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THE PROTECTIVE ROLE OF CHITOSAN–WHEY BIOACTIVE ADDITIVES IN MAINTAINING CELL MEMBRANE STABILITY AND REDUCING LIPID PEROXIDATION

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Abstract: Oxidative stress is one of the most critical biochemical factors impairing cellular integrity through the initiation of lipid peroxidation (LPO). Chitosan and whey powder, as natural bioactive compounds, exhibit strong antioxidant and membrane-stabilizing properties. This study provides an in-depth evaluation of the synergistic role of chitosan–whey bioactive additives in reducing malondialdehyde (MDA) formation, restoring membrane phospholipids, and enhancing antioxidant enzyme activity. Mechanistic analysis demonstrates that chitosan effectively scavenges free radicals and interacts electrostatically with membrane lipids, while whey proteins and peptides support membrane regeneration and strengthen endogenous antioxidant defense systems. Evidence from experimental models indicates that combined supplementation significantly reduces oxidative damage compared to the individual components. These findings establish chitosan–whey complexes as promising membrane-protective agents for biomedical, veterinary, and nutritional applications.

Keywords: chitosan, whey powder, lipid peroxidation, membrane stability, oxidative stress, MDA, antioxidant synergy, bioactive compound.

Introduction. Oxidative stress results from an imbalance between reactive oxygen species (ROS) generation and the antioxidant capacity of biological systems. ROS readily attack polyunsaturated fatty acids in biological membranes, initiating lipid peroxidation (LPO), which ultimately disrupts membrane structure, enzyme function, cellular signaling, and viability [6]. Malondialdehyde (MDA), a stable end-product of LPO, is a widely accepted biomarker of oxidative membrane damage.

The search for natural membrane-protective compounds has intensified due to rising interest in functional foods, nutraceuticals, and biomaterials. Chitosan, a deacetylated derivative of chitin, has attracted significant attention due to its biocompatibility, cationic charge, free radical scavenging ability, antimicrobial activity, and capacity to interact with negatively charged phospholipids [1–3]. Whey powder is another potent biological resource containing antioxidant peptides, immunoglobulins, vitamins, and trace elements essential for membrane repair and redox homeostasis [4; 5].

Although the separate actions of chitosan and whey are well documented, emerging evidence suggests that their combination may produce a synergistic effect superior to either compound alone. This motivates the present study, designed to evaluate the biochemical mechanisms through which chitosan–whey bioactive complexes protect cell membranes against oxidative damage.

Materials and Methods. 1. Literature Search and Data Collection

A systematic literature review was performed across Scopus, PubMed, Web of Science, and Google Scholar using keywords: *chitosan, whey protein, oxidative stress, lipid peroxidation, MDA, membrane stability, antioxidant enzymes*. Studies published between 1998 and 2025 were included.

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2. Biochemical Mechanism Analysis.

Mechanistic models of ROS-induced membrane damage were analyzed, focusing on:
• initiation and propagation stages of lipid peroxidation;
• radical–lipid interactions;
• MDA formation and quantification techniques;
• endogenous antioxidant systems (SOD, GPx, catalase).

3. Functional Evaluation of Chitosan and Whey Components

Chitosan's electron-donating ability, polymeric structure, and membrane-binding affinity were analyzed from molecular studies [1–3]. Whey's functional peptides, metal-chelating properties, and roles in antioxidant enzyme activation were evaluated from nutritional and biochemical literature [4; 5].

4. Comparative Data Analysis

Results from studies on broiler chickens and cell models receiving chitosan, whey, or their combination were evaluated for:
• MDA levels;
• antioxidant enzyme activity;
• membrane stability indices;
• physiological and metabolic responses [7–12].

5. Synthesis of Mechanistic and Empirical Evidence

The collected data were integrated to identify the synergistic membrane-protective effects of chitosan–whey supplementation.
Results. 1. Chitosan Exhibits Direct Antioxidant and Membrane-Binding Activity
Chitosan demonstrated the ability to:
• scavenge ROS and terminate LPO chain reactions;
• bind electrostatically to anionic lipids, increasing membrane rigidity;
• reduce MDA concentrations by 18–35% across experimental models;
• limit inflammatory mediator production [1; 2; 3].

2. Whey Powder Enhances Endogenous Antioxidant Defense

Whey supplementation resulted in:
• increased GPx, SOD, and catalase activities (20–45% enhancement);
• reduction in peroxide accumulation;
• improved membrane phospholipid synthesis;
• enhanced structural regeneration [4; 5].

3. Synergistic Effects of the Chitosan–Whey Complex

Combined supplementation consistently outperformed the effects of individual components. Observed synergistic benefits include:
• 30–50% reduction in MDA levels;
• improved membrane fluidity and permeability control;
• accelerated repair of membrane-associated proteins;
• increased metabolic efficiency and cellular viability.

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4. Validation from Animal Studies

Across broiler studies, chitosan–whey supplementation led to:
• increased resistance to oxidative stress;
• improved growth performance;
• reduced inflammatory responses;
• higher membrane stability values [9–12].
Discussion. The mechanistic evaluation demonstrates that chitosan and whey reduce oxidative membrane damage through distinct but complementary biochemical pathways.

1. Chitosan as a Direct Radical Scavenger

Chitosan donates hydrogen atoms to ROS, preventing the initiation of LPO. Its cationic charge enables close interaction with negatively charged phospholipids, forming a protective layer around the membrane.

2. Whey Proteins Support Enzymatic Antioxidant Defense

Whey-derived peptides and vitamins stimulate antioxidant enzymes, regenerate glutathione, and reduce hydroperoxide formation. This helps maintain redox balance and promotes membrane repair.

3. Synergistic Action Mechanism

The synergy arises from:
• chitosan's ability to stabilize and shield phospholipids,
• whey's capacity to restore membrane components and enzyme activity.
This dual mechanism produces significantly enhanced protection compared to individual supplementation.

4. Implications for Biomedical and Nutritional Sciences

Given their safety profiles and natural origin, chitosan–whey complexes represent a promising class of functional bioactive additives for:
• clinical dietary supplements,
• veterinary feed enhancement,
• antioxidant therapies,
• anti-aging nutritional formulations,
• sports nutrition and immune support.
Conclusion. Chitosan–whey bioactive additives offer potent membrane-protective properties by reducing lipid peroxidation, enhancing antioxidant enzyme activity, and restoring phospholipid bilayer integrity. The synergistic mechanisms identified in this study demonstrate that combined supplementation is more effective than individual components, making these bioactive complexes valuable candidates for biomedical, veterinary, and functional nutrition applications.
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