Obesity as the 21st Century's Major Disease: The Role of Probiotics and Prebiotics in Prevention and Treatment

Kanwal Tahir[1,*], Zhaojie Chen[2,3], Fan Zhang[3], Areeba Zaheer[4], Hrishik Iqbal[5], Francesco Ernesto Alessi Longa, Ume Habiba[7], Nida Hafeez[8] and Namra Tahir[9]

[1]Department of Chemistry, Government College Women University, Faisalabad, Pakistan
[2]Department of Food Science and Nutrition, the Hong Kong Polytechnic University, Hong Kong SAR, China
[3]STS Sugar Company Limited, Hong Kong SAR, China
[4]Department of Biochemistry, University of Agriculture Faisalabad, Pakistan
[5]Renata PLC, Bangladesh
[6]Department of International Law, Azteca University- Mexico, Italy
[7]Department of Physics, Government College Women University, Sialkot, Pakistan
[8]Instituto Politécnico Nacional (IPN), Centro de Investigación en Computación (CIC), Mexico City, Mexico
[9]Department of Home Economics, Food and Nutrition, University of Agriculture Faisalabad, Subcampus Toba Tek Singh, Pakistan
*Corresponding author: kanwalk.t21@gmail.com

Abstract

Obesity, a common disorder resulting from the combination of the environment and genetics, is influenced by physiological, cultural, social, behavioral, metabolic, and genetic factors. According to a World Health Organization (WHO) consultation, obesity is a chronic condition that is becoming so common in both industrialized and developing nations that it is overtaking more conventional public health issues like infectious diseases and undernutrition as the primary cause of illness. Obesity and socioeconomic level (SES) are significantly and negatively correlated, especially for women. Because they consume less calories than their contemporaries, older people with more issues may buy fewer foods and weigh less, but they may also purchase less costly, high-energy-density meals, which can result in obesity. Obesogenic variables, such as those changes in CNS-endocrine signaling, interact intricately in the pathophysiology of obesity. Therefore, the interaction of neuro-hormonal activation with obesogenic factors produces further heterogeneity in obesity-related characteristics. Insulin, type 2 diabetes, obesity, and resistance syndrome are among the conditions for which probiotic bacteria are believed to hold tremendous therapeutic promise.

Keywords: Prebiotics, Obesity, Human health, Probiotics, Overweight, Gut microbiota

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Introduction

Physiological, cultural, social, behavioral, metabolic, and genetic factors all take part in the expansion of obesity, a frequent condition that comes from the interaction of the genotype and environment (Górczyńska-Kosiorz et al., 2024).Various studies have shown the adverse impacts of obesity on population health, which is why general practitioners are advised to play a serious role in managing obesity and its related comorbidities, including hyperlipidemia, hypertension, and hyperinsulinemia/insulin resistance (Magwire et al., 2024).It is well-known that hypertension and obesity are related in both adults and childern (Wuehl, 2019). Obesity remains a significant public health issue. In 2000, 30.5% of adults aged 20 and over were obese (classified as having a BMI of 30 kg/m2), and 15 years later, that number rose to 39.8%. Approximately 93 million adult Americans suffer from obesity at the moment.In young people (ages 2 to 19), the issue is equally concerning because the frequency rose from 13.9% in 2000 to 18.5% in 2016. From 3.9% in 2000 to 6.6% in 2010, the prevalence of extreme obesity (BMI > 40) among adults rose at an even more concerning rate. Ten years ago, around 15.5 million adults in the United States were considered severely obese (Kelly et al., 2024). Additionally, the frequency of BMI > 50 cases rose even more significantly. According to some recent estimates, the future appears dire. According to estimates, 50% of adults will be obese by 2050. The most prevalent BMI category among Black, non-Hispanic, female, and low-income persons will be BMI > 35. Particularly, the global obesity epidemic is becoming more noticeable in rural regions (Zare et al., 2023).

Due to the increased risk of hypertension, myocardial coronary artery disease, stroke, type 2 diabetes, gall bladder disease, several types of cancer, arthritic conditions insomnia, and other conditions, being overweight or obese is a significant public health concern. According to a World Health Organization (WHO) consultation, obesity is a chronic illness that is becoming so common in both developed and developing nations that it is displacing more conventional public health issues like infectious diseases and undernutrition as a major cause of illness (Mohajan & Mohajan, 2023).The importance of this discovery has been highlighted in the US in Healthy People 2010, a comprehensive national agenda for disease prevention and health promotion created under the direction of the US Department of Health and Human Services. Indeed, tracking the percentage of obese or overweight children and adolescents as well as obese adults has been named one of the top ten health indicators linked to Healthy People 2010 (Drozdz et al., 2021). Obesity and SES, as measured by conventional measures of social class or education, are significantly and negatively correlated, especially for women. However, it has been acknowledged that traditional SES is insufficient to understand the connection between a person's economic position and their body mass index (BMI) or waist circumference (WC), and that differences in obesity among adults in the UK by income or education are not always apparent (Kowalkowska & Poínhos, 2021).

