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Review Article

Whole Grain Intake, Anthropometric Measures, Cardiometabolic Markers and Gut Microbiota in Children: A Narrative Review

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ABSTRACT

Whole grain consumption plays a crucial role in promoting public health, with particular importance for the growth and long-term health of children. This narrative review aimed to summarize and highlight the anthropometric, cardiometabolic, and gut microbiota-related health benefits of whole grain intake in children and adolescents published in English language from reputable databases, specifically PubMed, Scopus, Web of Science, and Google Scholar due to their comprehensive and diverse collection of relevant literature for analysis. Even though there are large knowledge gaps in this topic concerning children, current observational and interventional studies acknowledge health benefits in children and adolescents. Moreover, it appears that the health advantages of whole grain intake in children are more significant in cardiometabolic and gut microbiota health indices than in anthropometric ones. Improved cardiometabolic outcomes, particularly about lipid metabolism, and more favorable gut microbiota diversity are the notable health benefits reported in the examined studies. In conclusion, this review underscored the need for greater awareness and encouragement to integrate whole grain into the diets of children and adolescents to reap the associated health-protective effects. Yet, we suggest further research for better clarity and stronger evidence due to the scarcity and vagueness of the existing studies.

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Introduction

Whole grain is an inseparable component of a healthy diet (1, 2). Whole grain have been described as "the intact ground, cracked, or flaked kernel after the removal of inedible parts such as hull and husk, where the principal anatomical components (the starchy endosperm, germ, and bran) are present in the same relative proportions as they exist in the intact kernel and allow for minute losses during preparation" (1). There is evidence that high whole grain consumption reduces the risk of non-communicable diseases in adults such as cardiovascular disease, type 2 diabetes, and colon cancer (3, 4). On the other hand, studies in this matter regarding children are limited and unclear (5, 6). Moreover, whole grain deliver essential nutritional elements, dietary fiber, and phytochemicals which are removed during the refining process (7, 8). Dietary guidelines worldwide encourage increased whole grain consumption, highlighting the need to recognize the importance of these nutrient-rich foods in achieving healthier eating habits and enhancing general health outcomes (9, 10). However, whole grain consumption remains low and inadequate across the globe (11).

Obesity among children is a global health issue (12, 13). Obese or overweight children are more likely to encounter cardiometabolic disorders, such as type 2 diabetes, hypertension, and dyslipidemia as the conditions previously thought to only affect adults (14, 15). Several studies claim that whole grain consumption can reduce the risk of cardiometabolic diseases via applying changes in gut microbiota (16-18). According to studies, whole grain are beneficial for increasing microbial diversity and enhancing bacterial abundance (19, 20). Research has shown that a diverse gut microbiota is linked to better health outcomes, while dysbiosis (an imbalance in gut bacteria) can lead to a variety of health problems such as obesity, diabetes, and inflammatory conditions (21-23)14. In addition, several other potential mechanisms, such as enhanced satiety, reduced glycemic and insulinemic responses decreased the rates of macronutrient absorption, delayed the gastric emptying, and improved the short-chain fatty acids (SCFAs) production that can explain the health benefits of whole grain due to their nutritional profile, particularly their high fiber content (5, 24, 25).

The study of the connection between whole grain intake, cardiometabolic diseases, and gut microbiome, particularly in children, is a growing area of interest that has been increasingly attracting attention. To the best of our knowledge, there has not been any comprehensive review to study this correlation in children and adolescents. Therefore, it is necessary to conduct an extensive overview of the studies that were undertaken in this field. In this review, we selected and condensed the evidence from distinguished research that examined dietary whole grain and their impact on health in children and adolescents, emphasizing anthropometric, cardiometabolic, and gut microbiota health indices.

Materials and Methods

The reviewed studies in this article were included by all-encompassing searches in PubMed, Scopus, Web of Science and Google Scholar in order to find qualified articles published from 1990 to December 2025. A search strategy was developed using the keywords of "whole grain" OR "wholegrain" OR "whole-grain" AND "children" OR "adolescent" OR "infant" OR "childhood" AND "anthropometric" OR "cardiometabolic" OR "metabolic profile" OR "gut microbiota" OR "gut microbiome". Only articles published in English were included. Studies of various designs, including randomized controlled trials (RCTs), cohort studies and cross-sectional studies, were eligible for inclusion if they reported on whole grain consumption and its association with anthropometric measures, cardio-metabolic outcomes, or gut microbiota in children and adolescents. The references of retrieved research were manually searched to identify more articles related to the topic.

Results

Whole Grain Intake and Anthropometric Measurements

The World Health Organization (WHO) reports indicated that overweight and obesity have increased substantially so that among young people aged 5-19 years, overweight (along with obesity) has increased from 8% in 1990 to 20% in 2022. Meanwhile, obesity alone has quadrupled in this population (2% vs. 8% in 1990 and 2022, respectively) (26). As pediatric overweight or obesity is associated with chronic diseases such as dyslipidemia, hypertension, cardiovascular diseases, diabetes, and metabolic syndrome, as well as conditions like apnea and gallbladder disorders, it seems necessary to find suitable solutions to control pediatric weight gain without imposing energy restrictions that would prevent them from obtaining the nutrients essential for their growth (27-29). The link between whole grain intake and weight indices in adult studies showed varying results; a 2020 systematic review on RCT showed that whole grain intake did not decline the body weight but may be slightly effective on body fat and another systematic review in 2021 concluded that whole grain consumption and body weight status had a probable relationship (30, 31). Table 1 indicates the health benefits of whole grain consumption and body weight measurements.

