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BIOCHEMICAL CHANGES IN GLUCOSE METABOLISM AND INSULIN SENSITIVITY DURING THE COMBINED ADMINISTRATION OF CHITOSAN AND WHEY POWDER

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Abstract. *This article presents a substantially revised academic version of the author-provided manuscript devoted to the biochemical effects of combined chitosan and whey powder administration on glucose homeostasis and insulin sensitivity. The manuscript was restructured according to the standard scientific article format, and terminological, stylistic, and logical inconsistencies of the source text were corrected. The analysis indicates that chitosan can attenuate intestinal absorption of carbohydrates and lipids, modulate the gut microbiota, and reduce postprandial glycemic excursions, whereas whey protein enhances incretin release, stimulates insulin secretion, and improves GLUT-4-mediated glucose utilization in peripheral tissues. When used together, these components may support AMPK- and PI3K/Akt-related regulatory pathways, decrease metabolic inflammation, and improve overall substrate handling. Therefore, the combination may be regarded as a promising nutritional-biochemical strategy for metabolic syndrome, obesity, and states associated with impaired insulin sensitivity.*

Keywords: *chitosan, whey powder, glucose metabolism, insulin sensitivity, insulin resistance, AMPK, PI3K/Akt, GLUT-4, incretins, metabolic syndrome.*

Introduction

Insulin resistance, postprandial hyperglycemia, and altered energy metabolism are central elements in the pathogenesis of metabolic syndrome and type 2 diabetes mellitus. These disturbances are associated not only with elevated blood glucose but also with chronic low-grade inflammation, oxidative stress, dyslipidemia, and mitochondrial dysfunction [1,2,3]. For this reason, correction of metabolic

imbalance with functional food components that complement standard therapy has become an important area of contemporary biochemistry and nutritional physiology [2,3].

Chitosan is a deacetylated derivative of chitin and functions as a cationic polysaccharide capable of forming a viscous matrix in the intestinal lumen, adsorbing specific substrates, and modifying absorption kinetics. Whey powder, by contrast, is a source of high-biological-value protein rich in leucine, isoleucine, and valine, amino acids known to stimulate insulin release, incretin activity, and skeletal-muscle protein synthesis [4-8]. Consequently, the combination of these two components may simultaneously influence intestinal glucose entry, endocrine response, and peripheral substrate utilization [4,5,9].

The aim of the present paper is to transform the source manuscript supplied by the authors into a complete academic article, deepen the biochemical interpretation of the proposed mechanisms, and integrate the discussion with international and CIS literature while preserving the authorship-related scientific context, including publications associated with Rakhmonov Farkhod Kholbayevich [10,11,12].

Main part

1. Effects of chitosan on glucose homeostasis. The metabolic effect of chitosan is primarily related to its physicochemical behavior in the intestine. In aqueous conditions it forms a viscous colloidal system that slows carbohydrate diffusion, changes enzyme-substrate contact, and attenuates the rate at which digested sugars reach the enterocyte surface [9,10]. As a result, the postprandial rise in blood glucose becomes less abrupt, glycemic load is reduced, and the acute secretory demand placed on pancreatic beta cells may be moderated [1,10].

Chitosan also interacts with the gut microbiota. Increased representation of beneficial bacteria and enhanced production of short-chain fatty acids, especially butyrate and propionate, may strengthen barrier function, decrease endotoxemic signaling, and indirectly suppress hepatic gluconeogenesis [9,12]. In such a biochemical background, inflammatory pressure on insulin signaling is diminished, which may improve insulin responsiveness in peripheral tissues [2,3].

2. Insulinotropic and anabolic properties of whey powder. Whey protein fractions are rapidly digested and absorbed, increasing the plasma availability of amino acids within a short time. In particular, leucine-rich whey fractions stimulate pancreatic beta-cell insulin release and augment secretion of incretin hormones such

as GLP-1 and GIP [4,5,6,7]. Therefore, under isocaloric conditions, whey-enriched meals can generate a stronger but still physiological insulin response than many alternative protein sources [4,5].

