

Research Article

Crosstalk between antioxidant enzymes and interleukin-10 in rats fed a high-fat diet: The impact of exercise and *Lactobacillus bifidus* supplementation

Seyed Ramin Rasouli¹, Mandana Gholami^{1*}, Farshad Ghazalian,¹Hossein Abednatanzi¹

Abstract

The present study will investigate the changes and correlation between the antioxidant enzyme superoxide dismutase (SOD) and the expression of interleukin 10 (IL-10) in rats fed a high-fat diet (HFD) after 6 weeks of aerobic exercise supplemented with the probiotic *Lactobacillus bifidus*. 40 male Wistar rats were divided into 5 groups (8 each): healthy control, high-fat diet (HFD), HFD+aerobic exercise (Tr), HFD+probiotic supplementation (Sup), and HFD+Tr+Sup. The rats in the HFD group received a special high-fat diet for 2 months prior to the main protocol. The rats in the exercise groups ran on a rodent treadmill for 6 weeks, 5 days a week. *Lactobacillus bifidus* supplementation was gavaged at a dose of 1 cc to the rats in the supplementation groups after each exercise session. Finally, the rats were sacrificed, and the IL-10 variable was measured using the Real-Time PCR method. The results of the present study indicated that the high-fat diet increased cholesterol and triglyceride levels ($p < 0.05$). The HFD and HFD+Sup groups showed a significant decrease in SOD compared to the healthy control group ($p < 0.05$). All treatment groups demonstrated a significant increase in SOD compared to the HFD group ($p < 0.05$). The HFD+Tr and HFD+Tr+Sup groups showed a significant increase in IL-10 compared to the HFD group ($p < 0.05$). However, the correlation between SOD and IL-10 was not confirmed ($p > 0.05$). There was no correlation between the antioxidant enzyme and IL-10. Nevertheless, exercise and *Lactobacillus bifidus* were able to regulate the lipid profile, SOD, and IL-10 after a high-fat diet.

Key Words: Antioxidant, IL-10, *Lactobacillus Bifidus*, Exercise, High-fat diet

Introduction

Weight gain and related metabolic disorders are major health issues worldwide, with current reports indicating that obesity rates have tripled since 1980 (Finucane et al., 2011). In animal models, obesity is associated with various physiological changes in the body, including reduced intestinal barrier function, intestinal inflammation, metabolic endotoxemia, and chronic low-grade systemic inflammation (Raybould, 2012). The initial response to the consumption of high-fat and high-calorie (HF) diets in rodents is a decrease in the ability of gut satiety factors, such as cholecystokinin, to inhibit food intake (Paulino et al., 2009). There is evidence suggesting that this is due to the desensitization of vagal afferent neurons to gut satiety factors, leading to hyperphagia and ultimately weight gain. Changes at the cellular level and the disruption of gut homeostasis caused by high-fat diets can have autocrine, paracrine, and endocrine effects. At the cellular level, it can influence signaling pathways in intestinal tissue.

The importance of IL-10 signaling in metabolic diseases related to obesity is well established. This anti-inflammatory cytokine signals through the ligand-binding subunit of the IL-10 receptor (IL-10R1) and is induced during inflammation, reducing the excessive production of pro-inflammatory mediators in various cell types, including intestinal epithelial cells (IEC) (Engelhardt & Grimbacher, 2014; Kominsky et al., 2014). Functional IL-10 signaling is associated with enhanced mucosal barrier function, leading to the maintenance and homeostasis of the epithelium (Kominsky et al., 2014). Research has shown that epithelial IL-10R1 significantly contributes to resistance against intestinal inflammation and represents a part of the epithelial innate immunity that is induced by cytokines such as interferon- γ (IFN- γ) (Colgan et al., 1993). Additionally, it has been confirmed in animal studies that mice lacking IL-10 or IL-10 receptor develop severe colitis spontaneously, and mice that are conditionally deficient in epithelial IL-10R1 show increased susceptibility to colitis (Chaudhry et al., 2011; Kominsky et al., 2014). Therefore, increasing this factor could serve as a therapeutic target in met-

1. Department of Physical Education and Sport Sciences, Science and Research Branch, Islamic Azad University, Tehran, Iran.

