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Modified Atmosphere Packaging (MAP): Functional Role of Low Oxygen Levels in Enhancing Food Quality and Safety

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Abstract

Modified Atmosphere Packaging (MAP) extends the shelf life of perishable foods by altering the gas environment inside the package. Traditional MAP designs focus heavily on stripping oxygen to prevent lipid oxidation and suppress aerobic spoilage organisms. However, completely removing oxygen can create an anaerobic environment that favors dangerous pathogens and causes off-flavors in fresh produce. This review systematically examines the functional role of low-to-intermediate oxygen levels (typically 1–10%) across red meat, horticultural produce, seafood, and bakery products. While keeping oxygen within this range can help maintain oxymyoglobin bloom in fresh meats and keep plant tissues above their anaerobic compensation point, intermediate oxygen concentrations cannot be considered universally optimal or sufficient alone to prevent anaerobic pathogen proliferation. Rather, oxygen partial pressure operates as a context-dependent variable whose preservation efficacy is governed by the food matrix, storage temperature, substrate pH, water activity, and surrounding carbon dioxide concentrations. Tailored gas formulations integrated with rigorous cold-chain management and secondary preservation hurdles remain essential for safe packaging design.

Keywords: Modified Atmosphere Packaging, low oxygen, food preservation, shelf life extension, microbial safety, oxidation control, anaerobic pathogens, packaging systems

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1. Introduction

Preserving perishable foods presents a constant challenge for the food industry. Microbial growth, tissue respiration, and chemical oxidation quickly break down fresh products, leading to safety risks, unappealing textures or odors, and financial loss. Global estimates from the Food and Agriculture Organization indicate that nearly a third of all food produced for human consumption is lost or wasted annually, with fresh items making up a large portion of that total (FAO, 2023). Modified Atmosphere Packaging (MAP) addresses this issue by adjusting the headspace gases inside the package to slow down these degradation pathways (Robertson, 2016; Ahmed et al., 2023).

Historically, packaging engineers focused on removing as much oxygen as possible because oxygen exposure accelerates lipid rancidity and supports the growth of aerobic bacteria. The drawback to this approach is that near-zero oxygen levels create anaerobic conditions. These conditions allow facultative and obligate anaerobes—such as non-proteolytic *Clostridium botulinum*—to grow while causing fresh produce to switch to fermentative pathways that ruin flavor (Brody et al., 2008; Parlapani et al., 2023). Modern food packaging research is moving away from seeing oxygen as purely harmful, treating it instead as an active variable that can be controlled to balance product safety, color, and flavor (Zhang & Xie, 2024; McMillin, 2024).

MAP is applied across a wide variety of commodities, including fresh vegetables, red meat, poultry, seafood, and ready-to-eat products (Hassoun & Karoui, 2023). Beyond retail display, it supports broader supply chains, catering services, and food security initiatives by extending product shelf life and reducing waste (United Nations Environment Programme, 2024; García-García et al., 2024). However, defining precise oxygen thresholds for different food categories remains a key challenge. Moving from standardized gas mixtures toward precision packaging requires a thorough understanding of how oxygen interacts with food chemistry, packaging film permeability, and microbial ecology (Caleb et al., 2023; Habiba et al., 2025).

2. Literature Review / Related Work

Modified Atmosphere Packaging typically relies on varying combinations of carbon dioxide (CO_2), nitrogen (N_2), and oxygen (O_2). Carbon dioxide serves as the primary antimicrobial agent by dissolving into the aqueous phase of food, lowering intracellular pH, and inhibiting key bacterial enzymes (Parry, 1993; Hassoun & Karoui, 2017). Nitrogen acts as an inert filler gas that prevents package collapse without directly affecting microbial growth or chemical reactions (Robertson, 2016).