Whey protein additionally affects signaling networks related to mTOR and, indirectly, AMPK, supporting muscle protein synthesis and metabolic flexibility [6-8]. Since skeletal muscle is a major sink for circulating glucose, enhancement of muscle anabolic and functional capacity facilitates glucose disposal and is commonly accompanied by improved insulin sensitivity [2,8].

3. Insulin signaling and cellular mechanisms. Following insulin-receptor binding, the IRS-1/IRS-2, PI3K, and Akt cascade promotes GLUT-4 translocation to the plasma membrane. In insulin-resistant states, defects often emerge at the post-receptor level, reducing glucose uptake despite preserved or elevated insulin concentrations [2,19]. Chitosan may support this system by lowering inflammatory and lipotoxic burden, whereas whey may reinforce it through amino-acid-mediated endocrine and metabolic effects [4,5,9,19].

AMPK serves as a cellular energy sensor coordinating glycolysis, fatty-acid oxidation, and glucose entry. Chitosan may indirectly modulate AMPK-related physiology through microbial and substrate-driven pathways, while whey affects energy handling via amino acid signaling and tissue-level metabolic adaptation [8-11]. The overall consequence may include improved ATP balance, lower ROS generation, and better biochemical efficiency of insulin signaling [3,20].

4. Theoretical advantages of the combined approach. From a mechanistic standpoint, the combination offers advantages on at least three levels: first, chitosan delays intestinal glucose entry; second, whey supports a physiological insulinotropic response; third, both components may reduce long-term metabolic stress through favorable effects on lipid handling, inflammation, and substrate partitioning [3,4,5,9]. Accordingly, the combination may contribute not only to attenuation of postprandial glycemia but also to improved fasting glucose, HOMA-IR, and lipid-related indices [10,11].

The scientific context is further strengthened by publications associated with Rakhmonov F.K. and co-authors, which have described beneficial effects of chitosan- and whey-based complexes on enzyme activity, mineral metabolism, and hepatic metabolic markers [14-18]. Although these studies arise from adjacent

experimental fields, they provide an additional rationale for considering chitosan-whey combinations as metabolically relevant bioactive systems.

Methodology

The article was prepared as an analytical review and academically revised manuscript. The literature base covered international and CIS publications from 2003 to 2026, with priority given to studies addressing glucose metabolism, insulin resistance, whey protein, chitosan, incretin biology, AMPK, PI3K/Akt signaling, and gut microbiota [1-12,19-23].

The sources were grouped into three clusters: (1) reviews that provide the theoretical biochemical framework; (2) studies examining the individual metabolic actions of chitosan or whey; and (3) open-database publications associated with Rakhmonov Farkhod Kholbayevich and collaborators, included at the user's request and retained in the final reference list [14-18]. Repetitions, broad non-academic statements, and logical gaps in the source manuscript were removed or rewritten in a coherent scholarly form.

No new human or animal experiment was performed for this paper. Consequently, the tables below should be interpreted not as a quantitative meta-analysis but as a structured biochemical synthesis of the reviewed evidence and the revised author manuscript.

Analysis

Analytically, chitosan and whey protein act through complementary rather than redundant mechanisms. Chitosan acts predominantly at the preabsorptive stage, influencing the luminal environment, enzyme-substrate interaction, and intestinal permeability. Whey acts more prominently at the postabsorptive stage through insulinotropic signaling, skeletal-muscle substrate utilization, and anabolic adaptation [4-10]. This complementarity is the main biochemical argument for combining the two components in a single nutritional strategy.

Nevertheless, several limitations should be recognized. The efficacy of chitosan depends on molecular weight, degree of deacetylation, formulation, and dose; the effect of whey depends on whether it is used as isolate, concentrate, or powder, as well as on amino acid profile and timing of intake [9-11,21]. In addition, high protein loads may not be equally tolerated in all individuals, and chitosan may modify the bioavailability of some micronutrients; therefore, clinical use requires dosage control and patient-specific evaluation [1,12,21,22].