*Author for correspondence: gholami_man@yahoo.com

-abolic diseases, as its elevation, both in the gut and in the bloodstream, can have anti-inflammatory effects.

Bifidobacterium, Lactobacillus, and Enterococcus faecalis are probiotics that have beneficial effects in the maintenance treatment of human intestinal diseases (Ventura et al., 2009). For example, oral treatment with specific probiotic bacteria can improve inflammatory and metabolic bowel disease (IBD). Furthermore, numerous studies have shown that colonization strategies using defined compounds or specific exogenous probiotic treatments may prevent host intestinal inflammation and enhance the function of the intestinal epithelial barrier (Madsen et al., 2001). Shi et al. (2014) demonstrated in their study that probiotic consumption reduced colonic inflammation in mice with knockout IL-10 and improved epithelial barrier function. It also decreased the secretion of pro-inflammatory cytokines (Shi et al., 2014).

Exercise is often prescribed for weight loss and weight maintenance, as well as for controlling the damage caused by high-fat diets (HFD). Exercise induces a diverse microbiome (Clarke et al., 2014). This is an important observation, although exercise is not fully associated with gut integrity. Existing evidence in this area indicates that intense and prolonged exercise in heat improves gut function in endurance athletes (Zuhl et al., 2014). This is an interesting observation because exercise typically reduces the risk of gastrointestinal cancer, reflux, and the incidence of ulcers, fatty liver, IBS, and diverticulitis (De Oliveira & Burini, 2009). Furthermore, it has been shown that exercise in older animals reduces the expression of inflammatory mediators and apoptosis markers in intestinal lymphocytes, indicating a protective role for exercise in gut health (Packer & Hoffman-Goetz, 2012). Additionally, exercise may enhance butyrate-producing bacteria, which leads to reduced inflammation and promotes cellular proliferation (Matsumoto et al., 2008). Therefore, it may also positively impact interleukin 10. Exercise may protect gut morphology and integrity while reducing systemic inflammation. Moreover, with its strong antioxidant effects, it can exert anti-inflammatory and antioxidant roles.

Since exercise and supplementation appear to have synergistic anti-inflammatory and antioxidant effects, the present study addresses the hypothesis of whether exercise and probiotic supplementation can regulate the anti-inflammatory factor IL-10 in intestinal tissue, thereby enhancing and strengthening the antioxidant system in circulation

Materials and Methods

Animals

In this experimental study, 40 male Wistar rats aged 10 to 12 we-

-eks with an average weight of 240 grams were purchased from the Pasteur Institute of Iran (Tehran, Iran) and were maintained under standard laboratory conditions at the Animal Biology Laboratory of the Islamic Azad University, Science and Research Branch. The animals were acclimatized to laboratory conditions for two weeks under a 12-hour light/dark cycle, with an average temperature of 20 ± 22 degrees Celsius and an average humidity of 50 ± 5 percent, in ten standard rodent cages measuring $30 \times 15 \times 15$ centimeters, based on the laboratory animal care checklist of the Islamic Azad University, Science and Research Branch, Faculty of Medical Sciences and Technologies. During the first two weeks, the subjects were fed a normal diet consisting of pellets provided by the Javaneh Khorasan Company, containing 19.6% protein, 3% fat, 6% fiber, 50.4% carbohydrates, 13% moisture, and other components. This study was conducted under the supervision of the Animal Ethics Committee of the Islamic Azad University, Science and Research Branch, Tehran, Iran, with ethical code IR.IAU.SRB.REC.1402.187.

High-Fat Diet

Apart from the healthy control group, which was randomly selected, the remaining subjects were placed on a high-fat diet for two months, with the addition of 40% solid vegetable oil to their meals compared to a normal diet. The amount of added oil was considered to be 37% of the weight of the normal diet. The weight of the subjects was measured before the start of the diet and during the high-fat diet twice a week using a digital scale model BLK-500 by Sunli, with an accuracy of 0.1 grams.

After two months, 32 subjects on the high-fat diet were randomly divided into four groups of eight, including the high-fat diet group (HFD), the HFD with exercise group (HFD+Tr), the HFD with supplementation group (HFD+Sup), and the HFD with supplementation and exercise group (HFD+Tr+Sup).