The disadvantage of traditional socioeconomic position indicators is that they don't adequately captivate people's material conditions and purchasing power; on the other hand, everyday financial hardships might be a more powerful indicator of obesity than things like education, wealth, or employment status (Gard et al., 2024). More general studies of poverty have highlighted the significance of economic suffering measures to ideas of inequality. Proof from two distinct groups supports the idea that financial hardship is a unique set of economic variables that have an independent impact on health beyond the evident influence of traditional SES. Another study found that smoking was associated with financial issues even among high-income groups. Women may be more likely than men to have trouble paying their bills, according to a longitudinal research of US teenagers that looked at a variety of financial hardships to date (DeAngelis, 2024). Greater problems may cause older folks to buy less food and weigh less because they consume fewer calories than their peers, but they may also buy less expensive, high-energy-density foods, which may lead to obesity. Therefore, we investigated the sex-specific associations between objectively measured obesity in individuals aged 50 and over and three types of self-reported financial issues. We postulated that, both generally and centrally, higher degrees of financial stress might be linked to higher odds of obesity, with sex-specific variations in the strength of these connections (Helman et al., 2023). After controlling for traditional SES, we also predicted that relationships would still be substantial.

Mechanism of Obesity

Obesogenic variables, such as those changes in CNS-endocrine signals, interact intricately in the pathophysiology of obesity (Figure 1). Information on the metabolic requirements of the stomach, muscles, bones, liver, and adipose tissue is detected by the central nervous system. Insulin, cholecystokinin, leptin and *glucagon-like peptide-1 (GLP-1)*, are among the hormones secreted to reduce food intake under satiety conditions. The main factors influencing the secretion of insulin and leptin are glucose and the quantity of adipose tissue, respectively (Picó et al., 2022). On the other hand,the ghrelin,the powerful orexigen stimulates food consumption. Leptin and glucose are chemicals that signal the supply of energy and impact diverse groups of neurons, such as *pro-opiomelanocortin/cocaine*,*amphetamine regulated transcript (POMC/CART)*and *agouti-related peptide/neuropeptide Y (AGRP/NPY)* .The basomedial hypothalamus is able to identify deficiencies in the delivery of nutrients. However, the sympathetic nervous system (SNS) is also paticipating in recovering energy balance, and obesity results from its imbalanced activity (Han & Weiss, 2021). For example, strave oneself reduces SNS activity while meal consumption, especially carbohydrate overfeeding, increases it. Insulin and leptin most likely mediate these changes in SNS activity. Therefore, further heterogeneity in obesity-related character traits is produced by the interaction of neurohormonal activation with obesogenic factors (Camacho-Barcia et al., 2023). The volume of the liver, skeletal muscle, and other bodily tissues and organs is increased by the positive energy balance (Mengeste et al., 2021). In this regard, a stable-weight obese person has more fat and lean mass than a person with a normal BMI, which raises blood pressure, heart rate, and resting energy expenditure as well as the mass of the pancreatic β-cells. It has been proposed that storing triglycerides in adipocytes guards against lipotoxicity (Stadler et al., 2021). The de novo lipogenesis pathway converts surplus carbs into fatty acids, which can subsequently be added to triglycerides for energy storage. These lipids are present in adipose tissue as well as liposomes, which are tiny cytoplasmic organelles that are located close to the mitochondria in a variety of cell types. Obesity can lead to lower intensity of the cholesterol, healthy high-density lipoprotein (HDL) and increased production and discharge of very-low-density lipoprotein (VLDL) and low-density lipoprotein (LDL) cholesterol (Stadler et al., 2021). Adipose and muscular tissues are the main extrahepatic tissues where VLDL molecules can release triglycerides due to endothelial lipoprotein lipase. These tissues can then use the triglycerides for metabolic purposes. Furthermore, the elevated sympathetic state associated with obesity triggers lipolysis, which releases fatty acids as a result of the extra triglycerides stored in obesity. Excessive levels of plasma free fatty acid (FFA) restrict lipogenesis, which prevents serum triacylglycerol levels from being appropriately cleared. This leads to hypertriglyceridemia and may cause insulin-receptor dysfunction (Janssen, 2021).

