RESEARCH PAPER

Polyphenol–Dietary Fiber Complexes as Natural Synbiotics: A Comprehensive Review of Mechanistic, Functional and Clinical Evidence

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ABSTRACT

Polyphenols and fibers may function through subtype-specific biological mechanisms to modulate gut microbiota composition and health outcomes. Polyphenols have powerful antioxidant, anti-inflammatory, cardioprotective and neuroprotective effects, but their therapeutic efficacy in vivo is limited by high instability and low bioavailability. Dietary fibers may promote microbial diversity and the production of short-chain fatty acids (SCFAs), which is positively related to gut barrier integrity, metabolic control, and immune system balance. Recent investigations suggest that, when polyphenols bind to fibers, natural synbiotic complexes are formed which remain intact until the colonic level where they are fermented by gut bacteria and release both SCFAs and bioactive phenolic metabolites such as butyrate. Together, these activities enhance epithelial response and limit inflammation. This review integrates mechanistic aspects of polyphenols and fibers interactions, their synergy to modulate gut microbiome and its physiological benefits. It also discusses the challenges related to polyphenol instability in response to environmental stressors and their possible uses in functional foods, nutraceuticals, synbiotic formulations and cosmetics as well as valorization of agro-food by-products. In general, when polyphenols are combined with dietary fibers, it provides a promising strategy for belly health and age preventing diseases; however, more clinical evidence is needed to translate into practical treatment.

Keywords: Polyphenol, Dietary Fiber, Gut Microbiota, Synergy, Antioxidant.

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Introduction

Polyphenols are bioactive compounds from plant sources with two phenyl rings and multiple hydroxyl groups, which are classified broadly as flavonoids and non-flavonoid[1]. They are considered to have a wide range of health-benefiting properties, but in general, they are limited in their effectiveness by poor intestinal absorption and low bioavailability. They exert therapeutic effects and have potential technological use in disease prevention and industry[2]. They serve important roles as potent antioxidants, helping to eliminate free radicals and reduce oxidative stress while strengthening the body's natural defense systems, particularly during ischemic conditions.

They also decrease the activity of ROS-generating mechanisms in the brain, thereby protecting cellular components and oxidative damage[3]. Along with this, polyphenols show strong anti-inflammatory actions by suppressing cytokines such as IL-1β, IL-6, IL-8, and TNF-α. They additionally influence key inflammatory pathways, including NF-κB (Nuclear factor kappa) and iNOS (inducible nitric oxide synthase). They demonstrate cardioprotective benefits by enhancing endothelial performance and increasing nitric oxide availability. They also limit LDL oxidation, promote balanced lipid metabolism, and contribute to lowered blood pressure, reducing cardiovascular disease[4]. Their neuroprotective effects are notable, as they can cross the blood–brain barrier to limit neuroinflammation and oxidative damage. By supporting neuronal communication and cognitive processes, polyphenols may help delay or prevent the onset of neurodegenerative disorders (Fig 1)[5]. Dietary fibers, in contrast, are non-digestible plant polysaccharides that are resistant to human enzyme digestion and act as prebiotics by providing substrates for fermentation by gut microbes, resulting in the generation of beneficial short-chain fatty acids (SCFAs)[6]. Dietary fibres provide numerous health benefits and are used in many food and pharmaceutical applications to enhance nutrition and health[7]. The fermentable dietary fibre like inulin, fructo-oligosaccharides (FOS), galacto-oligosaccharides (GOS), resistant starch, pectin, and arabinoxylans are known to have prebiotic activity. A prebiotic, as defined by the International Scientific Association for Probiotics and Prebiotics (ISAPP), is a substrate that is selectively fermented by the host microorganisms that confers a health benefit. As these fibers do not get digested in the upper parts of the gastrointestinal tract, they arrive at the colon intact, where they are selectively fermented by beneficial microbes like Bifidobacteria and Lactobacilli[8]. The synergistic co-action between polyphenols and dietary fibre is the basis of synbiotics, which consist of live probiotic microorganisms in combination with selectively used substrates to optimize gut microbiota performance and host health[9]. The combination not only shields polyphenols from premature degradation but also allows for microbial metabolism into bioactive metabolites.

This is associated with enhanced biological activities, which underscore the importance of the gut microbiome in mediating the health effects of these dietary constituents. The gut microbiome is defined as the rich network of symbiotic microorganisms inhabiting the human gastrointestinal tract and their combined genomes. It is an important factor in the etiology and course of many systemic diseases, such as obesity and cardiovascular disease, as well as in gastrointestinal diseases such as inflammatory bowel disease. Understanding more about microbiome functions is thus critical to furthering personalized medicine and could also create new opportunities for therapeutic drug discovery. The purpose of this review is to summarize the current understanding of dietary fibers and polyphenols working together, and to highlight their combined effects on gut health and overall well-being.