Before starting the exercise protocol and supplementation, four rats from the control group and 3 rats from the experimental group on a high-fat diet were randomly subjected to ultrasound examination of the liver and organs by a veterinarian. It was confirmed that, apart from one healthy control rat, the HFD subjects showed visible evidence of fatty liver.

Exercise

The HFD+Tr and HFD+Tr+Sup groups were subjected to exercise on a treadmill from the leading engineering company, Pishro Andisheh Sanat, model Navid Line, product code 12603, for 6 weeks, 5 days a week. The exercise method involved changes in intensity and duration as follows: Throughout the training period, a warm-up and cool-down phase of 5 minutes at a speed of 10 meters per minute was maintained at the beginning and end of each session. In the first week, the speed was set at 15 m/min for 30 minutes; in the second week, 18 m/min for 35 mi-

-nutes; in the third week, 21 m/min for 40 minutes; in the fourth week, 23 m/min for 45 minutes; in the fifth week, 25 m/min for 50 minutes; and in the sixth week, 27 m/min for 60 minutes, implementing the exercise protocol (Karakioulaki et al., 2020).

Supplement

The HFD+Sup and HFD+Tr+Sup groups were supplemented with *Lactobacillus bifidus* obtained from the pharmaceutical company Zist Takhmir, registered under number 368211, containing a concentration of 10^9 CFU/ml of the solution, which was gavaged at a dose of 1 cc after each exercise session. The available strains were ready to use and were stored in the refrigerator under cold chain conditions. To prevent temperature shock during gavage, they were kept at room temperature for half an hour before the start of the exercise.

Sacrifice

Forty-eight hours after the last exercise session, the animals were transferred to Kimia Andisheh Teb Biotechnology and Genetics Company, registered under number 205932, for necessary tests and sampling. The euthanasia procedures included blood collection and preparation of tissue samples (intestine) within 8 hours by a veterinarian and the accompanying team. Blood samples were collected in two forms: whole blood and citrate for biochemical, enzymatic, and oxidative tests, and intestinal tissue samples were collected for examining the expression of IL-10 using the Real-Time PCR method.

Laboratory measurements

In the present study, cholesterol was measured using the kit from Delta Therapeutic Part (Tehran, Iran) with code PI012. The coefficient of variation for this kit was 0.9986. Triglycerides were also measured using the kit from Delta Therapeutic Part (Tehran, Iran). HDL and LDL were assessed using the kits from Delta Therapeutic Part (Tehran, Iran) with the Direct-Enzymatic method for photometric measurement. The activity level of the SOD enzyme was measured using an ELISA kit based on the protocol provided by the purchased company.

Expression of IL-10

To investigate the expression of IL-10 genes in each group, the Real-Time PCR technique was utilized. For primer preparation, 10 microliters of lyophilized primer in distilled water, 0.5 microliters of forward primer, 0.5 microliters of reverse primer, 1 microliter of cDNA, and 8 microliters of diethylpyrocarbonate (DEPC) water were used. For gene expression analysis, total RNA was extracted using the Qiazol solution based on the protocol provided by Sinagen. The quality of the extracted RNAs was assessed using a spectrophotometer. To prepare single-stranded cDNA, Oligo dt primers and reverse transcription enzy-

-me were used according to the relevant protocol. Each PCR reaction was performed in the ABI Step One device following the manufacturer's protocol. The Real-Time PCR reaction cycles for the IL-10 gene were conducted at three temperatures: 94, 60, and 72 degrees Celsius. A melting curve analysis was performed to verify the accuracy of the PCR reactions. Glyceraldehyde 3-phosphate dehydrogenase (GAPDH) was used as the reference gene for IL-10. The expression levels of control and experimental genes were measured simultaneously. The primers used are listed in Table 1.

Statistical analysis

Data were expressed as mean \pm standard deviation. The normality of the data was confirmed using the Shapiro-Wilk statistical test. To examine the changes in the research variables among different groups, one-way ANOVA was used. Additionally, the Tukey post-hoc test was employed to assess the changes in each of the variables between the groups. Pearson correlation was used to analyze the correlation between serum SOD and intestinal IL-10. Data were analyzed using SPSS software version 26, and Graph Pad Prism 9 was used for plotting graphs. A significance level of $p < 0.05$ was considered.

