygen scavenger sachet inside the package. Means with different lowercase superscripts within each row (a, b, c …) and different uppercase superscripts within each column (A, B, C …) differ significantly ($p<0.05$).

Table 2: Pattern of total aerobic plate count (TPC, log_{10} CFU/g) and overall sensory acceptability scores (8-point hedonic scale) of pork nuggets tray-packaged in food-grade polypropylene trays sealed with LDPE, LLDPE, HDPE and PVC wrap films and stored for 23 days at 4±1 °C with and without iron-based oxygen scavenger (Mean ± SE, n=9)

Parameter	Packaging	Days of storage at 4±1 °C							
		0	5	10	13	16	19	21	23
TPC log_{10} CFU/g	CLDPE	1.54±0.01^{Aa}	1.95±0.00^{Bc}	2.55±0.01^{Cd}	3.03±0.02^{Ce}	3.44±0.02^{Cf}	4.03±0.00^{Dg}	*Sp*	*Sp*
	TLDPE	1.54±0.01^{Aa}	1.86±0.02^{Ab}	2.41±0.00^{Bc}	2.92±0.02^{Bd}	3.23±0.02^{Be}	3.77±0.01^{Bf}	5.24±0.03^{Bg}	*Sp*
	CLLDPE	1.54±0.01^{Aa}	1.96±0.02^{Bc}	2.75±0.01^{Dd}	3.09±0.02^{De}	3.80±0.02^{Ef}	4.17±0.09^{Dg}	*Sp*	*Sp*
	TLLDPE	1.54±0.01^{Aa}	1.91±0.01^{Bb}	2.46±0.01^{Bc}	3.02±0.01^{Cd}	3.51±0.01^{De}	3.93±0.05^{Cf}	5.49±0.07^{Cg}	*Sp*
	CHDPE	1.54±0.01^{Aa}	1.64±0.01^{Ab}	2.06±0.03^{Ac}	2.38±0.01^{Ad}	3.10±0.03^{Ae}	3.58±0.08^{Af}	4.05±0.03^{Ag}	*Sp*
	THDPE	1.54±0.01^{Aa}	1.64±0.01^{Ab}	2.06±0.03^{Ac}	2.38±0.01^{Ad}	3.10±0.03^{Ae}	3.58±0.02^{Af}	4.05±0.03^{Ag}	4.99±0.00^{Ah}
	CPVC	1.54±0.01^{Aa}	1.86±0.01^{Ab}	2.50±0.06^{Cd}	2.89±0.04^{Bd}	3.41±0.03^{Cf}	3.96±0.05^{Cg}	*Sp*	*Sp*
	TPVC	1.54±0.01^{Aa}	1.81±0.03^{Ab}	2.20±0.01^{Ac}	2.81±0.01^{Bd}	3.24±0.03^{Be}	3.78±0.06^{Bf}	5.15±0.01^{Bg}	*Sp*
Sensory acceptability scores	CLDPE	7.88±0.04^{Aa}	7.49±0.01^{Cc}	7.29±0.05^{Cd}	7.01±0.01^{Ce}	6.64±0.03^{Df}	6.44±0.02^{Dg}	*Sp*	*Sp*
	TLDPE	7.88±0.04^{Aa}	7.64±0.01^{Bb}	7.39±0.00^{Bc}	7.24±0.05^{Bd}	6.98±0.05^{Be}	6.76±0.04^{Bf}	6.26±0.02^{Bg}	*Sp*
	CLLDPE	7.88±0.04^{Aa}	7.44±0.04^{Dd}	7.19±0.02^{De}	6.98±0.03^{Df}	6.86±0.04^{Cf}	6.54±0.05^{Cg}	*Sp*	*Sp*
	TLLDPE	7.88±0.04^{Aa}	7.58±0.00^{Cb}	7.34±0.01^{Bc}	7.12±0.04^{Cd}	6.92±0.02^{Be}	6.78±0.03^{Bf}	6.25±0.01^{Bg}	*Sp*
	CHDPE	7.88±0.04^{Aa}	7.66±0.00^{Bb}	7.44±0.03^{Ac}	7.14±0.30^{Cd}	7.01±0.01^{Ae}	6.86±0.01^{Af}	6.51±0.04^{Ag}	*Sp*
	THDPE	7.88±0.04^{Aa}	7.70±0.00^{Ab}	7.58±0.00^{Ac}	7.32±0.02^{Ad}	7.11±0.00^{Ae}	7.01±0.00^{Af}	6.91±0.04^{Ag}	6.49±0.02^{Ah}
	CPVC	7.88±0.04^{Aa}	7.59±0.00^{Cc}	7.33±0.02^{Bc}	7.10±0.04^{Cd}	6.84±0.01^{Be}	6.54±0.05^{Cg}	*Sp*	*Sp*
	TPVC	7.88±0.04^{Aa}	7.66±0.00^{Bb}	7.41±0.04^{Bc}	7.14±0.02^{Cd}	7.01±0.05^{Ae}	6.88±0.04^{Af}	6.37±0.04^{Bg}	*Sp*

"Sp" indicates spoiled & removed from analysis. C = control (no oxygen scavenger); T = oxygen scavenger sachet inside the package. Means with different superscripts within each row (a,b,c) and within column (A,B,C) differ significantly ($p<0.05$).

corresponds to a 21% gain in shelf life, equivalent to four additional days of retail display and consumer use without compromising the physico-chemical, microbiological or sensory quality of the product. The system uses materials and equipment already available in the Indian and South-Asian organised retail value chain (PP trays, commercial wrap films, manual heat-sealers and iron-based scavenger sachets) and therefore provides a low-capital, near-term shelf-life upgrade path that does not require investment in vacuum or MAP equipment. PVC delivered superior colour stability and may therefore be a viable alternative when visual presentation rather than microbial shelf life is the limiting commercial factor, and could potentially be combined with antimicrobial wraps to address its yeast-mould vulnerability.

Conclusions

Active tray packaging of pork nuggets in food-grade polypropylene trays sealed with HDPE wrap film and containing an iron-based oxygen scavenger maintained acceptable physico-chemical, microbiological and sensory quality during refrigerated storage at 4±1 °C for 23 days, compared with 19 days for the conventional LDPE pouch retail format used in India. The HDPE + oxygen scavenger system achieved the lowest TBARS, FFA, tyrosine value and microbial load and the highest sensory scores throughout the storage period. PVC wrap delivered superior colour stability but failed to control yeast and mould growth. The proposed packaging system is built from materials and equipment that are already commercially available in tropical retail markets and represents a viable, low-capital upgrade path for chilled pork-nugget retailing. Future work should evaluate the system under fluctuating temperature-abuse conditions, consumer-handling scenarios and against gas-flush MAP alternatives, and should consider integrating antimicrobial wraps with PVC to extend its commercial usefulness.

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