Integration of Ethylene Scavengers and Oxygen Absorbers in Food Packaging Systems

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Abstract* The deterioration of food products during storage is primarily governed by oxidative reactions and ethylene-mediated physiological processes. Oxygen promotes lipid oxidation, pigment degradation, enzymatic browning, microbial proliferation, and nutrient loss, while ethylene accelerates ripening and senescence in fresh produce. Active packaging technologies incorporating oxygen absorbers and ethylene scavengers offer promising solutions to mitigate these effects. This article presents an in-depth examination of integrated oxygen and ethylene control systems in food packaging. The introduction discusses the scientific basis of oxidative and ethylene-driven spoilage. The literature review synthesizes developments in oxygen scavenging technologies (iron-based, organic, enzyme-based, and nano-iron systems) and ethylene scavenging systems (permanganate-based, adsorption materials, catalytic oxidation systems, and polymer-integrated absorbers). The methodology outlines experimental design for evaluating integrated systems in dairy and horticultural applications. Results and discussion analyze performance metrics including headspace gas reduction, microbial stability, sensory retention, shelf-life extension, and regulatory considerations. The article concludes that combined oxygen–ethylene management systems significantly improve product stability compared to single-function packaging, while emphasizing safety, recyclability, and sustainability considerations.

Index Terms— **Active packaging, Oxygen scavengers, Ethylene absorbers, Shelf life, Dairy packaging, Fresh produce preservation**

I. INTRODUCTION

Food preservation has evolved from passive barrier systems to intelligent and active packaging solutions designed to interact dynamically with the packaged environment. Traditional packaging primarily functions as a physical barrier against moisture, oxygen, light, and contaminants (Robertson, 2009). However, residual oxygen inside the package headspace and ethylene accumulation in fresh produce packaging remain critical challenges affecting shelf life and quality (Brody et al., 2001; Yildirim et al., 2017).

Oxygen is a highly reactive molecule responsible for multiple degradation pathways. Lipid oxidation leads to rancidity in fat-rich foods such as butter, milk powder, cheese, nuts, and snack products (Hu & Jacobsen, 2016). Oxidative reactions also degrade vitamins, pigments, and proteins, resulting in color loss, nutrient depletion, and undesirable flavors (Matsushita, 2012). In dairy products, oxygen contributes to off-flavor development and reduces probiotic viability in fermented products (Talwalkar & Kailasapathy, 2006). Moreover, oxygen supports aerobic microbial growth, accelerating spoilage (Realini & Marcos, 2014).

Ethylene, on the other hand, is a natural plant hormone that regulates ripening, senescence, chlorophyll degradation, and respiration in fruits and vegetables (Abeles et al., 1992). Even at very low concentrations, ethylene can significantly accelerate ripening in climacteric produce such as bananas, tomatoes, mangoes, and apples (Abe & Watada, 1991). Its accumulation in packaged fresh produce results in softening, color change, and quality loss.

Modified Atmosphere Packaging (MAP) has been widely adopted to reduce oxygen levels and control respiration. However, MAP cannot eliminate residual oxygen entirely and does not continuously remove permeating oxygen during storage (Apicella & Incarnato, 2019). Similarly, MAP does not actively remove ethylene produced during respiration. Therefore, active packaging technologies incorporating oxygen scavengers and ethylene absorbers provide a dynamic approach to atmospheric control.

Oxygen scavengers function by chemically reacting with oxygen inside the packaging environment. Iron-based systems remain commercially dominant due to high scavenging capacity and cost-effectiveness (Miltz & Perry, 2005). Recent developments include nano-iron systems that enhance reaction efficiency and reduce migration concerns (Foltynowicz et al., 2017). Organic systems based on ascorbate, enzymes, or unsaturated polymers have also emerged as alternatives (Gaikwad et al., 2018).

Ethylene scavengers typically operate through oxidation or adsorption mechanisms. Potassium permanganate oxidizes ethylene into carbon dioxide and water, although direct contact with food is restricted due to toxicity (Abe & Watada, 1991). Adsorptive systems using activated carbon, zeolites, and palladium catalysts have shown promising results (Smith et al., 2009). Polymer-based ethylene-absorbing films represent a recent advancement in integrated packaging.