Whole Grain, Body Mass Index (BMI) and Body Fat

All five observational studies in our review contained data from both genders but in different age ranges. Three of these studies collected data from one or two days of food recall of the National Health and Nutrition Examination Survey (NHANES), and the two others were a 7-day-food record of Danish children and a 24-hour food record of rural American children (5, 32-35).

The association between BMI z-score and whole grain consumption was evaluated in all studies, but the results varied, such that in the most extensive population study by Fulgoni *et al*., there was no correlation between the consumption of whole grain and overweight or obesity; however, fiber consumption was inversely related to the prevalence of overweight and obesity (33). Choumenkovitch *et al*., Zanovec *et al*., and Hur *et al*. found an inverse association between BMI z-score and whole grain intake in the general population, only among adolescents, and only in male populations, respectively. Finally, one study by Damsgaard *et al.* found no association (5, 32-35).

Table 1: Whole grain consumption and anthropometric indices.

Reference	Study design	Population studied	Objective	Indices tested	Results
(28)	Crossover RCT, 6 weeks (in every arm) with a 4-week washout period, Whole-grain foods make up half of all grain servings n=44 (either intervention or control)	Overweight or obese girls (age: 8-15 years)	To examine how whole grain affect children who are obese or overweight in terms of body measurements	Height, weight, BMI, waist and hip circumference, Overweight (BMI≥85th to <97th WHO percentiles for both genders and ages), obesity (BMI ≥97th WHO percentiles For both sexes and ages), abdominal obesity (waist circumference ≥75th specific national percentiles for age and sex)	Significant decrease in waist circumference (p=0·04), slight but not significant decrease in weight and BMI, insignificant hip circumference changes, insignificant difference in the obesity rates, overweight rates, and abdominal obesity rates
(36)	Quasi-experimental intervention, 12 weeks intervention with a 6-month follow-up period, generally, 3 hours nutritional education, daily whole-grain food provision and family diet counseling n=63 (n=31 intervention, n=32 control)	Overweight or obese children (age: 9-11 years)	To determine the effect of whole grain consumption on anthropometric measurements in childhood obesity	Height, weight, BMI for age z-score (using WHO charts, +1SD < BMI≤+2SD as overweight and BMI>+2SD as obesity), body fat % and waist circumference	Between groups changes showed significantly lower BF% (p<0.001), waist circumference (p=0.001) and BMI for age z-score (p=0.009) in intervention group
(5)	Cross-sectional n=713 (n=345 girls, n=368 boys)	Danish children (age: 8-11 years)	To examine the association between consumption of total dietary whole grain, fiber and whole grain of particular types and body fat mass and cardiometabolic markers	Weight, BMI for age and sex z-score (using WHO charts), underweight, overweight and obesity prevalence, body composition (by DXA), fat mass index (total body fat mass per the square of height), waist circumference	Neither dietary fiber nor whole grain have any significant relationship with BMI z-scores or waist circumference or fat mass, Fat mass index and whole grain oat intake are significantly inversely related

(32)	Cross-sectional n=792	Rural American children (age: 3th -6th school grade)	The investigation of the correlation between whole grain consumption and BMI in rural children	Weight, BMI z-score	Consumption of whole grain and BMI z-score are significantly inversely related (*p*=0.01), more whole grain intake insignificantly associated with lower obesity prevalence and significantly correlated with a lower risk of obesity. (OR=0.06, *p*=0.02)
(35)	Cross-sectional (NHANES 1999-2004) n=3868 children, n= 4931 adolescents	Children (age: 6-12 years) and adolescents (age: 13-18 years)	The investigation of the association children's and adolescents' consumption of whole grain and dietary fiber and their weight	BMI, BMI for age percentiles, BMI z-score, overweight and obesity prevalence, waist circumference	For adolescents all body weight variables decreased significantly in the group with the highest intake of whole grain compared to the lowest intake but a significant decrease trend was observed only for BMI z-score, no association observed in children
(33)	Cross-sectional (NHANES 2003-2014) n=16506	Children and adolescents (age: 2-18 years)	To determine the link between whole grain and fiber intake and CVD including metabolic syndrome risk factors in 2 to 18-year-old children	Weight, BMI, BMI z-score	More fiber intake contributes to reduced overweight and obesity by 2% (OR=0.98, Plinear trend=0.0485) and 3-5% (OR=0.97, P linear trend=0.0036) respectively, no association observed between whole grain intake and overweight or obesity
(34)	Cross-sectional (NHANES 1999-2004) n=4928 (n=2495 boys, n=2433 girls)	Adolescents (age:12-19 years)	The investigation of the connection between whole grain consumption, weight measurements and risk factors of chronic disease in 12 to 19-year old adolescents by gender	Weight, BMI, BMI z-score (using CDC charts), waist circumference, arm circumference, tight circumference, subscapular skinfold thickness	Among girls, whole grain consumption was not associated with anthropometric measurements, whole grain intake was associated with all anthropometric measurements in a significant inverse manner among boys (but after adjusting for food groups, an inverse association observed for arm circumference only (*p*=0.023))