Correlation Between Fat, Low-grade Inflammation and Dropped Insulin Action

In healthy people, insulin causes peripheral organs to absorb glucose, and the increase in postprandial plasma glucose concentration activates the hormone's release. In addition to facilitating the body's utilization of extracellular glucose, which raises respiration and glycolysis, insulin also promotes protein synthesis and the reserve of lipids and glucose by stimulating *lipogenesis* and *glycogenesis*. By preventing *gluconeogenesis* and *lipolysis*, insulin also lessens the breakdown and circulation of fats and carbs (Eslami et al., 2021). Defective insulin activity in the peripheral tissues results in insulin resistance, sometimes referred to as lowered insulin sensitivity. Lack of insulin sensitivity results in hypertension, fasting hyperglycemia, dyslipidemia, hepatic lipid synthesis, and fat deposition in adipose tissues. Impaired insulin sensitivity is therefore a significant element that triggers some of the metabolic syndromes hallmarks (Szukiewicz, 2023). Furthermore, the primary cause of type 2 diabetes is chronic impaired insulin sensitivity, which follow in a persistently elevated level of systemic glucose concentration. Immune system activation is also linked to the metabolic illnesses that make up the metabolic syndrome, such as hypertriglyceridemia, hyperglycemia, hypertension and dyslipidemia (Bovolini et al., 2021). Increased fat buildup, lipotoxicity, and excessive caloric consumption trigger the synthesis of cells and effector chemicals (cytokines), which are mainly engaged in innate immunity. In metabolic tissues, especially adipose tissues, this production not only results in the recovery and stimulation of many mature immune cells (e.g., macrophages, mast cells, and dendritic cells), but it also promotes a long-term low-grade inflammatory status and attracts and activates other cells, including adipocytes, which change the tissue milieu and intensify the causing swelling response (Michailidou et al., 2022). It has been demonstrated by Cai and associates that desensitization of insulin signaling pathways is facilitated by the activation of inflammatory effector molecules (Zhao et al., 2023).

However, the *IκB kinase complex* and *JNK* activation do not have the same effect on inflammation or reduce insulin signaling in all organs (Jayaraman et al., 2021). In both humans and animals, the production of *cytokines* such as *interleukin (IL)-1β* or *tumor necrosis factor α (TNF-α)* in visceral adipose tissues affects insulin sensitivity via altering the expression of genes encoding *IRS-1*, the *glucose transporter GLUT4*, and *PPAR-α*. Insulin impairment and inflammation are associated with obesity (Rohm et al., 2022). Several molecular processes are involved in the connection between poor insulin function and the activation of inflammatory pathways: *Tyrosine phosphorylation* of the insulin receptor substrate (IRS) proteins is decreased in obese individuals due to the activation of inflammatory tissues' extracellular signal-regulated *protein kinases 1* and *2 (ERK1/2)*, *IκB kinase complex*, and *c-Jun N-terminal kinases (JNKs)*. Inflammation hinders the action of insulin, which in turn give rise to the development of metabolic diseases (Zhao et al., 2023). Action and inflammation are closely associated. Persistent inflammation in obese individuals has been referred to hasten the onset of metabolic syndrome and obesity-related disorders such as type 2 diabetes, often referred to as non-alcoholic fatty liver, and hepatic steatosis disease.

Probiotics

Over time, the term "probiotic," which is derived from the Greek word "for life," has acquired several connotations. The phrase was created in 1965 by Lilley and Stillwell to describe substances secreted by one microorganism that encouraged the growth of another (Patil et al., 2023). Consequently, it had the exact opposite meaning of "antibiotic," and its etymology was flawless. Later, it was utilized to characterize tissue extracts that stimulated microbial growth, but this usage was short-lived. It wasn't until 1974 that Parker used it in this sense. According to his definition, "Organisms and substances which contribute to intestinal microbial balance". Although the phrase "substances" gave it a broad definition that would include antibiotics, this explanation connected the use of probiotics to the intestinal flora. Probiotics were defined as "A live microbial feed supplement which beneficially affects the host animal by improving its intestinal microbial balance (Settles, 2021).

Probiotics Mechanisms of Action

Latest -omics and improved next-generation sequencing tools hold up the idea that gut bacteria may have systemic effects and have a major impact on host metabolism in addition to local effects within the colon. We may therefore modify the gut microbial population to reduce the risk of obesity by knowing how probiotics impact host metabolism (da Silva et al., 2021). This will also have significant implications for therapeutic procedures in pediatric endocrinology, nutrition, and gastroenterology. Probiotic bacteria are essential for maintaining the equilibrium of the human gut microbiota. Numerous scientific investigations confirm their positive outcomes on the host's health. Type 2 diabetes, Obesity, and insulin resistance syndrome are among the conditions for which probiotic bacteria are believed to hold tremendous therapeutic promise (Abouelela & Helmy, 2024).

Probiotics are known to have a number of effects on the host, such as immunomodulation, which involves modifying the human immune system; immunomodulation, which involves increasing mucus production and enhancing barrier integrity; and antimicrobial activity, which involves epithelium and competitive adherence to the mucosa and antagonistic effects on various microorganisms. All of these activities influence the development of the microbiota and inhabit the host in a manner that preserves the proper ratio of bacteria to pathogens needed for optimal host function (Figure 2) (Wilde et al., 2024).