Results

The changes in the lipid profile of the animals in the different research groups are shown in Figure 1. The results of the one-way ANOVA indicated that there was a significant difference in cholesterol among the different research groups ($F=4.112$, $p=0.0084$). The results of the Tukey post-hoc test showed that only the HFD group exhibited a significant increase in cholesterol compared to the healthy control group ($p < 0.05$). However, the treatment groups did not show significant changes in cholesterol compared to the HFD group (Figure 1A).

The results of the one-way ANOVA statistical test indicated that there were significant differences in triglyceride levels among the different research groups ($F=7.024$, $p=0.0004$). The Tukey post-hoc test results showed that all HFD groups exhibited a significant increase in triglycerides compared to the healthy control group ($p < 0.05$) (Figure 1B).

The results of the one-way ANOVA statistical test indicated that there were significant differences in LDL levels among the different research groups ($F=3.522$, $p=0.0172$). The Tukey post-hoc test results showed that the HFD+Tr and HFD+Sup groups demonstrated a significant decrease in LDL compared to the HFD group (Figure 1C).

Table 1. Characteristics of the primers used in the study

Gene	Primer sequence
IL-10	F: 5' CGGGAAGACAATAACTGCACCC 3'
	R: 5 CGTTAGCAGTATGTTGTCCAGC 3'
GAPDH	F: 5' CGGGAAGACAATAACTGCACCC 3'
	R: 5' CGTTAGCAGTATGTTGTCCAGC 3'

The results of the one-way ANOVA statistical test indicated that there were no significant differences in HDL levels among the different research groups ($F=0.4162$, $p=0.7957$) (Figure 1D).

The changes in the antioxidant index SOD in the different research groups are shown in Figure 2. The results of the one-way ANOVA statistical test indicated that there were significant differences in the antioxidant index GPX among the various research groups ($F=26.86$, $p<0.0001$). The results of the Tukey post hoc test showed that the HFD and HFD+Sup groups had a significant decrease in SOD compared to the healthy control group ($p<0.05$). Compared to the HFD group, all treatment groups demonstrated a significant increase in SOD ($p<0.05$).

The changes in IL-10 gene expression in the different study groups are shown in Figure 3. The results of the one-way ANOVA statistical test indicated that there is a significant difference in IL-10 gene expression among the various research groups ($F=6.677$, $p=0.0005$). According to the Tukey post-hoc test, the HFD+Tr and HFD+Tr+Sup groups showed a significant increase in IL-10 compared to the HFD group ($p<0.05$). Additionally, the increase in IL-10 in the HFD+Tr+Sup group compared to the HFD+Sup group was significant ($p<0.05$).

To examine the correlation between the antioxidant index SOD and the expression of the IL-10 gene, Pearson correlation testing was used. The results of this test indicated that there was no correlation between SOD and the expression of the IL-10 gene in the different research groups (Figure 4).

Discussion

A high-fat diet (HFD) has been linked to various adverse effects on metabolic health, primarily through the induction of oxidative stress and inflammation. These processes are critical factors in the development of numerous chronic diseases, including metabolic syndrome, cardiovascular diseases, and neurodegenerative disorders. High-fat diets pose significant risks to metabolic health through mechanisms involving oxidative stress and inflammation. These processes not only contribute to immediate metabolic disturbances but also lay the groundwork

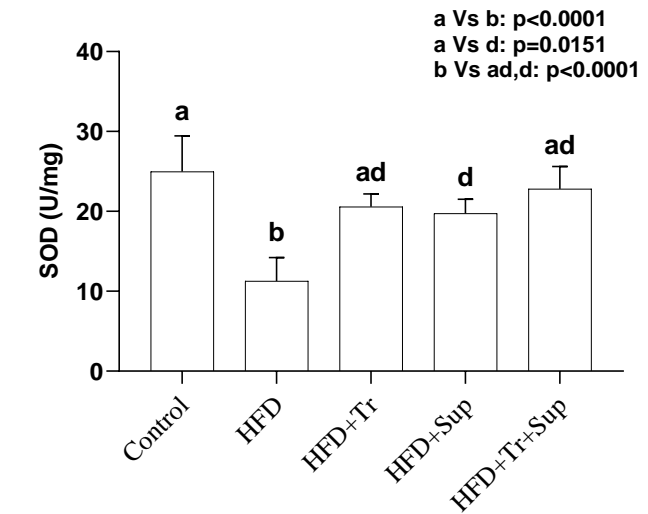


Figure 2. Changes in SOD in Different Study Groups. Data are presented as mean \pm standard deviation. A significance level of $p<0.05$ was considered. Abbreviations: HFD: High-Fat Diet, Tr: Exercise, Sup: Supplement.

for chronic diseases that can have long-term health implications. Understanding these mechanisms highlights the importance of dietary choices in maintaining metabolic health and preventing chronic diseases.

