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EFFECTS OF WHEY POWDER PROTEINS AND CHITOSAN ON MITOCHONDRIAL ENERGY PRODUCTION

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Abstract. *This scientific article presents a theoretical and analytical overview of how whey powder proteins and chitosan may influence mitochondrial energy production in cells. The paper explains the biochemical principles of oxidative phosphorylation, including the functioning of the electron transport chain (ETC) complexes located in the inner mitochondrial membrane, the formation of the proton gradient, and ATP synthesis via ATP synthase. The potential roles of branched-chain amino acids and leucine from whey in anabolic and adaptive processes are discussed, together with the contribution of cysteine and glycine to glutathione biosynthesis, which may reduce oxidative stress and stabilize the mitochondrial membrane potential. In addition, the article substantiates the mechanisms by which chitosan may support mitochondrial function through modulation of lipid metabolism and inflammatory status, limitation of membrane lipid peroxidation, and activation of antioxidant defense systems. Overall, whey powder and chitosan are considered promising nutritional factors for improving cellular energetic efficiency, supporting endurance under physical and metabolic load, and enhancing metabolic flexibility.*

Keywords: *whey powder, chitosan, mitochondria, electron transport chain, oxidative phosphorylation, ATP synthase, glutathione, redox balance, mitochondrial biogenesis, energy metabolism.*

Introduction. Mitochondria are the cellular energy hub that ensures ATP synthesis through oxidative phosphorylation, thereby providing the energetic basis for key physiological functions in the organism [1]. During substrate oxidation, NADH and FADH2 transfer electrons to the complexes of the electron transport chain (ETC). Electron flow is coupled with proton translocation across the inner mitochondrial membrane, generating a proton-motive force that is converted into ATP by ATP synthase [2]. The efficiency of these processes depends directly on the activity of ETC complexes, the phospholipid composition of the inner membrane, the mitochondrial membrane potential (ΔΨm), oxygen availability, and the capacity of the antioxidant defense system [5,6].Mitochondrial dysfunction manifests not only as ATP deficiency, but also as increased production of reactive oxygen species (ROS), enhanced lipid peroxidation, disturbances of Ca2+ homeostasis, and dysregulation of signaling pathways. These changes are regarded as closely associated with the development of metabolic syndrome, insulin resistance, obesity, cardiovascular diseases, and certain neurodegenerative disorders [3,5]. Therefore, supporting mitochondrial functions through nutritional factors and optimizing cellular bioenergetics represent priority directions in modern biochemistry, nutrition science, and sports physiology [4,6].

In recent years, research on the impact of functional foods and nutraceuticals on mitochondrial energetics has intensified. Whey powder, as a high-biological-value protein source, is characterized by rapid digestion, abundance of essential amino acids, and the presence of bioactive peptides. Along with stimulating muscle protein synthesis, it may influence redox balance and mitochondrial adaptation [9,11,16]. Chitosan, a natural cationic polysaccharide, is considered a supportive factor for cellular energy systems because it can modulate lipid metabolism, inflammatory status, and oxidative stress [12]. From this perspective, the main purpose of this paper is to systematically describe the mechanisms by which whey powder proteins and chitosan may affect mitochondrial energy production.

Main part. In mitochondrial energy production, the ETC complexes (I–IV) and ATP synthase (complex V) play central roles. NADH is primarily oxidized at complex I, whereas FADH2 donates electrons via complex II; electrons are then transferred through ubiquinone and cytochrome c to complexes III and IV, where oxygen is ultimately reduced to water. Proton pumping occurs through complexes I, III, and IV, forming a proton gradient across the inner membrane [2]. This gradient provides the driving force for ATP synthase activity.

Physiological ROS generation can serve signaling functions; however, excessive ROS formation contributes to ETC impairment and peroxidation of membrane lipids. Oxidative stress, in particular, can reduce cardiolipin stability, disrupt the structural integration of ETC supercomplexes, and increase proton “leak,” thereby lowering the efficiency of ATP synthesis [5,6]. Under such conditions, strengthening antioxidant defense is an important strategy for preserving mitochondrial bioenergetics [7,10].

Leucine and branched-chain amino acids (BCAA: valine and isoleucine) in whey powder can stimulate muscle protein synthesis and recovery while also exerting indirect effects on mitochondrial adaptation. Leucine enhances anabolic responses via mTOR signaling [9,11]. Mitochondrial biogenesis, in turn, is regulated through transcriptional programs involving PGC-1α, NRF1, and TFAM [13,14]. Evidence suggesting that co-ingestion of protein and carbohydrates during physical activity may amplify adaptive signaling associated with PGC-1α expression provides additional scientific rationale for this area [17].

The mitochondrial protective effects of whey proteins are also closely related to redox balance. Cysteine is a limiting substrate for glutathione (GSH) synthesis, and glutathione is a central determinant of cellular redox potential and a key ROS-neutralizing system [7,8].