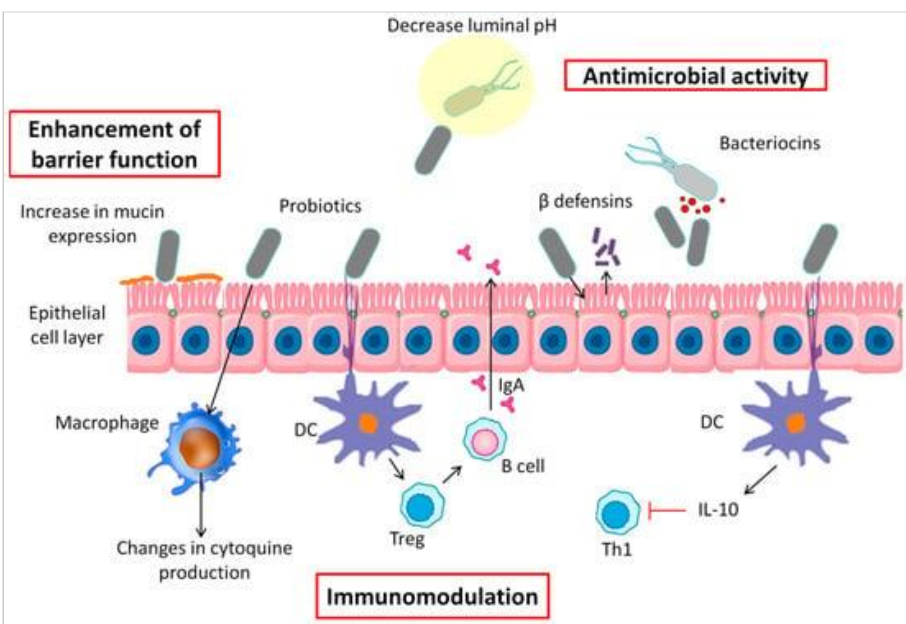

Fig. 2: Mechanism of Probiotics (Retrieved from Bio render)

Prebiotic

"Prebiotic" was the term that Gibson and Roberfroid came up with by using the word "pro" instead of "pre," which means "before" or "for" (Bisht et al., 2024). They described prebiotics as "a non-digestible food ingredient that selectively stimulates the growth and/or activity of one or a limited number of bacteria in the colon, thereby beneficially affecting the host." When prebiotics change the anatomy of the gut microbiota, some potentially beneficial bacteria, especially but not limited to *lactobacilli* and *biidobacteria*, become more common. Oligosaccharides with varying degrees of polymerization—from two to twenty monomers—such as galacto-oligosaccharides (GOSs), inulin, fructo-oligosaccharides (FOSs), and xylo-oligosaccharides (XOSs) are the most commonly used prebiotics (Sharma et al., 2024).

Prebiotics: Mechanism of Action

Modifying the gut microbiota community's extensive genetic potential, which is involved in multiple metabolic processes, may improve the host's health (Fan & Pedersen, 2021). This regulation can be achieved by using prebiotics, which are short-chain carbohydrates that are indigestible by both human and animal digestive enzymes and have a degree of polymerization ranging from two to around sixty. The ability to selectively utilize prebiotics sets them apart from other undigested food elements and compounds, including minerals, vitamins and antibiotics as they are not the only chemicals that have the ability to change the gut environment (Vlaicu et al., 2023). Consuming prebiotics, which are generally found in fruits and vegetables, may have several health benefits. The immune system is strengthened, calcium absorption is increased, the pH level in the intestines is maintained, blood levels of low-density lipoproteins are decreased, and these prebiotics are low in calories (Obayomi et al., 2024). Recent research indicates that the mechanisms through which prebiotics help the host (Figure 3) are mediated by microbial metabolic products, particularly SCFAs; immune system regulation, which boosts IgA production and alters cytokine production; and improved absorption of ions and trace elements, such as calcium, iron, and magnesium (Figure 3) (Alghamdi et al., 2022).

Role of Probiotics in Current Treatments

Human studies have demonstrated the benefits of probiotic ingestion by improving lipid profiles, namely by lowering levels of plasma TG and total cholesterol,LDL cholesterol, and raising insulin sensitivity HDL cholesterol (Bajinka et al.,2024). Additionally, *Bifidobacterium bifidumi*, *Lactobacillus rhamnosus*, and *Lactobacillus acidophilus* were given to DIO mice in order to alter their gut microbiota.The hypothalamic control of food intake, insulin, and leptin signaling, in conjunction with the flora's equilibrium, improved insulin sensitivity and, as a result, reduced obesity (Pizarroso et al., 2021). The majority of research supports the anti-obesity advantages of certain probiotic strains, including *Bifidobacterium* (primarily *B. longum*, *B. infantis*, and *B. breve B3*) and *Lactobacillus* (*Lactobacillus strain Shirota (LAB13)*, *L. rhamnosus*, *L. plantarum*, and *L. gasseri*, among others), when taken for four to six weeks. Additionally, probiotics like *L. rhamnosus CGMCC1.3724* have anti-obesogenic properties and help prevent issues connected to obesity (Hati et al., 2025). However, several other research found that using placebos produced the same result, or that using different strains had negative effects. Another description links probiotic effects to the lowering of pro-inflammatory genes and the modulation of *cytokines* (*IL-10, IL-17*, and *IL-22*), and obesity is considered a subclinical low-grade inflammation. Pro-inflammatory *cytokines* like *IL-6*, tumor necrosis factor-a, IL-1b, and IL-17 were suppressed in certain in vitro and in vivo investigations of *Lactobacillus acidophilus*, while *IL-10* and regulatory T cells were also found to be elevated (Kaur & Ali, 2022). In obese mice fed a high-fat, high-fructose diet (HFFD), a recent study demonstrated that *L. rhamnosus LS-8* and *L. crustorum MN047* reduce inflammation by restoring normal mRNA expression levels (Ho et al., 2024). Additionally, lipid metabolism is regulated by fibroblast growth factor 21 (FGF21), and probiotics (*Lactobacillus rhamnosus GG*) have been demonstrated to reduce obesity and metabolic disorders in both humans and as well as in mice (López-Almada et al., 2024). In conclusion, *Lactobacillus* and *Bifidobacterium* species were found to have the most promising weight-loss outcomes (Czajeczny et al., 2021). However, probiotic use should be restricted in high-risk populations overall, as common side effects like diarrhea, headaches, and heartburn can cause permanent issues or even death.