Oxygen plays a multifaceted role across different food matrices. In fresh red meat, oxygen partial pressure governs the dynamic interconversion between three primary myoglobin redox states: purple-red deoxymyoglobin (Fe^{2+}, unliganded), bright cherry-red oxymyoglobin (Fe^{2+}, oxygenated), and brown metmyoglobin (Fe^{3+}, oxidized) (Sørheim et al., 1999; Suman et al., 2014; Lindahl et al., 2020; McMillin, 2024). High-oxygen MAP (70–80% O_2) promotes oxymyoglobin formation, giving beef the bright cherry-red appearance preferred by consumers. However, these elevated levels speed up lipid and protein oxidation, leading to rancidity and sensory decline over time (Lindahl et al., 2020; McMillin, 2024). In strictly anaerobic packaging (<0.1% O_2), pigment is maintained primarily as deoxymyoglobin, which rapidly blooms to oxymyoglobin upon atmospheric exposure. Conversely, low-to-intermediate oxygen partial pressures in the critical 0.5–5% O_2 window represent the zone where the rate of metmyoglobin formation peaks, resulting in undesirable brown surface discoloration that compromises retail marketability (Sørheim et al., 1999; Suman et al., 2014).

In horticultural produce, oxygen levels dictate respiration rate and metabolic activity (Kader, 2002). Reducing oxygen slows down tissue respiration and delays senescence (Caleb et al., 2023). However, if oxygen drops below the commodity's Anaerobic Compensation Point (ACP)—typically 2–3% O_2—tissues switch to fermentative respiration, producing ethanol and acetaldehyde that generate off-flavors and tissue breakdown (Sandhya, 2010; Yahia, 2019).

Oxygen availability also shapes the microbial ecology inside the package. Low oxygen levels suppress aerobic spoilage organisms like *Pseudomonas spp.*, which extends the raw shelf life of meats and fish (Church & Parsons, 1995). However, this suppression removes competitive stress, creating conditions where psychrotrophic pathogens like *Listeria monocytogenes* or obligate anaerobes like *Clostridium botulinum* can multiply if temperature control fails (Farber, 1991; Parlapani et al., 2023; Zhang et al., 2022). While conventional MAP relies on either high-oxygen or near-anaerobic extremes, intermediate oxygen levels (1–10%) offer a potential middle ground to mitigate oxidative damage while limiting anaerobic pathogen risks (Ahmed et al., 2023; Zhang & Xie, 2024).

3. Methodology

We conducted a systematic narrative review following a four-stage protocol aligned with PRISMA guidelines. Literature searches were executed across Scopus, Web of Science, PubMed, and Google Scholar in March 2025, focusing on peer-reviewed publications published within the primary 2000–2025 epoch (including foundational postharvest works such as Kader, 2002). A small group of pre-2000 studies (e.g., Farber, 1991; Church & Parsons, 1995; Sørheim et al., 1999) were retained as explicit foundational background exceptions due to their seminal role in establishing core physiological and biochemical mechanisms.

The search strategy utilized Boolean operators to link core concept domains across titles, abstracts, and keywords. Table 1 summarizes the databases contacted, the keyword approaches used, and the total number of records retrieved and included.

Table 1. Summary of Database Search Strategy and Record Selection

Database	Search Terms	Records Retrieved	After Deduplication	Included in Review
Scopus	"modified atmosphere packaging" AND "oxygen"	412	—	—
Web of Science	"MAP" AND "O_2 concentration" AND "food quality"	389	—	—
PubMed	"low oxygen" AND "shelf life" AND "microbial"	201	—	—
Google Scholar	"intermediate oxygen MAP" OR "controlled atmosphere" AND "food safety"	318	—	—
TOTAL		**1,320**	**847**	**63**

Retrieved articles were evaluated against predefined inclusion and exclusion criteria to ensure scientific rigor and thematic alignment (Table 2).

