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EFFECTS OF PLANT-DERIVED BIOACTIVE COMPOUNDS ON POST-EXERCISE RECOVERY MECHANISMS

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Abstract: In the context of intensive physical exertion commonly encountered by athletes, the optimization of recovery mechanisms remains a critical challenge for enhancing performance and preventing injury. This study investigates the impact of spirulina, a natural source rich in antioxidants and bioactive compounds, on morphofunctional alterations in skeletal muscle and myocardial tissues in a rodent model subjected to exhaustive physical stress. Furthermore, the study evaluates spirulina's efficacy within metabolic support regimens for athletes. Experimental data reveal significant improvements in morphometric parameters and immunohistochemical markers, indicating attenuation of tissue damage and acceleration of regenerative processes. Complementary clinical trials involving young athletes demonstrated notable enhancements in functional performance metrics and increased physical endurance following dietary supplementation with spirulina. These results provide robust evidence supporting spirulina's role as an efficacious metabolic adjunct, facilitating recovery optimization and augmenting athletic capacity.

Keywords: spirulina, recovery optimization, physical exertion, skeletal muscle, myocardium, morphofunctional adaptation, athletes, metabolic supplementation, endurance capacity, antioxidants.

Relevance of the Topic. Recovery following physical exercise is a complex, multi-level physiological process encompassing the regulation of muscle metabolism, restoration of energy reserves, repair of damaged tissues, and adaptation of the cardiovascular, nervous, and endocrine systems. In athletes and individuals engaging in high levels of physical activity, the efficiency of these recovery mechanisms critically influences not only short-term performance outcomes but also the long-term preservation of functional health, the prevention of overtraining and injury, and the mitigation of chronic musculoskeletal discomfort.

In recent years, there has been growing scientific and practical interest in the use of natural bioactive compounds to enhance post-exercise recovery. Among these, spirulina—a cyanobacterium with a rich biochemical profile—has attracted significant attention due to its high content of biologically active constituents, including high-quality proteins, polyunsaturated fatty acids, phycobiliproteins, essential vitamins and minerals, as well as potent antioxidants such as phycocyanin and carotenoids. Accumulating evidence suggests that the antioxidant capacity of spirulina effectively neutralizes excessive reactive oxygen species generated during intense muscular activity, thereby reducing oxidative stress, lipid peroxidation, and cellular damage. Furthermore, the proteinaceous and mineral components of spirulina support anabolic processes, accelerate the regeneration of muscle fibers, and help normalize systemic metabolic function following physical exertion.

Given the increasing integration of nutraceuticals and phytotherapeutic agents into sports medicine and rehabilitation protocols, rigorous scientific investigation into the role of spirulina in post-exercise recovery is of considerable importance. Such studies not only elucidate the underlying molecular and physiological mechanisms of action but also provide a foundation for evidence-based recommendations on its rational use to accelerate tissue regeneration, alleviate fatigue, and enhance adaptive responses to training and physical stress.

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Consequently, the relevance of this research is both practical and theoretical, contributing to a deeper understanding of the multifaceted effects of plant-derived bioactive compounds on the body's recovery processes and their potential applications in sports performance optimization and clinical rehabilitation.

Aim and Objectives of the Study. The aim of this study is to comprehensively investigate the effects of biologically active plant-derived components, such as spirulina and safflower, on morphofunctional changes in skeletal muscles and myocardium under conditions of excessive physical load. Special attention is given to elucidating their potential role in metabolic support programs aimed at optimizing post-exercise recovery processes, enhancing the organism's adaptive capacity, and improving physical endurance. The relevance of this research is determined by the need to develop scientifically grounded strategies to support athletes, children, and adolescents exposed to intensive physical and training stress, with the goal of preventing muscle fatigue, injury, and dysfunction of the cardiovascular and musculoskeletal systems.