The typical Western diet is characterized by high consumption of dietary fats and refined carbohydrates, along with low intake of plant fibers (Sproesser et al., 2019). Humans are less adaptable to unhealthy diets, and many diseases associated with the Western diet (such as obesity, diabetes, and cardiovascular diseases) involve disrupted metabolic changes between glucose and lipids or inappropriate fat storage (Soeters et al., 2012). Dietary fats play a significant role in the pathogenesis of intestinal disease. IL-10 has a major role in intestinal homeostasis. IL-10 is an anti-inflammatory cytokine that plays a crucial role in regulating immune responses and inflammation. It is secreted by various immune cells and helps to inhibit the production of pro-inflammatory cytokines, thereby mitigating inflammation. In the c-

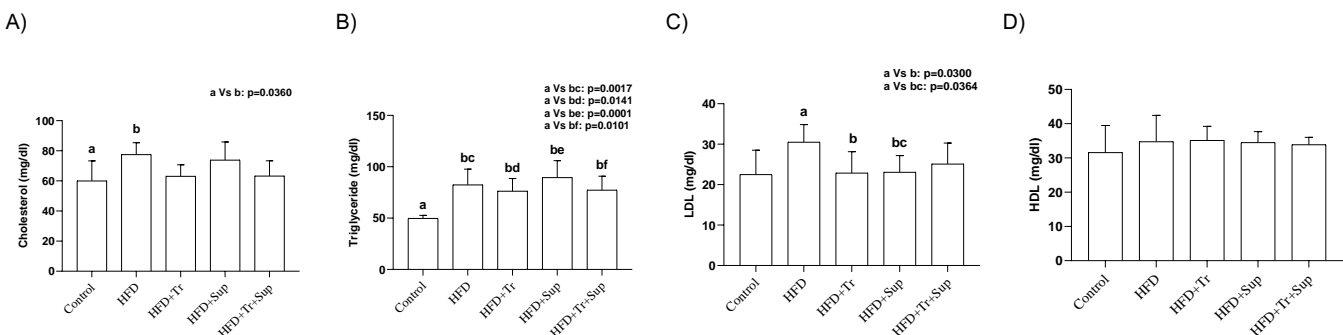


Figure 1. Changes in glucose levels (A), insulin (B), and HOMA-IR © in different research groups. Data are presented as mean \pm standard deviation. A significance level of $p < 0.05$ is considered. Abbreviations: HFD: high-fat diet, Tr: exercise, Sup: supplement.

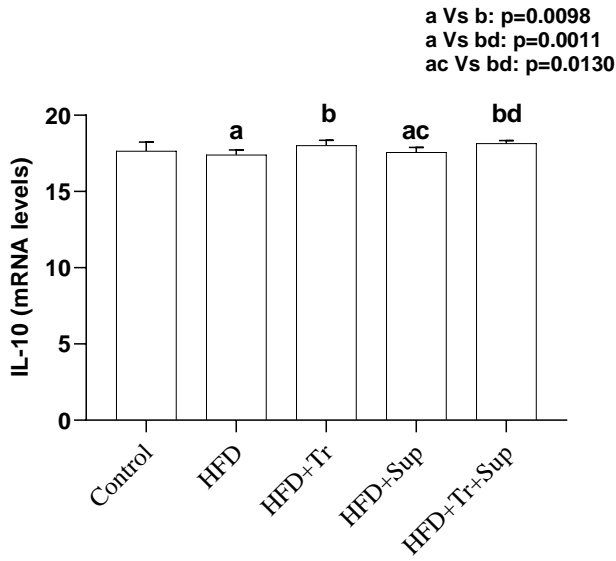


Figure 3. Changes in IL-10 Gene Expression in Different Study Groups. Data are presented as mean ± standard deviation. A significance level of $p < 0.05$ is considered. Abbreviations: HFD: High-Fat Diet, Tr: Exercise, Sup: Supplement.