Table 2. Inclusion and Exclusion Criteria for Study Selection

Inclusion Criteria	Exclusion Criteria
Peer-reviewed journal articles published 2000–2025	Conference abstracts, editorial notes, or non-peer-reviewed whitepapers
Studies on meat, fresh produce, seafood, or bakery MAP systems	Studies on non-food MAP applications (medical, pharmaceutical)
Studies reporting oxygen concentration as an independent variable	Studies evaluating packaging material properties without gas data
English-language publications measuring quality or safety metrics	Studies lacking defined gas compositions or control atmospheres

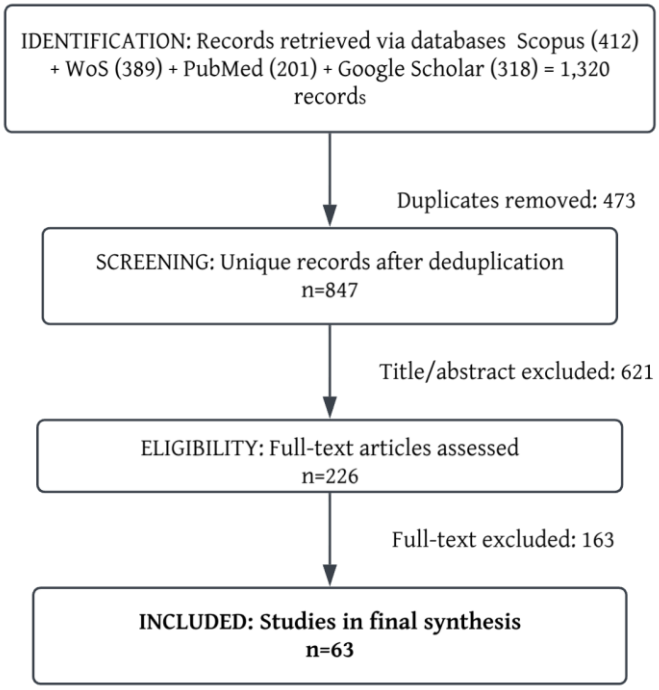
A total of 1,320 records were initially retrieved across Scopus, Web of Science, PubMed, and Google Scholar. After removing 473 duplicate entries, 847 unique titles and abstracts were screened. Of these, 621 records were excluded as non-relevant. Full-text evaluation of the remaining 226 articles resulted in the exclusion of 163

studies that failed to meet the predefined inclusion criteria (e.g., non-food applications, absence of defined gas compositions, or lack of measured quality/safety endpoints). The final review synthesis includes 63 peer-reviewed studies. A complete log of all 63 included studies is provided in Supplementary Table S1.

Figure 1 depicts the PRISMA flow diagram describing the study selection process, illustrating the progressive

reduction from the initial identification pool of 1,320 records to the final 63 included studies.

Figure 1. PRISMA Flow Diagram of Study Selection Process



4. Results and Discussion

Data extracted from the included studies demonstrate that oxygen impact varies significantly depending on the food matrix, storage temperature, and packaging film permeability. Table 3 summarizes these cross-matrix interactions across three distinct oxygen regimes high (>20% O_2), low-to-intermediate (1-10% O_2), and near-anaerobic (<1% O_2)

Table 3. Summary of Oxygen Concentration Effects by Food Category and Quality Outcome

Food Category	O_2 Range (%)	Microbial Safety	Oxidative Stability	Color / Appearance	Sensory Quality	Key References
Red Meat	70–80% O_2(High)	↑ Aerobic growth; inhibits anaerobes	↓ Rapid lipid oxidation; rancidity	✔ Bright red oxymyoglobin	↓ Off-flavors over time	McMillin 2024; Nowak et al., 2021
Red Meat	1–10% O_2 (Intermediate)	↓ Aerobic spoilage; ↑ anaerobe risk if <1%	✔ Reduced lipid oxidation	~ Metmyoglobin risk at 0.5–5% O_2	✔ Extended shelf life	Sørheim 1999; Suman 2014
Red Meat	<0.5% O_2(Near Anaerobic)	↑↑ C. botulinum risk	✔ Minimal oxidation	✗ Brown discoloration	↓ Consumer rejection	Brody 2008; Church 1995