Despite these caveats, the available evidence suggests that the combination may be useful in obesity, metabolic syndrome, and insulin-resistant states. Importantly, it should be seen not as a replacement for pharmacotherapy but as an adjunct biochemical-nutritional tool capable of improving the metabolic profile when integrated into a broader preventive or therapeutic program [2,3,11].

Results

The revised scientific synthesis indicates that combined administration of chitosan and whey powder may exert a multistage positive effect on glucose metabolism and insulin sensitivity. Chitosan slows the entry of glucose from the gut, whereas whey strengthens insulin and incretin responses; together these effects reduce the postprandial glycemic burden and increase peripheral glucose utilization.

From a broader metabolic perspective, the combination may attenuate inflammation and oxidative stress, support AMPK- and PI3K/Akt-related pathways, improve lipid handling, and enhance the anabolic status of skeletal muscle. In addition, modulation of the microbiota and barrier function may contribute to lower systemic insulin resistance.

Table 1. Principal biochemical targets of chitosan and whey powder

Biochemical target	Effect of chitosan	Effect of whey	Expected integrated outcome
Intestinal lumen and absorption kinetics	Slows carbohydrate diffusion and enzyme-substrate contact	Indirectly affects gastric emptying and satiety-related hormonal tone	Postprandial glycemia becomes smoother
Incretin and insulin response	Provides indirect support through changes in intestinal environment	Enhances GLP-1/GIP release and insulin secretion	Physiological insulin response is optimized
Peripheral glucose utilization	Improves sensitivity by lowering inflammatory background	Supports GLUT-4 translocation and muscle anabolism	Insulin sensitivity increases

Biochemical target	Effect of chitosan	Effect of whey	Expected integrated outcome
Lipid and energy metabolism	Binds lipids, alters bile-acid turnover, modulates microbiota	Supports AMPK/mTOR-related adaptation	Dyslipidemia and energy instability are reduced

Note: the table does not represent a formal quantitative meta-analysis; it summarizes the mechanistic patterns emerging from the revised manuscript and the reviewed literature. Its purpose is to systematize the likely metabolic advantages of the chitosan-whey combination.

Table 2. Practical interpretation of the expected metabolic shifts

Indicator	Direction	Biochemical explanation	Practical relevance
Fasting glucose	Downward tendency	Relative reduction of hepatic gluconeogenesis and absorptive load	Improved glycemic control
Postprandial glycemia	Clear attenuation	Slower intestinal entry and better balanced insulin response	Reduced glycemic peaks
Insulin sensitivity	Increase	Better IRS-PI3K/Akt and AMPK-related adaptation	Lower HOMA-IR expected
Lipid profile	Improvement	Lower LDL/triglyceride burden and reduced oxidative stress	Lower metabolic syndrome risk
Gut microbiota	Stabilization	Support of SCFA formation and barrier integrity	Lower systemic inflammation

Note: the directions shown in the table reflect a consensus-style synthesis of the revised manuscript and the analyzed literature. The magnitude of the effect in

practice depends on dose, phenotype, dietary background, and duration of administration.

Conclusion

The combination of chitosan and whey powder represents a biochemically plausible and potentially useful strategy for improving glucose metabolism and insulin sensitivity. Its value lies in simultaneous control of intestinal substrate flux, support of physiological insulinotropic response, enhancement of peripheral glucose utilization, and attenuation of inflammatory-oxidative metabolic stress.

The revised article preserves the scientific core of the author manuscript while aligning it with academic standards: the structure was reorganized, terminology was clarified from a biochemical standpoint, explanatory table notes were added, and the references were expanded with both international and CIS sources. Further randomized clinical studies and clearer dose-response models are needed to determine the translational value of this combination in human metabolic disorders.

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