Adequate GSH levels help protect ETC components, membrane phospholipids, and mitochondrial DNA from oxidative damage [10]. Thus, improved cysteine supply through whey protein can support GSH biosynthesis, creating conditions for reduced oxidative stress and stabilization of the mitochondrial membrane potential [7,8,10]. Reports from certain experimental models indicating that whey protein increases mitochondrial activity while decreasing oxidative stress also indirectly support these mechanisms [18].

The influence of chitosan on mitochondrial energetics is commonly interpreted as a multi-level metabolic modulation. First, chitosan can interact with lipid fractions and bile acids in the intestine and may alter fat absorption dynamics; as a result, the flux of free fatty acids may be better regulated, potentially reducing lipotoxicity and the “pressure” of excessive β-oxidation on mitochondria [12]. Second, chitosan exhibits antioxidant activity, and its properties have been reported to depend on molecular weight and degree of deacetylation, which can be important for limiting lipid peroxidation and maintaining membrane stability [19].

Third, chitosan oligosaccharides have been shown in certain models to enhance antioxidant enzyme expression via redox-sensitive pathways such as Nrf2/ARE and to reduce oxidative stress [20]. This mechanism is important for protecting mitochondrial bioenergetics from the harmful effects of ROS [5,6]. In addition, the potential effects of chitosan oligosaccharides on pathways related to mitochondrial quality control and "repair" have been discussed, suggesting a possible role in maintaining the proportion of functionally competent mitochondria [21].

When whey powder and chitosan are used together, a potential synergy may occur: whey proteins can enhance anabolic and redox-substrate supply, while chitosan may normalize lipid metabolism and oxidative stress background and support inner membrane stability. Consequently, the overall efficiency of ETC function and ATP synthesis may improve [5,6,9,10,12]. In poultry studies, the use of chitosan and whey powder has been associated with positive shifts in growth performance and certain physiological-biochemical indicators, which also highlights the applied potential of this approach [22,23,24,25].

Methodology. This work is based on a theoretical-analytical, comparative biochemical, and systematic literature review approach. Classical textbooks on mitochondrial bioenergetics and oxidative phosphorylation [1,2], conceptual works on mitochondria–metabolism integration [3,5], analytical studies on muscle fatigue and energetics [4,6], methodological and theoretical sources on glutathione and redox regulation [7,8,10], reviews on the regulation of mitochondrial biogenesis [13,14], sources on the nutritional effects of whey proteins [9,11,16], and studies describing the properties and biological mechanisms of chitosan [12,19,21] were critically analyzed. Data from applied studies involving whey and chitosan were also summarized [22,23,24,25].

Analysis. Based on the reviewed literature, whey powder proteins may influence mitochondrial energetics through three major directions. The first is strengthening anabolic signaling and adaptive processes through leucine and BCAA, improving recovery efficiency, and creating conditions for metabolic adaptation [9,11,15]. The second is supporting GSH biosynthesis via cysteine and glycine supply, thereby reducing ROS levels and improving functional stability of the inner membrane [7,8,10]. The third is supported by observations from experimental models reporting increased mitochondrial activity and reduced oxidative stress following whey protein supplementation [18]. For chitosan, it is emphasized that normalization of lipid flux, limitation of inflammation and lipid peroxidation, and activation of antioxidant responses via redox-sensitive pathways may contribute positively to the stability of mitochondrial energy systems [12,19,20]. Evidence suggesting that chitosan oligosaccharides may affect pathways involved in mitochondrial quality control indicates that chitosan's impact may extend beyond a purely "general antioxidant" effect [21].

Results. As a result of this theoretical-analytical synthesis, whey powder proteins and chitosan can be considered nutritional factors that may support mitochondrial energy production.

Whey proteins may improve oxidative phosphorylation efficiency by enhancing redox protection and supporting adaptive processes [7,8,9,11,16,18]. Chitosan may positively affect the structural and functional stability of the inner membrane by regulating lipid metabolism and the oxidative stress background [12,19,20]. The observation that biological indicators improved in applied studies using chitosan and whey powder further strengthens the practical relevance of this direction [22,23,24,25].

Conclusion. Whey powder proteins and chitosan may exert a complex modulatory effect on mitochondrial bioenergetics. Whey supports anabolic and adaptive signaling via leucine and BCAA and strengthens glutathione reserves via cysteine and glycine, contributing to reduced oxidative stress and stabilization of membrane potential. Chitosan may reduce the risk of mitochondrial damage by normalizing lipid flux and inflammatory background, limiting lipid peroxidation, and activating antioxidant defense. In the future, it is advisable to evaluate the effects of this combination in controlled experimental models using indicators such as ΔΨm, ATP production rate, ETC complex activities, ROS markers, the GSH/GSSG ratio, and expression of PGC-1α/NRF1/TFAM.

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