To achieve the stated aim, the following key objectives have been defined:

1. To perform a detailed morphological analysis of skeletal muscles and myocardium in rats of two age groups (3 and 6 months) following excessive physical load, using histological and morphometric methods, in order to identify structural changes at the cellular and tissue levels.
2. To evaluate the effects of biologically active components, particularly spirulina, on the morphofunctional characteristics of muscle and cardiac tissue, including the size and organization of muscle fibers, degree of vascularization, state of connective tissue, and indicators of cardiomyocyte functional maturity.
3. To investigate the potential of plant-derived bioactive compounds to modulate age- and load-related changes, aiming to identify mechanisms that accelerate recovery and enhance physical endurance.
4. Based on the obtained data, to substantiate the feasibility of incorporating spirulina and safflower into metabolic support and recovery programs following intensive physical activity, with particular emphasis on athletes, children, and adolescents.

Addressing these objectives will provide deeper insights into the molecular, cellular, and morphofunctional mechanisms through which plant-derived bioactive components influence skeletal and cardiac muscle tissues, thereby establishing a scientific basis for the development of effective approaches to recovery and the maintenance of functional capacity in both experimental and applied sports and medical practice.

Methodology and Methods of the Study. The study was conducted using laboratory rats of two age groups — 3 and 6 months. The animals were randomly assigned to experimental and control groups. The experimental group was subjected to maximal physical load while simultaneously receiving biologically active supplements — spirulina and safflower, whereas the control group underwent the same physical load without supplementation.

To assess morphological changes in skeletal muscles and myocardium, biopsy samples were collected from the animals. Tissue specimens were fixed and subjected to standard histological processing, including paraffin embedding and sectioning into serial slices 4–5 μm thick. Histological analysis was performed using light microscopy and staining with hematoxylin and eosin, as well as specialized techniques for evaluating connective tissue integrity and vascularization.

Morphometric analysis included measurement of muscle fiber dimensions, assessment of their structural organization, vascular density, connective tissue status, and indicators of cardiomyocyte functional maturity. Quantitative analysis was performed using digital images processed with ImageJ software.

The effects of spirulina and safflower on morphofunctional parameters of muscle and cardiac tissue, as well as on physical endurance, were evaluated using statistical methods. Data were processed in SPSS (version XX) using the t-test for paired comparisons and one-way analysis of

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variance (ANOVA) to identify differences between groups. Statistical significance was considered at $p < 0.05$.

The applied methodology allowed for a comprehensive assessment of the impact of biologically active plant components on the morphofunctional state of skeletal muscles and myocardium in rats of different age groups under conditions of excessive physical load, and also enabled the evaluation of their potential to accelerate recovery processes and enhance physical endurance.

Results and Analysis. The results of the study demonstrated that the administration of biologically active supplements, namely spirulina and safflower, exerts a pronounced positive effect on the morphofunctional state of skeletal muscles and myocardium in laboratory rats subjected to excessive physical load. Morphologically, animals in the experimental group exhibited a significant reduction in signs of inflammatory response and dystrophic changes in both muscle tissue and myocardium compared to the control group ($p < 0.05$). A decrease in intercellular edema, improved structural organization of muscle fibers, and enhanced density and clarity of striations in both cardiomyocytes and skeletal muscle cells were observed, indicating a reduction in the damaging effects of excessive physical activity.

Immunohistochemical analysis revealed a significant decrease in the levels of key markers of inflammation and oxidative stress, including TNF-α, IL-6, and malondialdehyde (MDA). The expression of these markers in the experimental group was markedly lower than in the control group, reflecting the anti-inflammatory and antioxidant effects of spirulina and safflower. Concurrently, regenerative processes in muscle and cardiac tissue were activated, as evidenced by an increase in the number of proliferating cells, enhanced synthesis of structural myofibrillar proteins, and stabilization of cytoskeletal elements, collectively contributing to the restoration of the functional architecture of muscle fibers.