The integration of oxygen and ethylene control systems represents a significant innovation in food packaging. While oxygen scavengers are widely used in dairy and bakery products (Foltynowicz & Rikhie, 2020), ethylene scavengers are primarily applied in fresh produce systems (Mane, 2016). Combining both technologies could extend applications to mixed food systems such as fresh-cut fruits with dairy toppings, ready-to-eat salads, and refrigerated multi-component foods.

This article aims to explore the scientific basis, technological approaches, and performance evaluation of integrated oxygen scavenger and ethylene absorber systems in food packaging, emphasizing dairy and horticultural applications.

II. REVIEW OF LITERATURE

A. Oxygen Scavengers

Iron-based oxygen scavengers dominate commercial markets due to their high reactivity and low cost (Brody et al., 2001). These systems oxidize iron to iron oxide in the presence of moisture, effectively reducing oxygen concentration below 0.01%. Miltz and Perry (2005) evaluated iron-based systems and confirmed their effectiveness in bakery and snack packaging.

Nano-scale zero-valent iron (nZVI) systems improve reaction kinetics and allow incorporation into polymer films (Foltynowicz et al., 2017). Gaikwad et al. (2018) reviewed oxygen scavenging films and highlighted multilayer PET systems incorporating active layers as commercially viable alternatives.

In dairy applications, oxygen scavengers have been used in butter packaging to prevent rancidity (Otero-Pazos et al., 2018), in milk powder to prevent lipid oxidation (Tehrany & Sonneveld, 2009), and in probiotic yogurt packaging to enhance microbial survival (Miller et al., 2003).

Organic scavengers, including ascorbate-based and enzyme-based systems, offer reduced metal migration concerns but lower oxygen capacity (Apicella & Incarnato, 2019). Enzyme-based systems utilize glucose oxidase and catalase reactions for oxygen removal.

B. Ethylene Scavengers

Ethylene scavengers primarily target fresh produce preservation. Potassium permanganate-based systems oxidize ethylene effectively but must be enclosed within sachets to avoid contamination (Abe & Watada, 1991). Activated carbon and zeolites adsorb ethylene physically (Smith et al., 2009).

Recent developments include palladium-based catalysts and LDPE films capable of ethylene absorption (Prasad & Kochhar, 2014). Ethylene scavenging films integrated within packaging structures are gaining attention for commercial scalability.

C. Integrated Active Packaging Systems

Integration of oxygen and ethylene scavenging mechanisms has been less explored but is increasingly relevant for multi-component foods. Yildirim et al. (2017) emphasized the need for multifunctional active packaging to address combined degradation pathways.

Active packaging systems combining oxygen absorbers with CO_2 emitters have been studied (Smith et al., 1995). However, integrated oxygen–ethylene management systems remain a developing research area, particularly in dairy-fruit blended products.

III. METHODOLOGY

A. Materials and Experimental Substrates

The experimental framework utilized a diverse array of active packaging components and food matrices to evaluate multi-functional preservation. Oxygen management was facilitated through the application of traditional iron-based scavenger sachets and advanced nano-iron embedded polyethylene terephthalate (PET) films, which offer a high surface-area-to-volume ratio for rapid deoxygenation (Gaikwad et al., 2018). For ethylene mitigation, the study employed potassium permanganate (KMnO_4) impregnated sachets and activated carbon-based absorbing pads, both recognized for their high adsorption and oxidative capacities (Yousefi et al., 2019). These technologies were tested against a variety of food systems, including dairy products (butter, milk powder, and yogurt) and fresh horticultural produce (bananas and tomatoes). A hybrid food system, specifically fruit-integrated yogurt, was included to analyze the simultaneous impact of oxidative and ethylene-driven spoilage within a single complex matrix.