Prebiotics for the Treatment of Obesity

The number of people with diabetes is rising worldwide, placing a significant social and financial strain on public health. Leg ulcers, retinopathy, neuropathy, and gangrene are all consequences of type 2 diabetes, a chronic metabolic syndrome characterized by faulty glucose and lipid metabolism (Baynes, 2022). Age, smoking, obesity, heredity, hypertension, and a sedentary lifestyle are all factors that may influence the development of type 2 diabetes. Recent research has suggested that the pathophysiology of type 2 diabetes may result from the remolding of the GM composition caused by fat.

As previously stated, *Firmicutes* and *Bacteroidetes* are the two main bacterial groups found in the human GIT (Duan et al., 2021). Human obesity and GM composition have been linked in studies, with a decrease in the diversity of *Bacteroidetes* and an increase in *Firmicutes*. Because of their capacity to alter GM composition, which impacts GIT health and has anti-diabetic effects, prebiotics have become increasingly important in the treatment of obesity and diabetes (Megur et al., 2022). Because prebiotics come in a variety of forms, taking supplements may be a dietary therapy for the prevention and treatment of type 2 diabetes. It may also help combat obesity by influencing appetite, food intake, and metabolic processes. Low-calorie content, diabetic safety, lack of carcinogenicity, and bifidus-stimulating properties are just a few of the many appealing qualities of FOS (Rawat et al., 2024). FOS is regarded as a functional food element that enhances health status because of these qualities. A growing number of research have shown that FOS has functional qualities, such as decreasing blood pressure, cholesterol, and glucose levels (Rahim et al., 2021). On the glycemic scale, inulin's effects as a prebiotic have been conflicting (Hughes et al., 2022). There were no discernible changes in body weight among the 54 middle-aged (35–65 years old) healthy persons (men and women) in a randomized, double-blind, placebo-controlled parallel group that received 10 g of inulin supplementation for eight weeks. Following four weeks of treatment, there was a drop in plasma insulin levels, which persisted until the eighth week. Additionally, there were decreased levels of plasma triglycerides. When compared to the placebo group, the inulin-supplemented group had lower total cholesterol (TC). The study concluded that inulin supplementation might affect how triglyceride-rich lipoprotein particles break down (Megur et al., 2022). Greater amounts of *Bifidobacterium* and *Faecalibacterium* were seen in human trials involving obese women receiving inulin; this effect was correlated with decreased fat mass and serum lipopolysaccharide. Recent research has shown that *Bifidobacterium longum* plays a significant role in the battle against obesity in both humans and preclinical obesity models (Park et al., 2023).

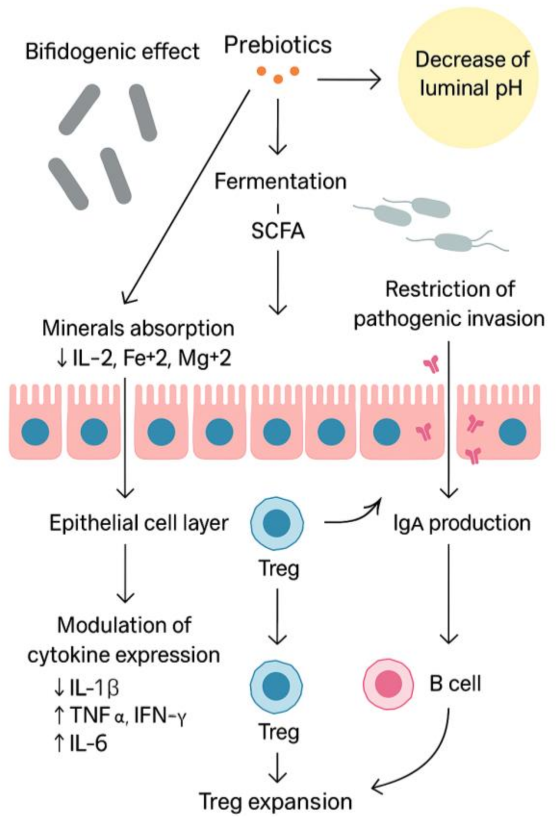

Fig. 3: Mechanism of Prebiotics (Retrieved from Bio render)

According to XOS research, they may lower blood levels of triglycerides and cholesterol, the primary risk factors for diabetes. After receiving XOS for 28 days, wild-type rats' body weight, triglycerides, serum TC, and LDL levels all decreased.