In the context of obesity induced by a high-fat diet, IL-10 levels are often found to be decreased, which can exacerbate inflammatory responses in adipose tissue and other organs (Liu et al., 2018). It has been shown that mice deficient in IL-10 and IL-10 receptor deficiency develop spontaneous colitis (Kuhn et al., 1993). Changes in IL-10 have also been confirmed in studies involving

high-fat diets (Kondo et al., 2018). Since exercise and probiotics are effective factors in improving gut homeostasis, controlling inflammation, and enhancing antioxidant systems, the present study investigates the effects of 6 weeks of treadmill exercise and probiotic supplementation on the relationship and changes in SOD and IL-10 in rats made obese by a high-fat diet.

Antioxidant enzymes, such as superoxide dismutase (SOD), catalase, and glutathione peroxidase, are critical for neutralizing reactive oxygen species (ROS) generated during metabolic processes, including those exacerbated by high-fat diets. A high-fat diet can lead to increased oxidative stress, which is linked to inflammation and metabolic disorders. Research indicates that IL-10 can influence the expression of antioxidant enzymes. For example, IL-10 administration has been shown to ameliorate oxidative stress in models of obesity (Kondo et al., 2018). This suggests that IL-10 might enhance the activity or expression of antioxidant enzymes, thereby reducing oxidative damage associated with HFD. The protective role of IL-10 against diet-induced insulin resistance has been highlighted, indicating that it may help maintain the balance between pro-inflammatory and anti-inflammatory processes in the body. By reducing inflammation, IL-10 might indirectly support the function of antioxidant enzymes, leading to better management of oxidative stress (Kondo et al., 2018). Given that both IL-10 and antioxidant enzymes play roles in combating inflammation and oxidative stress, targeting these pathways could provide therapeutic benefits for individuals on high-fat diets. Strategies that increase