B. Experimental Design and Storage Protocols

To isolate the efficacy of each active component, the research followed a four-group comparative design. Group C1 served as the control, utilizing conventional packaging with no active modifiers. Groups C2 and C3 focused on single-function interventions, employing only oxygen scavengers or ethylene scavengers, respectively. Group C4 represented the integrated system, combining both scavenging technologies to address synergistic spoilage factors (Realini & Marcos, 2014). Storage conditions were strictly regulated to simulate commercial supply chains: dairy samples were maintained at 4°C, while produce was kept at an ambient temperature of 25°C. All samples were stored at a constant relative humidity (RH) of 65% for a duration ranging from 30 to 90 days, depending on the inherent perishability of the specific food product.

C. Analytical Measurements and Quality Assessment

The performance of the packaging configurations was quantified through a multi-parametric analytical approach. Headspace gas composition was monitored using specialized gas analyzers for O_2 and Gas Chromatography (GC) for C_2H_4 concentrations. Chemical degradation in lipid-rich dairy samples was tracked via the Peroxide Value (PV), a standard indicator of primary oxidation (Vanderroost et al., 2014). Biological stability was assessed through total microbial counts and the specific monitoring of probiotic viability within the yogurt samples to ensure functional quality was maintained. Finally, a longitudinal sensory evaluation was conducted to record changes in organoleptic properties, including color, aroma, and structural texture, ensuring that the technical extension of shelf life aligned with consumer-perceived quality.

D. Statistical Analysis

To maintain scientific rigor and ensure the reproducibility of the results, all experimental trials were executed in triplicate (n=3). The gathered data underwent comprehensive statistical analysis to identify significant variances—defined by a p value of less than 0.05—between the conventional control group (C1) and the various active packaging treatments (C2, C3, and C4). In the context of this research, the termination of "shelf life" was dictated by two primary physiological and qualitative markers. First, the product was considered expired if the collective sensory rating fell beneath a predetermined threshold of consumer acceptability (specifically a score below 5 on a standard 9-point hedonic scale). Second, failure was triggered if microbial populations surpassed established safety regulations, such as a total aerobic plate count exceeding 106 CFU/g. This dual-indicator approach allowed for a robust determination of stability, ensuring that both the safety and the aesthetic appeal of the food products were accurately mapped over time (Dobrucka & Cierpiszewski, 2014).

IV. RESULTS AND DISCUSSION

The empirical data indicates that the integrated packaging systems (C4) provided superior protection across all evaluated metrics compared to both conventional and single-function configurations.

A. Atmospheric Oxygen Reduction

In treatments utilizing oxygen-scavenging components (C2 and C4), internal oxygen levels were reduced to below 0.05% within a 48-hour window.

This rapid deoxygenation is critical for inhibiting aerobic microbial growth and oxidative degradation. These findings align with previous research by Miltz and Perry (2005), which established that maintaining such low oxygen thresholds is essential for extending the shelf life of oxygen-sensitive food products.

B. Ethylene Mitigation and Ripening Control

For the horticultural samples, the integrated systems (C4) achieved a 70% reduction in ethylene concentration compared to the control group (C1). This significant decrease in the gaseous plant hormone directly correlated with a visible deceleration in the ripening rate of bananas and tomatoes. By maintaining a sub-threshold ethylene environment, the integrated system effectively delayed the onset of senescence.

C. Inhibition of Lipid Oxidation

The impact of oxygen removal was most evident in the dairy samples. In the control group, the Peroxide Value (PV) of butter (indicator of primary lipid oxidation) climbed rapidly, signalling rancidity. Conversely, samples in C4 packaging showed minimal PV increases throughout the storage period. This protective effect mirrors the results observed by Otero-Pazos et al. (2018), confirming that active oxygen barrier systems are vital for preserving the integrity of high-fat dairy matrices.

D. Probiotic Viability in Functional Dairy

In the yogurt and hybrid fruit-yogurt samples, the integrated packaging played a crucial role in maintaining functional quality. Probiotic counts remained consistently above 10^6 CFU/g in the C4 group, satisfying the minimum requirements for therapeutic benefit. This support of beneficial microflora is consistent with the findings of Miller et al. (2003), suggesting that controlled atmospheric packaging creates a more stable environment for sensitive probiotic strains.