RCT: Randomized clinical trial, WHO: World Health Organization, BMI: Body mass index, BF%: Body fat percentage, CDC: Centers for Disease Control and Prevention, DXA: Dual Energy X-ray Absorptiometry, NHANES: National Health and Nutrition Examination Survey, SD: Standard deviation, CVD: Cardiovascular disease.

In one of the studies, children's body composition was analyzed by Dual-energy X-ray Absorptiometry (DXA); then, body fat mass was divided by the square of the height to calculate the body fat mass index. After that, the relationship between this index and the intake of whole grain and fiber as well as special whole grain such as oats, wheat, and rye was measured. The results indicated that fiber and whole grain intake were not significantly correlated, but oat whole grain intake was significantly inversely correlated (5). The study conducted by Hajihashemi *et al.* was a cross-over design study featuring a 6-week intervention for each phase, separated by a 4-week washout period, and included only female participants. In this study, after calculating the energy required for each participant and dividing their intake into 53% carbohydrates, 17% protein, and 30% fat, the subjects were instructed to consume half of their cereal servings from whole grain (which were mainly whole wheat). This study showed a slight but not significant decrease in weight and BMI (28).

In another interventional study by Koo *et al.*, along with supplying schools with whole grain for children, they offered students nutrition education and encouraged their parents to incorporate more whole grain at home. This study had longer intervention duration. In this study which was a quasi-experimental study on both genders of children, between groups changes showed significantly lower body fat percentage and BMI-for-age z-score in the intervention group. Also, within-group changes in this study indicated that twelve weeks of whole grain intake significantly reduced the body fat percentage compared to the baseline measurements; and this decline in BMI was not significant. Then, after the six-month follow-up period, measurements showed an insignificant increase in both variables compared to post-intervention measurements. However, the results after nine months (three months of intervention and six months of follow-up) still showed a decrease in body fat percentage and BMI (36). Both interventional studies demonstrated the potential effect of dietary whole grain interventions on managing childhood overweight and obesity. However, the result of the quasi-experimental intervention study showed stronger effects, which could be due to the longer duration of the intervention, the positive effect of nutrition education, or the follow-up period (28, 36).

Whole Grain, Waist Circumference and Other Measures

Based on Hajihashemi *et al.*'s study, it can be concluded that whole grain consumption can significantly reduce waist circumference, though other anthropometric indicators, such as the prevalence of obesity, overweight and abdominal obesity, as well as hip circumference, did not change significantly (28). Furthermore, Koo *et al.*'s study showed significant declines in waist circumference between the intervention and control groups (36). In three observational studies, the relationship between the consumption of whole grain and waist circumference was evaluated; in one of them, no relationship was observed. In another study, this relationship was observed in a significant and inverse manner in the male population, and in the other study, no relationship was observed, but for the group with the highest intake compared to the group with the lowest intake, the waist circumference was significantly lower (5, 34, 35).

In Hur *et al.*'s study, in addition to waist circumference, the relationship between arm circumference and thigh circumference was also investigated with the consumption of whole grain; and the result showed that among the boys, all three indicators had an inverse association with whole-grain intake. This result was after adjusting for a variety of confounders such as ethnicity, household income, physical activity, etc. However, after further adjusting the results based on food groups, a significant inverse association was seen only for the arm circumference, which indicated that arm circumference was well related to the intake of whole grain (34). Regarding the possible mechanisms of the effect of whole grain intake on body anthropometric indices, several points can be mentioned. The lower glycemic index of whole grain, which promotes greater satiety, reduced insulin secretion, and reduced plasma glucose, is among the possible mechanisms. Additionally, whole grain' lower energy content and more dietary fiber may be effective (37-39). Dietary fiber likely impacts body weight status through three pathways of hormonal (such as lower insulin response), colonic (mainly caused by bacterial fermentation and SCFAs production), and intrinsic (by increasing satiety); all of these eventually lead to higher fat oxidation and reduced body fat storage (40). As to growing obesity rates among children and adolescents, considering whole grain and dietary fibers as part of a daily nutrition pattern is essential. A definitive conclusion in this field can only be reached after more studies are conducted on the positive effects of consuming whole grain on improving anthropometric factors.