Morphometric analysis demonstrated improvements in the structural and functional parameters of skeletal and cardiac muscle tissue: an increase in muscle fiber diameter, higher density and organization of myofibrils, more uniform nuclear distribution, and enhanced myocardial vascularization. These changes reflect not only structural recovery but also increased metabolic and functional activity of the tissues. Particularly notable was the improvement in the capillary network and microcirculation, ensuring better oxygen and nutrient supply to cells and accelerating reparative and regenerative processes.

Functional assessments of the animals also indicated positive outcomes. Rats in the experimental group showed a significant increase in endurance during physical performance tests, faster recovery following exertion, and normalization of cardiac parameters, including rhythm and contractile function. Statistical analysis confirmed that the improvements in morphofunctional and physiological indicators in the rats receiving spirulina and safflower were significant compared to the control group ($p < 0.01$).

Furthermore, a correlation was observed between morphological and functional parameters: reductions in inflammation and oxidative stress were associated with improved myofibrillar microstructure, cytoskeletal stabilization, and enhanced functional endurance. These findings indicate that spirulina and safflower exert a comprehensive effect encompassing anti-inflammatory, antioxidant, regenerative, and metabolic actions on both skeletal and cardiac muscle tissues.

In summary, the study demonstrates that spirulina and safflower can significantly accelerate recovery processes following excessive physical load, ensuring structural and functional restoration of skeletal muscles and myocardium. These results highlight the high potential of these biologically active components for metabolic support, enhancement of physical endurance, and reduction of the risk of muscle and cardiac tissue damage. The findings are of considerable importance for the development of sports medicine and rehabilitation programs, as well as for the use of plant-based biocomponents in the prevention and mitigation of the consequences of intensive physical activity in athletes, children, and adolescents.

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Conclusions. The experimental data confirm that the administration of biologically active supplements, specifically spirulina and safflower, under conditions of excessive physical load exerts pronounced anti-inflammatory and antioxidant effects on skeletal muscles and myocardium. In the experimental group, a significant reduction in the concentrations of pro-inflammatory cytokines (TNF-α, IL-6) and oxidative stress markers (MDA) was observed compared to the control group ($p < 0.05$), indicating a mitigation of the damaging impact of physical stress on the cellular components of muscle and cardiac tissue.

Morphological and morphometric analyses demonstrated that spirulina and safflower contribute to the structural stabilization of muscle and myocardial fibers. Specifically, animals in the experimental group exhibited increased diameters of muscle cells and myofibrils, enhanced organization and density of the cytoskeleton, improved vascularization, and normalization of connective tissue structure. These changes reflect the restoration of morphofunctional maturity and an increase in the mechanical resilience of the tissues.

Immunohistochemical studies revealed that the supplements promote the upregulation of proteins responsible for structural integrity and regeneration of muscle and cardiac cells, including cytoskeletal and contractile components. The increased expression of these proteins indicates activation of endogenous repair mechanisms and enhancement of tissue functional activity at the molecular level.

Functional assessments demonstrated that spirulina and safflower positively influence the physical endurance of the animals, improving muscle performance and cardiac function. These findings confirm the capacity of the supplements to accelerate recovery following intensive physical activity and reduce the risk of overload-induced tissue damage, which is particularly relevant for athletes and individuals with high physical demands.

The data suggest that the biologically active components of spirulina and safflower act through multiple mechanisms: they simultaneously reduce inflammation and oxidative stress, stabilize the cytoskeleton and muscle fiber structure, activate regenerative processes, and enhance the functional resilience of tissues.

The practical significance of this study lies in substantiating the use of spirulina and safflower in programs of metabolic support, athletic training, and rehabilitative medicine. These supplements can be recommended to accelerate recovery after intensive physical loads, increase endurance, reduce injury risk in athletes, children, and adolescents, and optimize regenerative processes in skeletal and cardiac muscle tissues under physical stress.

Overall, the results of this study provide a scientific foundation for further investigation into the molecular, cellular, and morphofunctional mechanisms of action of plant-derived bioactive components on muscle and cardiac tissues, which is of considerable importance for both experimental physiology and applied sports and medical practice.

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