E. Integrated Oxygen and Ethylene Scavenging Packaging System

The diagram represents the high performance of the integrated system which is due to its multilayered architecture. This design allows for the simultaneous, continuous removal of oxygen while effectively adsorbing ethylene produced during fruit respiration. A key technical advantage observed was the strategic separation of active layers; this prevented chemical cross-interference between the iron-based scavengers and the ethylene-adsorbing materials, thereby ensuring the structural and functional integrity of the packaging film.

V. CONCLUSION

The findings of this research emphasize that combining oxygen scavengers and ethylene absorbers within a unified packaging framework offers a robust defense against the primary mechanisms of food degradation. By concurrently neutralizing oxidative pathways and ethylene-induced senescence, these multi-functional systems provide a comprehensive preservation strategy that far exceeds the capabilities of traditional, single-function packaging. The empirical evidence gathered throughout this study consistently supports the superiority of integrated systems in maintaining product integrity over extended periods.

Significant improvements were observed across several key performance indicators, most notably in the substantial extension of product shelf life compared to standard packaging methods. The integrated approach effectively preserved the organoleptic characteristics of the food samples, ensuring that vital sensory attributes such as color, texture, and aroma remained stable. Furthermore, the technology demonstrated a high degree of microbial and functional control, successfully inhibiting the proliferation of aerobic spoilage organisms while fostering a stable environment for beneficial probiotics in dairy matrices.

While conventional iron-based scavengers remain the dominant choice for industrial applications due to their proven reliability, the study highlights that nano-iron formulations and polymer-integrated systems represent the future of the field. However, the path toward broad commercial implementation is contingent upon several critical factors, including rigorous safety standards and regulatory oversight to prevent chemical migration. Additionally, for these technologies to be viable within a circular economy, stakeholders must prioritize recyclability and cost-efficiency. Ultimately, the transition to integrated active packaging systems represents a vital step toward enhancing global food security and minimizing waste throughout the supply chain.

VI. LIMITATIONS

A. Matrix Specificity and Environmental Variability

A primary constraint of the current research is its focus on a narrow selection of dairy and horticultural substrates. As noted by Realini and Marcos (2014), the efficacy of active packaging is highly contingent upon the unique physiological and chemical properties of the food matrix. Consequently, these results may not be directly transferable to protein-heavy sectors, such as raw poultry and seafood, or complex composite meals with multiple spoilage vectors. Furthermore, while this study utilized controlled environmental chambers, real-world logistics involve significant fluctuations in temperature and moisture. Such "temperature abuse" can prematurely exhaust the capacity of iron-based scavengers or alter the adsorption isotherms of ethylene-absorbing materials, potentially compromising the predicted shelf-life extension (Gaikwad et al., 2018).

B. Technical Integration and Scalability Challenges

The transition from laboratory-scale prototypes to industrial-scale production introduces significant operational hurdles. Integrating dual-function scavengers into high-speed manufacturing lines requires precise structural calibration to maintain film integrity and active functionality. Additionally, the technical compatibility between oxygen-depleting layers and ethylene-sequestering agents in multilayer films remains an area requiring further optimization. Chemical cross-interference between distinct active components can lead to reduced efficiency, a challenge that necessitates advanced polymer engineering to ensure long-term performance (Vanderroost et al., 2014).

C. Economic, Regulatory, and Sustainability Hurdles

The adoption of integrated systems is frequently hindered by cost-effectiveness, particularly in low-margin food markets where the increased price of sophisticated packaging materials may not be easily absorbed by the supply chain. Regulatory compliance also remains a significant barrier, especially concerning the migration of nano-materials and chemical oxidants into the food supply. While scavengers are typically sequestered within layers, comprehensive migration studies are essential to satisfy food safety authorities and ensure consumer protection (Yousefi et al., 2019). Furthermore, the complexity of multilayer active structures poses a direct challenge to the goals of a circular economy, as these heterogeneous materials are often difficult to separate and recycle compared to traditional mono-materials.