In individuals with metabolic syndrome, RS intake increases insulin sensitivity and seems to have a positive impact on insulin sensitivity (Ziolkowska et al., 2021). As a result, prebiotics are effective in regulating numerous processes linked to the onset and metabolic effects of obesity in addition to modifying, reorganizing, and maintaining the host microbiome. Additionally, prebiotics ought to be added to well-known foods to boost the likelihood of regular ingestion and enhance general health. At the very least, dietary prebiotic supplementation is a low-cost, safe, and well-tolerated therapeutic strategy that may be used to treat and prevent obesity and type 2 diabetes (Barthow, 2022).

Conclusion

Obesity is still a serious public health concern. In rural areas in particular, the global obesity epidemic is becoming more apparent. Due to the elevated risk of several cancers, rheumatic disorders, type 2 diabetes, gall bladder disease, myocardial coronary artery disease, stroke, and hypertension. Being overweight or obese is a serious public health concern, along with sleeplessness and other disorders. Prebiotics are essential for altering the gut microbiota, which can affect the onset of obesity and its metabolic effects. They are safe, economical, and efficient in controlling and preventing obesity and type 2 diabetes. *Bifidobacterium longum* is important in the fight against obesity, according to recent studies. Type 2 diabetes is largely caused by chronic insulin resistance, which is also linked to metabolic disorders including dyslipidemia and hypertension, both of which are linked to immunological activation. Probiotics have therapeutic potential for metabolic disorders and aid in preserving intestinal equilibrium. Unlike other food ingredients, prebiotics have a unique effect on the stomach, which makes them essential for controlling obesity and diabetes by affecting hunger, food consumption, and metabolism.

References

Abouelela, M. E., & Helmy, Y. A. (2024). Next-generation probiotics as novel therapeutics for improving human health: current trends and future perspectives. *Microorganisms*, *12*(3), 430.

Alghamdi, M., Gutierrez, J., & Komarnytsky, S. (2022). Essential minerals and metabolic adaptation of immune cells. *Nutrients*, *15*(1), 123.

Bajinka, O., Sylvain Dovi, K., Simbilyabo, L., Conteh, I., & Tan, Y. (2024). The predicted mechanisms and evidence of probiotics on type 2 diabetes mellitus (T2DM). *Archives of Physiology and Biochemistry*, *130*(4), 475-490.

Barthow, C. A. (2022). Diabetes prevention amongst those with pre-diabetes in Aotearoa New Zealand (Doctoral dissertation, University of Otago).Baynes, K. (2022). Diabetes Mellitus, Obesity, Lipoprotein Disorders and other Metabolic Diseases. In *Medicine for Finals and Beyond* (pp. 429-470). CRC Press.

Bisht, D., Pal, D., & Shrestha, R. (2024). Introduction to Probiotics, Prebiotics, and Synbiotics: A Holistic Approach. In *Probiotics* (pp. 1-28). CRC Press.

Bovolini, A., Garcia, J., Andrade, M. A., & Duarte, J. A. (2021). Metabolic syndrome pathophysiology and predisposing factors. *International Journal of Sports Medicine*, *42*(03), 199-214.

Camacho-Barcia, L., Lucas, I., Miranda-Olivos, R., Jiménez-Murcia, S., & Fernández-Aranda, F. (2023). Applying psycho-behavioural phenotyping in obesity characterization. *Reviews in Endocrine and Metabolic Disorders*, *24*(5), 871-883.

Cerdó, T., García-Santos, J. A., G. Bermúdez, M., & Campoy, C. (2019). The Role of Probiotics and Prebiotics in the Prevention and Treatment of Obesity. *Nutrients*, *11*(3), 635. https://doi.org/10.3390/nu11030635

Czajeczny, D., Kabzińska, K., & Wójciak, R. W. (2021). Does probiotic supplementation aid weight loss? A randomized, single-blind, placebo-controlled study with Bifidobacterium lactis BS01 and Lactobacillus acidophilus LA02 supplementation. *Eating and Weight Disorders-Studies on Anorexia, Bulimia and Obesity*, *26*, 1719-1727.

da Silva, T. F., Casarotti, S. N., de Oliveira, G. L. V., & Penna, A. L. B. (2021). The impact of probiotics, prebiotics, and synbiotics on the biochemical, clinical, and immunological markers, as well as on the gut microbiota of obese hosts. *Critical Reviews in Food Science and Nutrition*, *61*(2), 337-355.

DeAngelis, R. T. (2024). Racial Capitalism and Black–White Health Inequities in the United States: The Case of the 2008 Financial Crisis. *Journal of Health and Social Behavior*, 00221465241260103.