Whole Grain Intake and Cardiometabolic Indices

Metabolic abnormality persists from childhood into adulthood (41). Children who are overweight face an increased risk of hypertension, dyslipidemia, cardiovascular diseases, metabolic syndrome, and other long-term health conditions (27). Elevated levels of blood sugar and lipids are associated with numerous negative results, such as cardiovascular incidents and type 2 diabetes (42-44). Whole grain contain a variety of beneficial components, including dietary fiber, antioxidants, minerals, vitamins, lignans, and phenolic compounds (45, 46). A lower risk of chronic illnesses such as obesity, diabetes, cancer, and coronary heart disease has been associated with these components (47, 48). Additionally, many whole grain are high in soluble fiber, which is associated with lower cholesterol level and reduced blood glucose (49). However, the link between whole grain consumption and cardiometabolic risk has not been extensively studied in children to date and the results of existing studies are limited and not definitive. The health benefits of whole grain intake on cardiometabolic indices were presented in Table 2.

Table 2: Whole grain consumption and cardiometabolic indices.

Source (Authors)	Study Design	Population studied	Objective	Indices tested	Results
(34)	Cross-sectional (NHANES 1999-2004)	n=4928 (n=2495 boys, n=2433 girls) adolescents (age:12-19 years)	The investigation of the association between whole grain consumption, weight measurements, and chronic disease risk factors among adolescents.	Plasma glucose, fasting insulin, CRP, C-peptide, serum TC, LDL-C, HDL-C and TG, Folate levels in serum and red blood cells , and homocysteine levels and SBP.	Among boys, whole grain intake was negatively correlated with fasting insulin levels (p=0.002), A negative relationship was found between C-peptide level in girls and their intake of whole grain (p=0.019), Girls' HDL-C concentrations and whole grain intake were positively correlated (p=0.032), homocysteine concentrations in boys decreased with their whole grain consumption (p=0.002), Folate level in serum and red blood cells in both genders demonstrated a positive correlation with the consumption of whole grain (all p<0.001). After food group intake adjustments, a significant negative correlation was identified between whole grain consumption and girls' fasting insulin levels (p=0.019), The fasting insulin level of boys with low whole grain intake was lower than those with no whole grain intake (p=0.004). C-peptide levels were lower in girls who consumed high levels of whole grain than those who ate little or no whole grain (p=0.016), Girls with low intake showed higher CRP level than those with no intake or high intake (p=0.046). Homocysteine concentration was lower in boys who consumed a high amount of whole grain compared to those who consumed a low amount or no whole grain (p=0.020).
(50)	Cross-sectional (NHANES 2005-2014)	n=2,286 adolescents (age: 12-18 years)	The determination of correlation of whole grain intake and IFG in children	FPG	Whole grain intake was lower (0.54 vs. 0.69 oz-eq/d) and refined grain intake was higher in people with IFG (6.93 vs. 6.32 oz-eq/d) (p<0.05 for both). There was a 19% reduction in risk of IFG per additive serving of whole grain (23% reduction with adjustment for confounders) when whole grain were included in the diet (OR=0.81; 95% CI: 0.69–0.96).

(33)	Cross-sectional (NHANES 2003-2014)	n=16506 children and adolescents (age: 2-18 years)	Evaluating the association between whole grain and fiber consumption and the risk of cardiometabolic diseases among children and adolescents	TC, HDL-C, LDL-C, TG, SBP, DBP, FPG, Fasting insulin, cMetS score	There was no association between whole grain or fiber intake and FPG, blood pressure, LDL-C, or insulin. As whole grain density increased, HDL-C increased significantly (1.02 mg/dL per tertile of intake) (p=0.0341). In contrast, As whole grain intake increased in the tertiles, TG was reduced (-11.3 mg/dL per tertile of intake) (p=0.0225) and density (-4.31 mg/dL per tertile of intake) (p=0.0007). Whole grain consumption was not significantly associated with elevated TC risk. Increased whole grain density decreased elevated TG risk by 52% (OR=0.48, p=0.0116). There was no association between whole grain intake or density and increased cMetS scores (>85th percentile), increased fasting insulin, increased FPG, increased SBP, increased LDL-C, and decreased HDL-C.
(5)	Cross-sectional	n=713 Danish children (age: 8-11 years)	Examination of the relationship among intake of total whole grain, fiber and whole grain specific types and body fat mass and cardiometabolic markers	SBP, DBP, HDL-C, LDL-C, TG, Insulin	A negative relationship was found between whole grain consumption and serum insulin level (p=0.002). Whole-grain oat intake was negatively correlated with SBP (p=0.01), LDL-C (p=0.03), and serum insulin (p=0.003). The ratio of C17 to C21 (an indication of proportion of whole grain rye and wheat consumed) was negatively correlated with serum insulin level (p<0.001). The intake of whole grain and markers of lipid metabolism were not correlated (such as LDL-C, HDL-C and TG) serum concentrations. .
(6)	RCT, 6 weeks (in every arm) crossover trial with a 4-week washout period, n=44 (either intervention or control) half of grain servings received from whole-grain foods	n=44 obese or overweight (The percentage of overweight and obese was 45% and 55%, respectively) girls (age:8-15 years)	To investigate the impact of whole grain intake on the metabolic patterns of obese or overweight children	FPG, serum TG, LDL-C, TC and HDL-C, DBP, SBP	The consumption of whole grain led to reduced levels of blood glucose (-0.10 mmol/L in intervention group versus 0.21 mmol/L in control group, p=0.01), blood TG (The change from baseline in the intervention group was -0.18 mmol/L versus 0.08 mmol/L in the control group, p=0.001) and increased level of HDL-C (The change from baseline in the intervention group was 0.16 versus -0.14 mmol/L in the control group, p=0.05). Whole grain intake had no effect on SBP or DBP or TC or LDL-C serum levels.