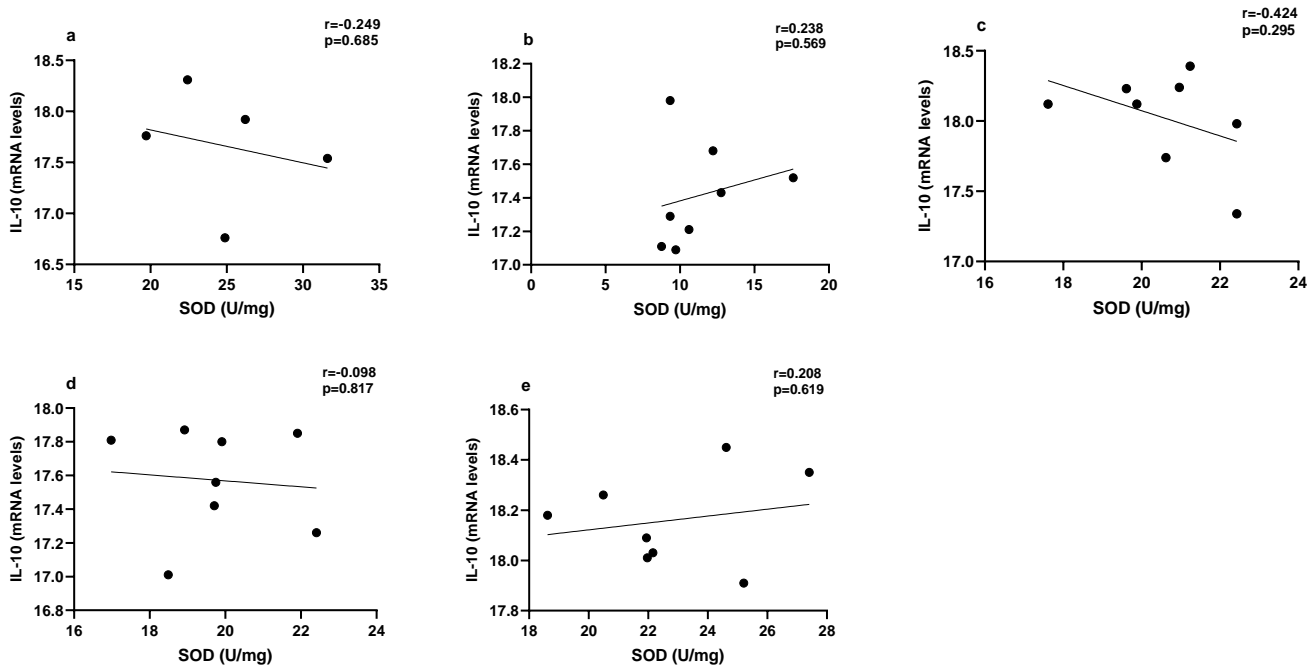


Figure 1. Correlation Between the Antioxidant Index SOD and IL-10 Gene Expression in Different Research Groups. a: Control group, b: HFD group, c: HFD+Tr group, d: HFD+Sup group, e: HFD+Tr+Sup group. Data are presented as mean ± standard deviation. A significance level of $p < 0.05$ is considered. Abbreviations: HFD: High-Fat Diet, Tr: Exercise, Sup: Supplement.

IL-10 levels or enhance antioxidant enzyme activity (such as exercise training and probiotic) may help mitigate the adverse effects of HFD on metabolic health (Liu et al., 2018).

Exercise and *Lactobacillus bifidus* supplementation may modulate the interactions between interleukin-10 (IL-10) and superoxide dismutase (SOD) in several ways, particularly in the context of inflammation and oxidative stress. Both exercise and *Lactobacillus bifidus* supplementation can modulate the interactions between IL-10 and superoxide dismutase (SOD). Exercise enhances IL-10 production while increasing SOD activity, contributing to reduced oxidative stress and inflammation. Similarly, *Lactobacillus bifidus* may support IL-10 levels and overall gut health, further complementing the beneficial effects of exercise on inflammation and oxidative stress management. Together, these strategies may provide synergistic benefits for individuals looking to improve their metabolic health and reduce inflammation-related conditions. Further research is warranted to elucidate these interactions fully.

The results of the present study indicated that lipid profile indices (LDL, cholesterol, and triglycerides) significantly increased with the consumption of a high-fat diet (HFD). However, LDL levels in the HFD+Tr and HFD+Sup groups showed a significant decrease compared to the HFD group. SOD levels also decreased in the HFD group but significantly increased in the treatment groups, especially in the combined treatment group. Additionally, intestinal IL-10 levels significantly increased in the HFD+Tr group compared to the HFD group. The IL-10 levels in the combined treatment group were also significantly different from those in the HFD+Sup group. The essential role of IL-10 in maintaining gut homeostasis has been confirmed (Kole & Maloy, 2014). IL-10 acts on myeloid cells and T cells in the gut to suppress both innate and adaptive inflammatory responses and enhance regulatory circuits (Kole & Maloy, 2014). Although several distinct cellular sources of IL-10 have been identified in the gut, CD4+ T cells are a vital non-redundant source of IL-10 for regulating intestinal inflammation. In other words, changes in intestinal IL-10 are also influenced by the immune system.

Probiotics play a significant role in influencing gut microbiota composition, which can subsequently affect systemic inflammation and metabolic processes. The mechanisms through which probiotics exert these effects are multifaceted and involve interactions with both the gut microbiome and the host's immune system. Probiotics are defined as live microorganisms that confer health benefits to the host, primarily by restoring or enhancing the gut microbiota. They can help reestablish a balanced microbial community, especially after disturbances caused by factors such as antibiotics or poor dietary habits. Probiotics introduce beneficial bacteria that can outcompete pathogenic microorganisms, leading to improved gut health and function (Sánchez et al., 2017). Probiotics can modulate the host's immu-

-ne system by enhancing the production of anti-inflammatory cytokines and suppressing pro-inflammatory cytokines. This immunomodulatory effect helps reduce systemic inflammation, which is linked to various chronic diseases (Wieërs et al., 2020).

