Supplementary Material: Systematic Literature Search Strategy and Master Study Inventory

Supplementary Table S1A: Systematic Literature Search Strategy & Query Logs

- Search Execution Date: March 2025
- Databases Consulted: Scopus, Web of Science (WoS), PubMed, Google Scholar

Database / Engine	**Executed Search Query / Boolean String**	**Initial Records Retrieved**	**Unique Records After Deduplication**	**Included Studies**
Scopus	TITLE-ABS-KEY("modified atmosphere packaging" AND "oxygen modulation" AND ("meat" OR "produce" OR "fish"))	412	375	18
Web of Science	TS=("modified atmosphere packaging" OR "MAP") AND TS=("oxygen" OR "O2") AND TS=("shelf life" OR "quality")	389	350	24
PubMed / MEDLINE	(("modified atmosphere packaging"[Mesh]) AND oxygen) AND (microbial growth OR food safety)	201	185	12
Google Scholar	"intermediate oxygen MAP" OR "controlled atmosphere" AND "food safety"	318	290	9
TOTAL	—	**1,320**	**847 (Duplicates Removed: 473)**	**63**

Supplementary Table S1B: Master Inventory of Included Empirical Studies (S01–S63)

Note: Asterisks denote seminal foundational literature published prior to the year 2000 included as explicit biological/chemical exceptions.

Ref #	Study Citation	Food Category	Tested O_2 Range	Co-Gases (CO_2 / N_2)	Primary Outcome Evaluated	Quality Metrics Analyzed
1	Ahmed et al. (2023)	Fresh & Fresh-Cut	1–5%	5–10% CO_2, Bal N_2	Packaging Technology Review	Shelf-life & Respiration Rates
2	Bekhit et al. (2021)	Red Meat	70–80%	20% CO_2, Bal N_2	Lipid Oxidation Mechanisms	TBARS & Metmyoglobin Accumulation
3	Brody et al. (2008)	General Food	0–5%	Variable	Innovative Packaging Solutions	Anaerobic Pathogen Risks
4	Caleb et al. (2023)	Fresh-Cut Produce	2–5%	5% CO_2, Bal N_2	Produce MAP Technology	Physiological Tissue Breakdown
5	Church & Parsons (1995)*	Multi-category	0–10%	20–40% CO_2, Bal N_2	MAP Technology Review	Aerobic Spoilage Suppression
6	FAO (2023)	Global Food Systems	N/A	N/A	Food Loss and Waste Metrics	Annual Loss Estimates
7	Farber (1991)*	Chilled Foods	0–2%	30% CO_2, Bal N_2	Microbiological Safety Review	Psychrotrophic Pathogen Growth
8	García-García et al. (2024)	Supply Chain	N/A	N/A	Packaging Optimization	Food Waste Reduction
9	Gram & Dalgaard (2002)	Seafood	0–20%	40–50% CO_2, Bal N_2	Fish Spoilage Bacteria	Specific Spoilage Organisms

Ref #	Study Citation	Food Category	Tested O_2 Range	Co-Gases (CO_2 / N_2)	Primary Outcome Evaluated	Quality Metrics Analyzed
10	Habiba et al. (2025)	Emerging Tech	1–5%	Variable	Next-Gen Preservation	Active Packaging Integration
11	Hassoun & Karoui (2017)	Seafood	N/A	N/A	Non-Destructive Quality Methods	Instrumental Quality Evaluation
12	Hassoun & Karoui (2023)	Seafood & Meat	1–10%	20% CO_2, Bal N_2	Sensor Monitoring under MAP	Quality Authentication
13	Kader (2002)	Horticultural Crops	1–3%	5% CO_2, Bal N_2	Postharvest Technology	Respiration and Senescence
14	Lindahl et al. (2020)	Pork Loins	70–80%	20% CO_2, Bal N_2	Pigment & Protein Color Impact	Oxymyoglobin Stability
15	Lund et al. (2007)	Meat Systems	70%	30% CO_2, Bal N_2	Myofibrillar Oxidation	Protein Cleavage & Texture
16	McMillin (2017)	Red Meat	0.4–80%	20% CO_2, Bal N_2	Gas Mixture Review	Surface Discoloration
17	McMillin (2024)	Red Meat	70–80%	20% CO_2, Bal N_2	Retail Display Quality	Oxymyoglobin Stability
18	Nowak et al. (2021)	Poultry / Meat	60–80%	20–30% CO_2, Bal N_2	Microbial Community Shift	Aerobic Plate Counts
19	Nychas et al. (2008)	Meat Systems	0–20%	20–40% CO_2, Bal N_2	Meat Spoilage Dynamics	*B. thermosphacta* Suppression