Food Category	O_2 Range (%)	Microbial Safety	Oxidative Stability	Color / Appearance	Sensory Quality	Key References
Fresh Produce	5–10% O_2(Low)	✔ Inhibits aerobic pathogens	✔ Slower senescence	✔ Color retained	✔ Delayed ripening	Kader 2002; Riva 2021
Fresh Produce	<2% O_2(Very Low)	~ Mixed; anaerobic risk	~ Fermentation byproducts	↓ Tissue damage	↓ Ethanol/acetaldehyde off-flavors	Sandhya 2010; Zhu 2024
Seafood	30–40% CO_2+ 30% O_2	✔ Pseudomonas inhibited	~ Moderate oxidation	✔ Acceptable appearance	✔ Extended freshness	Sivertsvik 2002; Gram 2002
Seafood	<5% O_2	↑ Listeria, C. botulinum risk	✔ Reduced lipid oxidation	~ Variable	↓ Texture deterioration	Parlapani 2023; Peck 2006
Bakery Products	0–2% O_2+ CO_2/N_2	✔ Mold/yeast inhibited	✔ Minimal oxidative rancidity	✔ Crust appearance maintained	✔ Texture and aroma preserved	Robertson 2016; Parry 1993

✔ = *Beneficial effect* ↓ = *Detrimental effect* ~ = *Mixed/context-dependent* ↑ = *Increased* ↑↑ = *Substantially increased*

In red meat systems, high-oxygen MAP (70–80% O_2) remains common in retail settings because it promotes bright cherry-red oxymyoglobin (Fe^{2+}) formation (Lindahl et al., 2020; McMillin, 2024). However, lipid and protein oxidation accelerate rapidly in these environments, generating malondialdehyde and off-flavors that limit consumer acceptance after extended storage (Bekhit et al., 2021). Reducing oxygen to 1–10% mitigates lipid rancidity, but careful control is necessary because oxygen partial pressures within the 0.5–5% O_2 range represent the critical accumulation window where brown metmyoglobin (Fe^{3+}) formation peaks, causing surface browning before deoxymyoglobin (Fe^{2+}) can be stabilized or bloomed (Sørheim et al., 1999; Suman et al., 2014; McMillin, 2024).

In horticultural produce, oxygen control aims to reduce tissue respiration without triggering anaerobic fermentation. Maintaining oxygen between 5% and 10% effectively lowers respiration rates, delaying ripening and preserving green leaf color (Riva et al., 2021; Pareek et al., 2023). If oxygen drops below the commodity-specific ACP (typically 2–3% O_2), pyruvate decarboxylase and alcohol dehydrogenase pathways are activated, leading to ethanol accumulation and off-flavors (Sandhya, 2010; Zhu et al., 2024).

Microorganisms exhibit varied physiological responses to oxygen concentrations. Table 4 details the growth behaviors and risk profiles of key spoilage organisms and pathogens encountered in MAP environments.

Table 4. Microbial Organism Response to O_2 Level in MAP Systems

Microorganism	Physiological Classification	O_2 Requirements	Risk Level in MAP	Relevant O_2 Threshold
Pseudomonas spp.	Obligate aerobe	Requires O_2	High spoilage risk in aerobic environments	Growth inhibited below 2–5% O_2, highly sensitive to dissolved CO_2
Brochothrix thermosphacta	Facultative anaerobe	Aerobic & Anaerobic	Moderate spoilage risk in low O_2 meat	Tolerates low O_2, requires CO_2 concentrations > 20% for effective suppression
Clostridium botulinum	Obligate anaerobe	Inhibited by O_2	High safety risk in anaerobic packaging	Proliferates below 1% O_2, controlled by temperature. 3.3°C, pH < 4.6, or aw < 0.92.
Listeria monocytogenes	Facultative anaerobe	Aerobic & Anaerobic	High safety risk in refrigerated low O_2 foods	Psychrotrophic pathogen; survives low O_2, requires secondary hurdles like organic acids
Lactic acid bacteria	Aerotolerant anaerobe	Inhibited by O_2	Low to moderate spoilage risk	Dominate low O_2 environments, produces lactic acid that inhibits pathogenic competitors