Drozdz, D., Alvarez-Pitti, J., Wójcik, M., Borghi, C., Gabbianelli, R., Mazur, A., & Wühl, E. (2021). Obesity and cardiometabolic risk factors: from childhood to adulthood. *Nutrients*, *13*(11), 4176.

Duan, M., Wang, Y., Zhang, Q., Zou, R., Guo, M., & Zheng, H. (2021). Characteristics of gut microbiota in people with obesity. *Plos One*, *16*(8), e0255446.

Eslami, M., Bahar, A., Hemati, M., Rasouli Nejad, Z., Mehranfar, F., Karami, S., & Yousefi, B. (2021). Dietary pattern, colonic microbiota and immunometabolism interaction: new frontiers for diabetes mellitus and related disorders. *Diabetic Medicine*, *38*(2), e14415.

Fan, Y., & Pedersen, O. (2021). Gut microbiota in human metabolic health and disease. *Nature Reviews Microbiology*, *19*(1), 55-71.

Gard, H., Enskär, K., Ingvarsdotter, K., Isma, G. E., & Mangrio, E. (2024). Exploring young people's experiences of race, gender and socioeconomic status in relation to everyday challenges: A focus group study. *Children & Society*, *38*(1), 228-244.

Górczyńska-Kosiorz, S., Kosiorz, M., & Dzięgielewska-Gęsiak, S. (2024). Exploring the Interplay of Genetics and Nutrition in the Rising Epidemic of Obesity and Metabolic Diseases. *Nutrients*, *16*(20), 3562.

Gutiérrez-Cuevas, J., Santos, A., & Armendariz-Borunda, J. (2021). Pathophysiological Molecular Mechanisms of Obesity: A Link between MAFLD and NASH with Cardiovascular Diseases. *International Journal of Molecular Sciences*, *22*(21), 11629. https://doi.org/10.3390/ijms222111629

Han, J. C., & Weiss, R. (2021). Obesity, metabolic syndrome and disorders of energy balance. In *Sperling pediatric endocrinology* (pp. 939-1003). Elsevier.

Hati, S., Gawai, K. M., Shendurse, A. M., & Ramanuj, K. (2025). Efficiency of Probiotics and Prebiotics in Regulating Overweight, Obesity, and Metabolism. In *Body Recomposition* (pp. 482-508). CRC Press.

Helman, T. J., Headrick, J. P., Stapelberg, N. J., & Braidy, N. (2023). The sex-dependent response to psychosocial stress and ischaemic heart disease. *Frontiers in Cardiovascular Medicine*, *10*, 1072042.

Ho, P. Y., Chou, Y. C., Koh, Y. C., Lin, W. S., Chen, W. J., Tseng, A. L., ... & Pan, M. H. (2024). Lactobacillus rhamnosus 069 and Lactobacillus brevis 031: Unraveling Strain-Specific Pathways for Modulating Lipid Metabolism and Attenuating High-Fat-Diet-Induced Obesity in Mice. *ACS Omega*.

Hughes, R. L., Alvarado, D. A., Swanson, K. S., & Holscher, H. D. (2022). The prebiotic potential of inulin-type fructans: a systematic review. *Advances in Nutrition*, *13*(2), 492-529.

Janssen, J. A. (2021). Hyperinsulinemia and its pivotal role in aging, obesity, type 2 diabetes, cardiovascular disease and cancer. *International Journal of Molecular Sciences*, *22*(15), 7797.

Jayaraman, S., Devarajan, N., Rajagopal, P., Babu, S., Ganesan, S. K., Veeraraghavan, V. P., & Chandrasekar, K. (2021). β-sitosterol circumvents obesity induced inflammation and insulin resistance by down-regulating IKKβ/NF-κB and JNK signaling pathway in adipocytes of type 2 diabetic rats. *Molecules*, *26*(7), 2101.

Kaur, H., & Ali, S. A. (2022). Probiotics and gut microbiota: Mechanistic insights into gut immune homeostasis through TLR pathway regulation. *Food & Function*, *13*(14), 7423-7447.

Kelly, A. S., Armstrong, S. C., Michalsky, M. P., & Fox, C. K. (2024). Obesity in adolescents: a review. *Journal of the American Medical Association*, *332*(9), 738-748.

Kowalkowska, J., & Poínhos, R. (2021). Eating behaviour among university students: Relationships with age, socioeconomic status, physical activity, Body Mass Index, waist-to-height ratio and social desirability. *Nutrients*, *13*(10), 3622.

López-Almada, G., Mejía-León, M. E., & Salazar-López, N. J. (2024). Probiotic, Postbiotic, and Paraprobiotic Effects of Lactobacillus rhamnosus as a Modulator of Obesity-Associated Factors. *Foods*, *13*(22), 3529.

Magwire, M., Lamanna, J., Haydon-Greatting, S., Brown-Riggs, C., & Duker, P. (2024). Addressing Obesity in Diabetes. *ADCES in Practice*, *12*(6), 24-38.