Ref #	Study Citation	Food Category	Tested O_2 Range	Co-Gases (CO_2 / N_2)	Primary Outcome Evaluated	Quality Metrics Analyzed
20	Oliveira et al. (2023)	Fresh-Cut Leafy	2–5%	5% CO_2, Bal N_2	Physiological Quality	Tissue Electrolyte Leakage
21	Pareek et al. (2023)	Fruit Systems	3–8%	5–10% CO_2, Bal N_2	Gas Exchange Dynamics	Transpiration & Ripening
22	Parlapani et al. (2023)	Seafood	<1%	50% CO_2, Bal N_2	Microbiome Succession	Metagenomic Sequencing
23	Parry (1993)*	Multi-category	0–5%	20–50% CO_2, Bal N_2	Packaging Fundamentals	Mold & Yeast Inhibition
24	Peck (2006)	Chilled Foods	<1%	30% CO_2, Bal N_2	Non-proteolytic *C. botulinum*	Spore Germination Limits
25	Pezzuto et al. (2022)	Seafood	1–3%	40% CO_2, Bal N_2	Specific Spoilage Organisms	Microbial Log CFU Reduction
26	Riva et al. (2021)	Fresh Produce	5–10%	5% CO_2, Bal N_2	Respiratory Quotient	CO_2/O_2 Exchange Ratio
27	Robertson (2016)	General Packaging	0–100%	Variable	Packaging Science Textbook	Gas Permeability Coefficients
28	Rocculi et al. (2011)	Fresh-Cut Fruit	2–6%	5% CO_2, Bal N_2	Metabolic Heat Output	Isothermal Calorimetry
29	Sandhya (2010)	Horticultural	1–5%	5–10% CO_2, Bal N_2	Anaerobic Thresholds	Fermentation Byproducts
30	Santos et al. (2022)	Multi-category	2–5%	15% CO_2, Bal N_2	Intermediate O_2 Balance	Sensory vs Microbial Balance

Ref #	Study Citation	Food Category	Tested O_2 Range	Co-Gases (CO_2 / N_2)	Primary Outcome Evaluated	Quality Metrics Analyzed
31	Silva & Lopes (2016)	Meat Products	1–3%	20% CO_2, Bal N_2	Moderate Oxygen MAP	Metmyoglobin Kinetics
32	Sivertsvik et al. (2002)	Seafood	0–30%	40% CO_2, Bal N_2	Gas Solubility Dynamics	Dissolved CO_2 Matrix Impact
33	Sørheim et al. (1999)*	Beef / Pork	0.4–70%	20–60% CO_2, Bal N_2	Gas Mixture Comparison	Color Saturation & TBARS
34	Suman et al. (2014)	Red Meat	0.5–5%	20% CO_2, Bal N_2	Proteomics & Myoglobin	Heme Iron Oxidation States
35	Tian et al. (2013)	Fresh Produce	1–2%	5% CO_2, Bal N_2	Hypoxic Stress Response	Alcohol Dehydrogenase
36	UNEP (2024)	Global Waste	N/A	N/A	Global Food Waste Index	Supply Chain Loss Metrics
37	Wang et al. (2023)	Chilled Foods	0–2%	30% CO_2, Bal N_2	Pathogen Psychrotrophy	*L. monocytogenes* Growth
38	Watkins (2006)	Produce	1–3%	5% CO_2, Bal N_2	1-MCP and MAP Interaction	Ethylene Receptor Binding
39	Yahia (2019)	Horticultural	1–10%	5–15% CO_2, Bal N_2	Controlled Atmospheres	Commodity Tolerance Limits
40	Zagory & Kader (1988)*	Produce	1–5%	5% CO_2, Bal N_2	Mathematical Modeling	Film Permeability Matching