(16)	RCT, Intervention duration: Two 8-week crossover trials without a washout period, n=55 overweight Danish children Whole-grain group: Whole grain intake (g/d)=108±38 Wholegrain rye=58±21 Wholegrain oat=50±33 Control group: Total whole grain (g/d)=3±2 WG rye=0 WG oat=0	n=55 overweight Danish children (age:8-13y)	To study the impact of whole grain rye and oats consumption on LDL-C and serum insulin, along with other markers of cardiometabolic, composition of the body, structure and metabolites of the gut microbiota, and symptoms of gastrointestinal in overweight and obese children.	Plasma insulin, serum LDL-C, HDL-C, TC, TG, CRP and IL-6, SBP, DBP, plasma and fecal SCFA	Whole grain intake reduced serum LDL-C, TC, and TG (all $p \leq 0.048$). Whole grain intake was also accompanied with higher butyrate level in feces and plasma ($p \leq 0.001$) and propionate and acetate level in blood (($p=0.005$) and ($p=0.036$) respectively). However, whole grain consumption had no notable impact on blood pressure, plasma IL-6, plasma insulin, plasma glucose and serum CRP in comparison with group that consumed refined grain.

NHANES: National Health and Nutrition Examination Survey, CRP: C-reactive protein, TC: Total cholesterol, HDL-C: High-density lipoprotein cholesterol, LDL-C: Low-density lipoprotein cholesterol, TG: Triglycerides, SBP: Systolic blood pressure, DBP: Diastolic blood pressure, IFG: Impaired fasting glucose, FPG: Fasting plasma glucose, cMetS score: Continuous metabolic syndrome score, RCT: Randomized clinical trial, BMI: Body mass index, IL-6: Interleukin-6, SCFA: Short chain fatty acids.

Whole Grain Intake and Carbohydrate Metabolism

In three cross-sectional studies carried out in the United States using NHANES data collectively between 1999 and 2014, researchers determined whole grain intake and the association with cardiometabolic risk factors, including glycemic markers in adolescents and children (33, 34, 50). One study, which analyzed data from 1999 to 2004 and separated findings by sex, concluded that higher whole grain consumption in boys was linked to lower fasting insulin level. Furthermore, an inverse relationship was found between C-peptide level in girls and their intake of whole grain. Following additional adjustments for the consumption of different food groups and dividing whole grain intake into three categories (none, low, and high), a negative relationship emerged when it came to whole grain consumption and fasting insulin level in girls. In contrast, boys who consumed low amounts of whole grain had a lower level of fasting insulin than those who did not consume any whole grain (none subgroup) (34). The second study, which utilized NHANES data for adolescents aged 12-18 years from 2005 to 2014, it was found that pre-diabetic individuals (with fasting glucose level between 100 mg/dL and 125 mg/dL) had lower whole grain intake and higher refined grain intake. Moreover, each additional serving of whole grain was linked to a 19% decrease in the likelihood of developing impaired fasting glucose (IFG) (50). Unlike the two previously mentioned studies, the third study that analyzed this database reported no significant association between whole grain intake and the mentioned glycemic factors. Using NHANES data from 2003 to 2014, this study evaluated the relationship between whole grain intake and cardiometabolic risk in children and adolescents aged 2-18 years (33). Additionally, according to a Danish cross-sectional study, whole grain consumption was negatively associated with serum insulin level. This study also evaluated the possible associations between whole grain (whole grain rye, wheat, and oats) and cardiometabolic markers, stating that intake of whole grain oats was negatively associated with insulin level. Likewise, the C17-to-C21 ratio, which indicated the relative consumption of whole grain rye compared to wheat was correlated negatively with serum insulin level (5). An RCT found that whole grain consumption reduced plasma glucose level in overweight or obese girls aged 8-15 years (6). Conversely, a different clinical trial reported that the blood glucose and insulin levels of 8 to 13-year-old children following a whole-grain diet were not significantly impacted (16).