Suppressing strict aerobes like *Pseudomonas spp.* through oxygen reduction extends raw product shelf life. However, this suppression alters competitive dynamics, allowing psychrotrophic facultative anaerobes such as *Listeria monocytogenes* or obligate anaerobes like non-proteolytic *Clostridium botulinum* to multiply if the product is subjected to temperature abuse (Lianou & Sofos, 2020; Wang et al., 2023). Maintaining low-to-intermediate oxygen levels (1–5%) can suppress strict anaerobes while slowing aerobic spoilage, enabling competitive lactic acid bacteria to establish a stable microbiota (Santos et al., 2022; Pezzuto et al., 2022).

Figure 2 depicts the competing effects of high, moderate, and low/anaerobic oxygen on three key quality and safety dimensions: oxidative stability, microbiological safety, and sensory/color retention. As illustrated, intermediate oxygen (1–10% O_2) provides an optimal compromise across these dimensions; however, it is not a universal cure-all. Its preservation efficacy is context-dependent and requires integration with product-specific hurdles such as substrate pH, water activity, stringent cold-chain temperature management, and elevated CO_2 concentrations.

Figure 2: Context-Dependent Headspace Oxygen Dynamics Matrix

Quality/Safety Dimension	HIGH O_2 (>20%)	INTERMEDIATE O_2 (1–10%)	NEAR-ANAEROBIC (<1%)
Oxidative Stability (Lipids/Proteins)	POOR	GOOD	EXCELLENT
Aerobic Spoilage Control	POOR	GOOD	EXCELLENT
Anaerobic Pathogen Safety	EXCELLENT	MODERATE	POOR
Meat Color Stability	EXCELLENT	SATISFACTORY	POOR
Produce Sensory Retention (No ACP Shift)	MODERATE	EXCELLENT	POOR
Overall Preservation Balance	PARTIAL	OPTIMAL (Context-Dependent)	PARTIAL

The intermediate oxygen range (1–10%) avoids the rapid lipid oxidation seen in high-oxygen packaging and the anaerobic risks associated with zero-oxygen environments. However, because no single gas formulation guarantees safety across all food matrices, intermediate oxygen levels must be tailored to product-specific characteristics (pH, water activity, respiration rate) and paired with reliable cold-chain management (Santos et al., 2022; Oliveira et al., 2023).

The transition from standardized gas mixtures toward product-specific packaging design provides significant practical advantages for food processors attempting to optimize both safety and product quality. By treating oxygen as a controllable, dynamic parameter rather than a static detriment, packaging engineers can align headspace partial pressures with the specific metabolic demands of horticultural produce or the myoglobin oxidation kinetics of fresh red meats. This precision minimizes spoilage variability across production lots, stabilizes sensory attributes such as surface color, and reduces consumer rejection linked to premature browning or anaerobic off-flavors. From a theoretical standpoint, these findings support an expanded conceptual model that views modified atmospheres as interactive biological systems rather than inert physical barriers. Headspace gas ratios actively interact with plant respiratory quotients, post-mortem muscle chemistry, and microbial population dynamics. Integrating oxygen partial pressure as a core variable alongside storage temperature, film permeability coefficients, and substrate pH establishes a more robust foundation for predictive shelf-life modeling and precision packaging design.