Megur, A., Daliri, E. B. M., Baltriukienė, D., & Burokas, A. (2022). Prebiotics as a tool for the prevention and treatment of obesity and diabetes: classification and ability to modulate the gut microbiota. *International Journal of Molecular Sciences*, *23*(11), 6097.

Mengeste, A. M., Rustan, A. C., & Lund, J. (2021). Skeletal muscle energy metabolism in obesity. *Obesity*, *29*(10), 1582-1595.

Michailidou, Z., Gomez-Salazar, M., & Alexaki, V. I. (2022). Innate immune cells in the adipose tissue in health and metabolic disease. *Journal of Innate Immunity*, *14*(1), 4-30.

Mohajan, D., & Mohajan, H. K. (2023). Obesity and its related diseases: a new escalating alarming in global health. *Journal of Innovations in Medical Research*, *2*(3), 12-23.

Obayomi, O. V., Olaniran, A. F., & Owa, S. O. (2024). Unveiling the role of functional foods with emphasis on prebiotics and probiotics in human health: A review. *Journal of Functional Foods*, *119*, 106337.

Park, S. J., Sharma, A., & Lee, H. J. (2023). Postbiotics against obesity: perception and overview based on pre-clinical and clinical studies. *International Journal of Molecular Sciences*, *24*(7), 6414.

Patil, A. V., Shetty, S. S., & Padhye, A. M. (2023). Comparative evaluation of the inhibitory effect of Lactobacillus rhamnosus on halitosis-causing bacteria: an invitro microbiological study. *Cureus*, *15*(5).

Picó, C., Palou, M., Pomar, C. A., Rodríguez, A. M., & Palou, A. (2022). Leptin as a key regulator of the adipose organ. *Reviews in Endocrine and Metabolic Disorders*, *23*(1), 13-30.

Pizarroso, N. A., Fuciños, P., Gonçalves, C., Pastrana, L., & Amado, I. R. (2021). A review on the role of food-derived bioactive molecules and the microbiota–gut–brain axis in satiety regulation. *Nutrients*, *13*(2), 632.

Rahim, M. A., Saeed, F., Khalid, W., Hussain, M., & Anjum, F. M. (2021). Functional and nutraceutical properties of fructo-oligosaccharides derivatives: a review. *International Journal of Food Properties*, *24*(1), 1588-1602.

Rawat, H. K., Nath, S., Sharma, I., & Kango, N. (2024). Recent developments in the production of prebiotic fructooligosaccharides using fungal fructosyltransferases. *Mycology*, 1-21.

Rohm, T. V., Meier, D. T., Olefsky, J. M., & Donath, M. Y. (2022). Inflammation in obesity, diabetes, and related disorders. *Immunity*, *55*(1), 31-

55.
Settles, A. L. (2021). *Evaluating Escherichia Coli Nissle as a Potential Probiotic for Broiler Chickens* (Master's thesis, Tennessee State University).
Sharma, D., Dhiman, A., Thakur, A., Kumar, S., & Saini, R. (2024). Functional oligosaccharides as a promising food ingredient: a gleam into health apprehensions and techno-functional advantages. *Journal of Food Measurement and Characterization*, 1-32.
Stadler, J. T., Lackner, S., Mörkl, S., Trakaki, A., Scharnagl, H., Borenich, A., & Marsche, G. (2021). Obesity affects HDL metabolism, composition and subclass distribution. *Biomedicines*, *9*(3), 242.
Szukiewicz, D. (2023). Molecular mechanisms for the vicious cycle between insulin resistance and the inflammatory response in obesity. *International Journal of Molecular Sciences*, *24*(12), 9818.
Vlaicu, P. A., Untea, A. E., Varzaru, I., Saracila, M., & Oancea, A. G. (2023). Designing nutrition for health—Incorporating dietary by-products into poultry feeds to create functional foods with insights into health benefits, risks, bioactive compounds, food component functionality and safety regulations. *Foods*, *12*(21), 4001.
Wilde, J., Slack, E., & Foster, K. R. (2024). Host control of the microbiome: mechanisms, evolution, and disease. *Science*, *385*(6706), eadi3338.
Wuehl, E. (2019). Hypertension in childhood obesity. *Acta Paediatrica*, *108*(1), 37-43.
Zare, H., Aazami, A., Shalby, N., Gilmore, D. R., & Thorpe Jr, R. J. (2023). Measuring Racial Differences in Obesity Risk Factors in Non-Hispanic Black and White Men Aged 20 Years or Older. *American Journal of Men's Health*, *17*(6), 15579883231205845.
Zhao, X., An, X., Yang, C., Sun, W., Ji, H., & Lian, F. (2023). The crucial role and mechanism of insulin resistance in metabolic disease. *Frontiers in Endocrinology*, *14*, 1149239.
Ziolkowska, S., Binienda, A., Jabłkowski, M., Szemraj, J., & Czarny, P. (2021). The interplay between insulin resistance, inflammation, oxidative stress, base excision repair and metabolic syndrome in nonalcoholic fatty liver disease. *International Journal of Molecular Sciences*, *22*(20), 11128.