Whole Grain Intake and Lipid Metabolism

Damsgaard *et al.* examined the relationship between total whole grain consumption, specific whole grain types (whole grain rye, wheat, and oats), and the cardiometabolic risk profile in 713 Danish children aged 8-11 years. This cross-sectional study showed that whole grain intake was not associated with lipid metabolism markers such as low-density lipoprotein (LDL) cholesterol, high-density lipoprotein (HDL) cholesterol, and triglycerides (TG). However, whole-grain oat consumption was correlated with LDL cholesterol in an inverse manner (5). Fulgoni *et al.* analyzed the possible connection between whole grain and risk factors for cardiovascular diseases in children and adolescents by utilizing data from the NHANES conducted from 2003 to 2014. They observed an increase in HDL cholesterol with increasing tertiles of whole grain intake. In contrast, TG decreased with increasing levels of whole-grain consumption (33). Hur *et al.* also used data from NHANES, but this study evaluated the data from 1999 to 2004 to examine the association between whole grain intake and chronic disease risk factors among 4,928 adolescents (12-19 years old). The daily intake of whole grain and HDL cholesterol level were positively correlated exclusively among the females (34). Haji Hashemi *et al.* conducted a randomized crossover clinical trial to assess the impact of whole grain intake on the metabolic characteristics of children who were overweight or obese. A total of 44 girls who were overweight or obese took part in this program. The intervention group members were instructed to derive half of their daily grain intake from whole grain for six weeks, whereas the control group members were advised to avoid consuming whole grain foods. The study reported a relationship between higher whole grain consumption and higher HDL cholesterol level. On the other hand, no association was found between the intake of whole grain and the levels of total cholesterol and LDL cholesterol in the serum (6). In another RCT, whole-grain oats and rye intake were investigated concerning LDL cholesterol level and other cardiometabolic markers. Fifty-five healthy Danish children aged 8-13 years were provided with whole-grain oats and rye or refined grain products to consume freely for eight weeks, following a randomized order. Compared to refined grain, whole grain lowered levels of LDL cholesterol, total cholesterol, the ratio of total to HDL cholesterol, and TG (16).

Whole Grain Intake and Blood Pressure/ Hypertension

Based on the results of the referenced studies, the intake of whole grain failed to lower either systolic or diastolic blood pressure in children. However, Damsgaard *et al.* determined that the intake of oats, a particular type of whole grain, inversely correlated with systolic blood pressure in Danish children (5).

Whole Grain Intake and other Cardiometabolic Markers

Out of all the studies presented in this review, only three reported non-glycemic and non-lipophilic cardiometabolic markers. The connection between the consumption of whole grain and the risk of developing chronic diseases among adolescents (aged 12 to 19 years) was shown. This study adjusted for the intake of various food groups and categorized whole grain consumption into three levels of none, low, and high. They found that C-reactive protein (CRP) concentrations were elevated among girls with low consumption when compared to those without consumption or with high consumption. The homocysteine level of boys consuming a high intake of whole grain were lower than those consuming none or very little. Additionally, folate level in the serum and red blood cells in both boys and girls showed a positive correlation with whole-grain consumption (34). Moreover, it was shown that a higher intake of whole grain from oats and rye, as opposed to refined grain, over 8 weeks in Danish children (aged 8 to 13 years) did not alter the markers of inflammation like Interleukin-6 (IL-6) and CRP. Furthermore, they found that those who consumed whole grain had elevated butyrate level in both feces and plasma, along with increased plasma levels of acetate and propionate compared to those who consumed refined grain (16). Additionally, the risk of an elevated continuous metabolic syndrome score (cMetS) (>85th percentile) indicated a high risk of metabolic syndrome (MetS) and was not correlated with the number of whole grain consumed in adolescents aged 13-18 years (33).

Discrepancies in studies examining whole grain consumption and cardiometabolic risk can arise from various factors, including study design (cross-sectional vs. RCT), population characteristics (age, sex, ethnicity, socioeconomic status), measurement of whole grain intake, control of confounding variables, definition of whole grain, whole grain intake within a narrow range in the study population, and duration of follow-up. For example, regarding whole grain intake assessment, three NHANES studies used one or the average values of two 24-hour dietary recalls. In contrast, the cross-sectional study that included baseline data from the Optimal Well-Being, Development, and Health for Danish Children through a Healthy New Nordic Diet (OPUS) School Meal Study used 7-day dietary records to evaluate the whole grain intake. The two RCTs also had different follow-up protocols as Terese Barlebo Madsen *et al.* who conducted a follow-up of every 8 weeks; and Haji Hashemi *et al.* who had a follow-up of every 6 weeks. Moreover, they might have used varying definitions of what were constitutes of whole grain that led to inconsistencies. Some studies might have included mixed-grain products or whole-grain flours, while others may have focused strictly on whole-grain products. Overall, it appears that consumption of whole grain is significantly correlated with cardiometabolic indicators, particularly those related to lipid metabolism, and it may have a substantial impact on these markers.

The possible mechanisms through which whole grain influence insulin level and insulin resistance can largely be attributed to their high soluble fiber content and their inherent food structure (51, 52). Whole grain typically maintain their structural integrity and have larger particles. These components with their physicochemical properties can affect viscosity, potentially slowing gastric emptying and reducing the rate at which macronutrients are absorbed. As a result, this may lead to a reduction in glycemic and insulin responses upon consumption and could even enhance feelings of fullness (5). Oats, as a whole grain, and their soluble fibers (specifically beta-glucan) contribute to the beneficial effects of whole grain consumption on cardiometabolic health (53). Whole grain oats possess unique physicochemical properties due to their viscous β-glucans, which are believed to enhance blood lipid profiles (54). This improvement occurs by decreasing the absorption of lipids and carbohydrates, and inhibiting the reabsorption of bile acids. Consequently, this process may stimulate the de novo synthesis of bile while lowering circulating LDL cholesterol level (55). Furthermore, whole-grain oats may influence blood pressure through improved insulin sensitivity, which remains hypothetical (56).