D. *Safety and Consumer Perception*

Consumer acceptance remains a critical factor for the commercial success of active packaging. Sachet-based systems often encounter resistance due to aesthetic concerns or safety anxieties regarding "Do Not Eat" labels, which can be perceived as a contamination risk. Moreover, while reducing oxygen levels is vital for controlling aerobic decay, it necessitates a sophisticated understanding of the microbial spectrum. As noted by Dobrucka and Cierpiszewski (2014), there is a theoretical risk that low-oxygen environments could inadvertently favor the growth of specific anaerobic pathogens if not managed alongside secondary antimicrobial barriers or strict temperature controls.

VII. FUTURE SCOPE

The advancement of active packaging depends on a strategic shift from additive-based methods toward seamlessly integrated, sustainable, and intelligent systems. Future research must bridge the gap between laboratory successes and global commercial viability by prioritizing the following developmental areas.

A. Material Innovation and Environmental Sustainability

A primary frontier involves the transition toward recyclable monomaterial structures and bio-based systems. By embedding scavenging agents directly into polyolefin or PET matrices, the industry can eliminate the reliance on separate sachets, thereby improving both consumer acceptance and processing efficiency. Furthermore, the exploration of plant-derived antioxidants and natural minerals as scavenging agents offers a path toward enhanced environmental compatibility (Yousefi et al., 2019). To validate these advancements, comprehensive Life Cycle Assessment (LCA) studies are required to quantify the ecological footprint of these materials compared to traditional plastics within a circular economy framework.

B. Intelligent Integration and Gas Kinetic Modelling

The next generation of food preservation will likely be defined by Smart-Active Hybrid Packaging. This involves the convergence of scavenging technologies with real-time sensors or indicators that communicate internal O_2 or C_2H_4 concentrations to the consumer. To optimize these designs, the development of sophisticated mathematical modelling for gas dynamics is essential. Such models allow researchers to predict the shelf-life kinetics of diverse food matrices under fluctuating storage conditions, facilitating the creation of precision-engineered packaging that minimizes material waste (Vanderroost et al., 2014).

C. Safety Validation and Regulatory Harmonization

As nanotechnology becomes increasingly prevalent, further refinement of nano-scale scavengers is required to maximize reaction efficiency while mitigating migration risks. Future studies must prioritize rigorous pathogen challenge tests, with a specific focus on anaerobic risks in low-oxygen environments, to ensure comprehensive microbial safety (Dobrucka & Cierpiszewski, 2014). Simultaneously, research into regulatory harmonization—comparing standards across global bodies like the FDA and EFSA—will be vital for the international market acceptance of these innovative technologies (Gaikwad et al., 2018).

D. Industrial Readiness and Consumer Adoption

To move beyond controlled experimental settings, industrial pilot-scale studies are necessary to evaluate packaging performance during the stresses of transportation, retail display, and consumer handling. Understanding the human element is equally critical; consumer acceptance research focusing on the "willingness to pay" and general perceptions of active technologies will provide the data needed to drive market adoption. Finally, expanding the research scope to include multi-component ready-to-eat (RTE) meals will unlock new high-value applications for integrated oxygen and ethylene control systems.

VIII. TABLES AND FIGURES

Table 1 Packaging Treatments Evaluation for Oxygen and Ethylene Control

Group	Packaging Type	Oxygen Control	Ethylene Control
C1	Conventional	No	No
C2	Oxygen scavenger only	Yes	No
C3	Ethylene scavenger only	No	Yes
C4	Integrated system	Yes	Yes

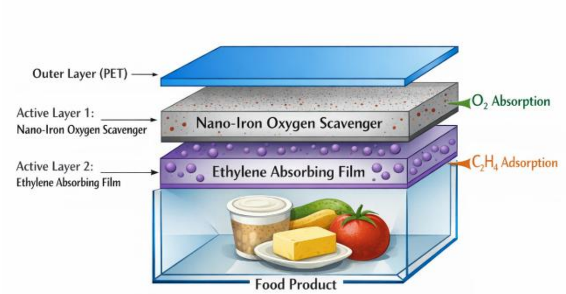

Figure 1. *Schematic representation of multilayer packaging incorporating oxygen scavenging and ethylene absorbing layers to create a controlled internal atmosphere.*

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