Since probiotics and exercise play significant roles in improving the immune system, an increase in these factors in the treatment groups is not unexpected. Recent genetic studies in humans have confirmed the essential role of IL-10 in preventing harmful inflammation in the gut. A better understanding of the molecular pathways involved in the induction and function of IL-10 in the intestine may facilitate the development of new treatments for inflammatory bowel disease (IBD) (Kole & Maloy, 2014). The mechanism of action of probiotics is not fully understood and is likely multifactorial, depending on the specific strain used. The anti-inflammatory activity appears to involve signaling with the gastrointestinal epithelium and interaction with mucosal regulatory T cells and dendritic cells, leading to the modulation of pro-inflammatory cytokines (Shanahan, 2005). Dendritic cells determine the balance between effector T cells and regulatory T cell responses, and various *Lactobacillus* strains have been shown to induce specific patterns in the activation of mouse dendritic cells in laboratory conditions (Christensen et al., 2002). On the other hand, *Lactobacillus* may enhance antioxidant capacity, which was also confirmed in the present study. Although the correlation and crosstalk between SOD and IL-10 were not confirmed, in line with the current study, Dashtbani and colleagues demonstrated that the use of a combined probiotic (*Lactobacillus rhamnosus*, *Lactobacillus helveticus*, and *Lactobacillus casei*) had anti-inflammatory, anti-apoptotic, and antioxidant effects on oxidative damage caused by cadmium in the small intestine and lungs (Dashtbani & Keshtmand, 2023). Meanwhile, exercise can also amplify the antioxidant effects of probiotics. Kim and colleagues (2024) confirmed that different intensities of aerobic exercise improve cardiorespiratory fitness and increase plasma levels of superoxide dismutase (Kim, 2024). Since the anti-inflammatory and antioxidant effects of aerobic exercise have been confirmed in multiple studies, the increase in SOD and IL-10, each separately, seems reasonable in both single and especially combined treatments.

Also, probiotics can help restore gut barrier function and reduce intestinal permeability, thereby mitigating the inflammatory response triggered by high-fat diets (McDermott et al., 2022). Exercise also plays a role in reducing inflammation by promoting anti-inflammatory cytokine production and enhancing immune function (Aykut et al., 2024). Together, probiotics and exercise may significantly lower levels of pro-inflammatory markers, contributing to better overall health. The combination of exercise and probiotics offers a promising approach to counteract the negative effects of high-fat diets on health. By enhancing gut microbiota composition, reducing systemic inflammation, and improving metabolic processes, this synergistic relationship can

lead to better health outcomes. Future research should continue to explore the specific strains of probiotics that are most effective when combined with exercise, as well as the optimal timing and dosage for maximum benefits.

Conclusion

Incorporating a structured exercise regimen alongside targeted probiotic supplementation can significantly enhance health outcomes for individuals on high-fat diets. By improving gut microbiota composition and reducing systemic inflammation, this combined approach supports better metabolic health and overall well-being. Regular monitoring and adjustments based on individual responses will optimize the benefits of these interventions.

What is already known on this subject?

Bifidobacterium, Lactobacillus, and Enterococcus faecalis are probiotics that have beneficial effects in the maintenance treatment of human intestinal diseases.

What this study adds?

There was no correlation between the antioxidant enzyme and IL-10. Nevertheless, exercise and Lactobacillus bifidus were able to regulate the lipid profile, SOD, and IL-10 after a high-fat diet.

Organ Cross-Talk Tips:

- Crosstalk between interleukin-10 (IL-10) and superoxide dismutase (SOD) following exercise and probiotic supplementation is an emerging area of research.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This study was conducted under the supervision of the Animal Ethics Committee of the Islamic Azad University, Science and Research Branch, Tehran, Iran, with ethical code IR.IAU.SRB.REC.1402.187.

Informed consent Not applicable

Author contributions

Conceptualization: S.R.R, M.GH, H.A, F.GH.; Methodology: S.R.R,

M.GH, Software: H.A, F.GH.; Validation: M.GH.; Formal analysis: H.A, F.GH.; Investigation: M.GH.; Resources: S.R.R.; Data curation: S.R.R, M.GH, H.A, F.GH.; Writing - original draft: S.R.R.; Writing - review & editing: S.R.R, M.GH, H.A, F.GH.; Visualization: S.R.R, M.GH, H.A, F.GH.; Supervision: M.GH.; Project administration: M.GH.; Funding acquisition: M.GH.

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