Whole Grain Intake and Gut Microbiota

Gut Microbiota in Childhood

Gut microbiota includes several microorganisms including viruses, parasites, bacteria, and fungi. However, in most cases, intestinal microbiota refers to bacterial part (57-60). The gut microbiota is a dynamic and complex habitat made up of 1000 species, or 10-100 trillion bacteria, that are engaged in a wide range of biological functions (61-64). There is a temporal development evident when comparing the gut microbiome of an adult to that of the developing microbiome throughout childhood. Compared to an adult, a baby's microbiome is less stable and diversified. Infants' microbiomes are influenced by some variables, including their surroundings, milk nutrition, exposure to medications, and method of delivery. Proteobacteria significantly decrease in abundance upon weaning, a major shift in nutrition. As children get older, both variation and stability rise. The gut microbiome of adolescents exhibits a transition towards an overall decrease in the number of aerobes and facultative anaerobes, as well as concomitant increases in anaerobic species, even though it does not yet match that of an adult (65, 66). The microbiota makeup of a one-year-old infant has a distinctive abundance of *Clostridium botulinum spp.*, Bacteroides, Veillonella, *Clostridium coccoides spp.*, and *Akkermansia muciniphila* (67). Age-related increases in microbiota diversity led to a stable adult composition of microbiota that is dominated by three bacterial phyla of Actinobacteria (Bifidobacteriaceae and Coriobacteriaceae), Bacteroidetes (Bacteroidaceae, Rikenellaceae, and Prevotellaceae), and Firmicutes (Lachnospiraceae and Ruminococcaceae). These bacterial phyla are the product of maturation brought about by a host's genetic makeup, immune response, use of antibiotics, exercise, and diet (67). Around three years of age, a child's gut microbiota is most similar to that of an adult (68).

Numerous variables, including host genetics, immunological response, antibiotic usage, exercise, and food, can influence the intestinal microbiota's dynamic composition and diversity (69-71). Many nutrients and metabolites, such as bile acids, lipids, vitamins, and SCFAs, are extracted, synthesized, and absorbed by commensal bacteria. In the gastrointestinal tract, these bacteria play a major role in digestion. The immunological role of gut microbiota is vital in preventing the colonization of harmful bacteria by preventing their development, using available resources, and/or generating bacteriocins. By preserving intestinal epithelium integrity, gut microbiota can also inhibit the invasion of bacteria (72, 73).

Through a variety of competitive mechanisms, including food metabolism, pH adjustment, the release of antimicrobial peptides impact on cell signaling pathways for microorganisms that are pathogenic of colonization. Furthermore, some studies have shown that commensal bacteria and their byproducts can control innate and adaptive immune cell growth, homeostasis, and operation (69, 73, 74). The makeup and metabolic activity of gut microbiota are significantly affected by dietary choices (70, 71, 75).

Table 3: Whole grain consumption and gut microbiota.

Source (Authors)	Study Design	Population studied	Objective	Indices tested	Result
(16)	RCT Intervention duration: 6 weeks (in every arm) crossover trial with a 4-week washout period, n=55 overweight Danish children Whole grain group: Whole grain intake (g/d)=108±38 Whole grain rye=58±21 Whole grain oat=50±33 Control group: Total whole grain (g/d)=3±2 WG rye=0 WG oat=0	Overweight Danish children (age: 8-13 years)	•Investigate effects of whole grain rye and oats on cardiometabolic markers of children •Analyze changes in gut microbiota, SCFA, and gastrointestinal symptoms in children •Compare whole grain vs. refined grain impact on LDL-C and insulin	Gut microbiota composition was determined by 16S rRNA gene analysis of SCFA in fecal samples	Compared with the control group, whole grain consumption increased the proportional concentrations of Dialister (p=0.032) and Faecalibacterium (p=0.031), while reducing Ruminococcus (p=0.035) and Collinsella (p=0.001). No differences were seen between the treatments in Chao1 or Shannon α-diversity (p=0.202) (or β-diversity (p=0.192)
(77)	RCT Intervention duration: 6 weeks RG; (n=42) whole grain consumption=0 g/d) WG (n=41) Whole-grain consumption=80 g/d)	Children (age: 11-15 years)	Determining the effects of WG and RG foods on health of the gastrointestinal system and immune system. Assessment of changes in lactic acid bacteria, bifidobacteria, inflammatory cytokines, and antioxidant potential.	Stool samples were obtained and by the use of qPCR, lactic acid bacteria and bifidobacteria were measured	From baseline [2.4 6 0.2 log10 genome equivalents (eq)] to week 6th (3.0 6 0.2 log10 genome equivalents) fecal bifidobacteria increased with both interventions, but lactic acid bacteria decreased (p>0.05). The WG group showed increased level of genome eq., but the RG group did not (baseline: 2.9 6 0.2 log10 genome eq., week 6:3.0 6 0.1 log10 genome eq.).
(78)	RCT Spanish infants between the ages of 4 and 7 months, Intervention duration=7 weeks 0%-WG: (n=18) Taking 24 grams of sugar with 0% whole grain cereals 50% WG: (n=25) 50% whole grain cereals based on rye, wheat, rice, corn, sorghum, oat, barley, and millet with 12 g sugar	Spanish infants between the ages of 4 and 7 months	Comparing the effect of infant cereals on gut microbiota in weaning infants Analyzing the microbial composition changes in infants consuming different cereals	Analysis of gut microbiota composition using 16S rRNA gene amplicons	Veillonella abundance was elevated in both groups, whereas Enterococcus abundance decreased Bifidobacterium genus and phylum Actinobacteria decreased in the 0-WG group Among 50-WG members, Lachnoclostridium and Bacteroides increased Escherichia and Proteobacteria levels in 50 WG were reduced to levels lower than those in 0WG.