While this systematic review provides a comprehensive synthesis of oxygen dynamics in packaging systems, several inherent limitations must be noted. Because the underlying data were compiled from diverse secondary studies, the literature reflects considerable variation in experimental protocols, packaging materials, storage temperatures, and analytical methodologies. This heterogeneity prevents the establishment of rigid, universal oxygen thresholds that can be applied without modification across all commercial packaging formats. To address these gaps and facilitate industrial implementation, future research should prioritize three key areas. First, researchers must advance dynamic mathematical modeling that integrates commodity respiration rates, film gas transmission rates, and microbial growth kinetics to predict real-time headspace evolution. Second, intermediate oxygen strategies should be coupled with smart packaging innovations, such as non-destructive optoelectronic sensors and active scavenging films, to enable real-time monitoring and headspace correction along the supply chain. Finally, future work must evaluate how low-to-intermediate oxygen atmospheres function within multi-hurdle systems—combining gas modulation with protective

cultures, natural antimicrobials, or organic acid washes under actual commercial cold-chain conditions.

5. Conclusion

This systematic review demonstrates that oxygen partial pressure exerts a decisive influence on the preservation efficacy and microbial stability of Modified Atmosphere Packaging systems. The evidence indicates that neither high-oxygen atmospheres nor total oxygen evacuation universally optimizes food preservation across commodity groups. Rather than functioning as an independent antimicrobial or antioxidant barrier, intermediate oxygen levels (1–10% O_2) must be evaluated as context-dependent parameters governed by the specific food matrix, storage temperature, substrate pH, water activity, and dissolved carbon dioxide levels. Intermediate oxygen levels alone are insufficient to guarantee safety against psychrotrophic or spore-forming anaerobic pathogens such as non-proteolytic *Clostridium botulinum* without stringent temperature control and complementary hurdle technologies.

These findings reinforce the conceptual shift in packaging science toward treating headspace oxygen as a tunable, functional parameter rather than a purely deleterious contaminant. Precision MAP systems require aligning gas formulations with dynamic physiological responses, such as plant respiration rates and muscle myoglobin redox kinetics. Establishing commodity-specific threshold databases will enable packaging engineers to design targeted atmospheres that balance oxidative stability, visual quality, and microbiological safety.

Nevertheless, notable methodological limitations characterize the existing evidence base. Significant heterogeneity in packaging materials, gas barrier properties, storage temperatures, and analytical methodologies across secondary literature precludes the establishment of universally applicable oxygen thresholds across all commercial food categories.

In conclusion, controlled oxygen management represents a vital component of advanced preservation strategies. Due to the rigorous PRISMA-guided methodology, explicit selection criteria, and cross-matrix synthesis employed in this study, these findings provide a standardized framework for future empirical research. Combining tailored headspace gas regimes with intelligent, sensor-equipped packaging capable of dynamic gas adjustment will drive scalable, commercially viable preservation systems for perishable foods.

Declarations & End Matter

Sakshi Patwardhan conceptualized the review methodology, executed the systematic database searches and data extraction, authored the original draft, implemented all subsequent editorial revisions, and constructed the illustrative figures and tables. This research received no specific grant from any funding agency in the public, commercial, or non-profit sectors, and the author declares no conflicts of interest regarding the publication of this manuscript. Supplementary Table S1, containing the comprehensive inventory of the 63 analyzed studies alongside exact database search strings, query logs, and data extraction metrics, is provided as part of the formal manuscript record.

Contribution:Author's

Oxygen is a functional and controllable variable when designing Modified Atmosphere Packaging (MAP). This study brings together evidence from various food systems to build a thorough and critical understanding of this characteristic. By including oxygen into a dynamic, system-level preservation strategy, it challenges the conventional view of it as a component that only accelerates deterioration, thereby improving current understanding. The study, which combines microbiology, biochemistry, and packaging science, reveals severe shortcomings in current oxygen management systems and emphasizes the growing need for product-specific, personalized oxygen thresholds to improve food quality and safety.

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