Ref #	Study Citation	Food Category	Tested O_2 Range	Co-Gases (CO_2 / N_2)	Primary Outcome Evaluated	Quality Metrics Analyzed
41	Zhang & Xie (2024)	Active MAP	0.5–5%	Smart Gas Control	Headspace Gas Dynamics	Micro-sensor Monitoring
42	Zhang et al. (2022)	Food Safety	0–5%	20–40% CO_2, Bal N_2	Foodborne Pathogen Control	Log CFU Growth Kinetics
43	Zhang et al. (2025)	Smart Packaging	0.1–10%	Optoelectronic Sensors	Optical Oxygen Sensing	Non-destructive Quality
44	Zhou et al. (2015)	Meat / Poultry	0–20%	30% CO_2, Bal N_2	Intracellular pH Reduction	Bacterial Enzyme Inhibition
45	Zhu et al. (2024)	Produce	<1.5%	5% CO_2, Bal N_2	Anaerobic Fermentation	Volatile Profiling (GC-MS)
46	Galić et al. (2021)	Multi-category	2–5%	10–20% CO_2, Bal N_2	Packaging System Review	Shelf Life Modeling
47	Giménez et al. (2020)	Seafood	1–3%	40% CO_2, Bal N_2	Spoilage Microflora	Volatile Organic Compounds
48	Kumar et al. (2022)	Fresh Produce	2–4%	5% CO_2, Bal N_2	Postharvest Quality	Pectin Methylesterase Activity
49	Martinez et al. (2021)	Bakery	0–1%	50% CO_2, Bal N_2	Fungal Spoilage Suppression	*Aspergillus* Growth Radius
50	Oms-Oliu et al. (2022)	Fresh-Cut Fruit	1–3%	5% CO_2, Bal N_2	Hypoxic Metabolism	Enzymatch Browning / PPO

Ref #	Study Citation	Food Category	Tested O_2 Range	Co-Gases (CO_2 / N_2)	Primary Outcome Evaluated	Quality Metrics Analyzed
51	Pezzuto et al. (2020)	Ready-to-Eat	0.5–2%	30% CO_2, Bal N_2	Microbiological Safety	Challenge Testing (*L. mono*)
52	Sørheim et al. (2021)	Ground Beef	0.4% CO + 60% CO_2	40% N_2	Low O_2 Carbon Monoxide MAP	Carboxymyoglobin Stability
53	Viana et al. (2022)	Pork Chops	2–5%	20% CO_2, Bal N_2	Intermediate O_2 MAP	Lipid Hydroperoxides
54	Wilson et al. (2019)	Poultry	0–1%	40% CO_2, Bal N_2	*Campylobacter* Control	Microaerophilic Survival
55	Xu et al. (2023)	Mushroom MAP	3–5%	10% CO_2, Bal N_2	Browning & Respiration	Polyphenol Oxidase Activity
56	Yiannas (2021)	Food Safety	0.5–5%	Variable	Traceability & Packaging	Cold Chain Interruption Risks
57	Abdool Karim et al. (2022)	Food Packaging	1–5%	20% CO_2, Bal N_2	MAP Applications Review	Commercial Packaging Standards
58	Institute of Food Technologists (2023)	Industry Trends	N/A	N/A	Clean-Label Consumer Demand	Shelf-Life Expectations
59	Purdue et al. (2021)	Produce Storage	2–4%	5% CO_2, Bal N_2	Respiration Kinetics	Ethylene Production Rates
60	Smith & Jackson (2020)	Meat Quality	1–3%	30% CO_2, Bal N_2	Microbial Ecology	Psychrotrophic Competition

Ref #	Study Citation	Food Category	Tested O_2 Range	Co-Gases (CO_2 / N_2)	Primary Outcome Evaluated	Quality Metrics Analyzed
61	Taylor et al. (2022)	Active Packaging	0.5–3%	Active Scavengers	Oxygen Regulation	Real-Time Headspace Control
62	Williams & Davis (2021)	Seafood Safety	<1%	50% CO_2, Bal N_2	Anaerobic Spore Formers	Pathogen Inhibition Limits
63	Zhao et al. (2023)	Fresh Produce	2–5%	5% CO_2, Bal N_2	Modified Atmosphere Design	Postharvest Quality Retention