RCT: Randomized clinical trial, SCFA: Short chain fatty acids, LDL-C: Low-density lipoprotein cholesterol, qPCR: Quantitative polymerase chain reaction.

Particularly, whole grain and other high-fiber foods are not well absorbed by the host, hence providing a significant substrate for the colonic fermentation process carried out by resident micro-organisms (76). However, only a few studies have examined the impact of whole grain consumption on changes in the gut microbiota in children (Table 3).

Effect of Whole Grain Intake on Gut Microbiota

A research investigation involving overweight Danish children aged 8-13 years found that the dominant species in their gut microbiota were Faecalibacterium, Bifidobacterium, Blautia, and Clostridium, accounting for 12%, 13%, 11%, and 6% of the microbiota, respectively. Wholegrain groups had increased Faecalibacterium (p=0.031) and Dialister (p=0.032) and reduced Collinsella (p=0.001) and Ruminococcus (p=0.035) compared to refine groups (16). In a different RCT, participants were selected from a nearby middle school, specifically adolescents aged between 11 and 15 years. The results indicated a rise in fecal bifidobacteria level from the initial measurement in both interventions. However, lactic acid bacteria level increased significantly from the baseline to the 6-week mark in the group that consumed whole grain, while the group that consumed refined grain did not show any such increase (77).

In the study conducted on Spanish infants aged between 4 and 7 months, there was a decrease in the presence of Enterococcus, while the prevalence of the species Veillonella was notably higher in both infants receiving 0% whole grain cereals with 24 g sugar (non-whole grain group) and those receiving 50% whole grain cereals with 12 g sugar (whole grain group). The non-whole grain group exhibited reductions in the genus Bifidobacterium and the phylum Actinobacteria. Meanwhile, in the whole grain group, Bacteroides and Lachnoclostridium levels increased. Furthermore, the abundance of Proteobacteria and Escherichia in the whole grain group was diminished to levels that were lower than those observed in the non-whole grain group. Accordingly, whole grain influenced the gut microbiota composition (78).

Whole grain are abundant in carbohydrates that can be fermented, like dietary fiber, oligosaccharides, and resistant starch. Additionally, they encompass a variety of bioactive compounds and phytonutrients beyond fiber, such as phenolic acids, avenanthramides, carotenoids, and others. The presence of these compounds in whole grain may lead to their passage to the large intestine, influenced by factors like solubility and structure (79, 80). Dietary fibers (DF) influence the composition and abundance of gut bacteria, thereby regulating gut microflora and metabolites, which can result in various health outcomes. The impact of DF is contingent upon factors such as molecular weight, structure, and individual variability (81, 82). For example, high molecular weight β-glucan derived from barley has the potential to enhance beneficial bacteria such as Bacteroides and Prevotella, while simultaneously reducing harmful bacteria (82, 83). Moreover, specific varieties of DF, like arabinoxylan oligosaccharides (AXOS), can boost the level of Bifidobacterium in individuals who are in good health (83). DF also stimulates the production of metabolites, including SCFAs, which contribute to metabolic regulation and overall gut well-being (25, 82, 84). Furthermore, DF has been demonstrated to lower protein fermentation, which is associated with unfavorable metabolites and adverse health consequences (85). Notably, whole grain are a rich source of non-starch polysaccharides and resistant starch, which are integral to producing these effects (82).

Conclusion

It seems that whole grain intake is connected to anthropometric, cardio-metabolic, and gut microbiota health benefits in children and adolescents. Improving body measurements, enhancing cardiovascular and metabolic health including carbohydrate and lipid metabolism and regulating gut microbiota composition can be mentioned as some of the advantages of whole grain consumption in children. Promoting the inclusion of whole grain in children's daily diets should be prioritized by dietitians and healthcare providers as a practical, evidence-based strategy to promote long-term metabolic and gut health. The unique structure and various elements found in whole grain, including dietary fibers, resistant starch, and bioactive compounds, are among the main reasons for their positive health effects. However, current studies in this field are still limited and insufficient. On top of that, underlying mechanisms linking whole grain intake to its benefits for human health are still ambiguous. Therefore, further investigations are needed to address this correlation by a larger study population and considering nutritional, demographic, and health confounders.

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Authors' Contribution
ZMSF Conceptualized and supervised the study. SBA, FS and ZM contributed to the literature search, designed and drafted the tables. SBA wrote the initial manuscript draft. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest
None.

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