POLYPHENOL AND DIETARY FIBERS MECHANISM

In the brain, natural polyphenolic compounds inhibit the activity of both nicotinamide adenine dinucleotide phosphate (NADPH) oxidase and NF-κB, while enhancing endothelial eNOS activity. The NO produced by this reaction further inhibits NADPH oxidase and NF-κB. In contrast, ROS facilitates the activation of NF-κB by releasing its subunits p50 and p65 from the inhibitor IκB. These subunits then translocate into the nucleus, inducing the transcription of many genes, including iNOS. Overall, these bioactivities based on their multifaceted nature underscore the importance of dietary polyphenols as potential agents for maintaining overall health and disease prevention (Fig 1).The main effects of dietary fibers are exerted through changes in digestion, fermentation, and metabolic signaling. Soluble fibers absorb water to form a viscous gel in the gut, which slows gastric emptying and reduces the absorption of glucose and lipids[10]. Insoluble fibers increase stool bulk and accelerate intestinal transit, contributing to regular bowel movements. Fermentable fibers are broken down into SCFAs by gut microbiota in the large intestine, promoting gut barrier integrity, reducing inflammation, and supporting the growth of healthy gut microbiota[11]. Dietary fibers also bind bile acids and cholesterol, aiding in cholesterol reduction. Through SCFA-mediated signaling, fibers influence appetite-regulating hormones and improve metabolic processes[12]. Overall, these combined actions enhance digestive health, metabolic balance, and overall physiological function.

Effects of high and low fiber diet on gut health

Low-fiber diets contain high amounts of glycan-degrading microbes like *Akkermansia muciniphila* and weakens the intestinal mucus barrier, which further enhances inflammation and infection risk. This diet also reduces the gut microbiota diversity which leads to reducing SCFAs production and impairing immune protection. High fiber provides a healthy gut microbiota that produces SCFAs which further strengthen mucus and tight junction proteins and maintain immune balance. Shifting to a low fiber western diet can reduce these benefits and increase risk of infection and IBD[10,13].

POLYPHENOL-DIETARY FIBER SYNBIOTICS

Polyphenols and Dietary Fibers often act synergistically as synbiotics, promoting both intestinal health and systemic immune function[11,12]. Recent studies indicate that co-fermentation of polyphenols with fibres by colonic microbes supports beneficial microbial populations, increases SCFA production, and liberates bioactive phenolic metabolites, while concurrently reducing inflammation[10]. Such properties make polyphenol–fiber synbiotics attractive candidates for preventing chronic diseases and maintaining gut health.synbiotics attractive candidates for preventing chronic diseases and maintaining gut health.

Interaction mechanism and synergy

Non-extractable polyphenols (NEPP) such as proanthocyanidins, tannins and bound phenolic acids form tight complexes with insoluble dietary fibers (e.g. pectin, cellulose, arabinoxylan) via hydrogen bonding, hydrophobic interactions and ester linkage[14,15]. This binding lowers NEPP solubility in the upper gastrointestinal tract, ensuring that most NEPP reach the colon intact. In the colon, microbial enzymes cleave these polyphenol–fiber complexes, releasing monomeric phenolics (e.g. catechins, ferulic acid) which can exert local effects[16]. For example, cereal arabinoxylans often have ferulic acid esterified to the polysaccharide; certain Bacteroides species produce esterases that cleave these bonds to free ferulic acid, a potent antioxidant[17]. Among the SCFAs produced by microbialfermentation of fiber, butyrate is especially critical for gut barrier integrity[18]. It serves as the preferred energy source for colonic epithelial cells, thereby fueling epithelial metabolism and promoting overall mucosal health[19]. Butyrate also upregulates the expression of tight junction proteins e.g. claudins, occludin, Zonula Occludens-1 (ZO-1), which reinforces the epithelial barrier and reduces intestinal permeability[10,20]. SCFAs stimulate production of antimicrobial peptides and modulate host immune responses via G-protein–coupled receptor signalling and inhibiting histone deacetylases, actions that collectively reduce inflammation and protect the barrier[10,20]. Overall, fiber derived SCFAs play a central role in preserving epithelial integrity, reinforcing the mucus layer, and regulating immune responses to maintain gut barrier function[11].

The combined presence of polyphenols and dietary fibers yields synergistic gut health benefits beyond the effects of each component alone[12]. Fibers serve as fermentable substrates for the gut microbiota, boosting the levels of SCFAs such as acetate, propionate, butyrate that help preserve barrier function, modulate immune responses, and support metabolic health[21]. Polyphenols embedded in the fiber matrix selectively stimulate the growth of fibre-degrading commensals (e.g. *Bifidobacterium, Lactobacillus, Faecalibacterium, Eubacterium, Roseburia*) and inhibit certain pathogens (e.g. *Clostridium* spp.), thereby promoting a balanced microbial ecosystem[10,20].

Pro-inflammatory mediators including IL-8, TNF-α, and Vascular Cell Adhesion Molecule-1(VCAM-1) are downregulated, which mitigates inflammation and supports gut homeostasis. This broad synergy indicates the potential of polyphenol–fiber combinations as potent synbiotic systems that optimize gut health through coordinated microbial and biochemical mechanism highlighting the importance of considering dietary fibres and polyphenols as integrated bioactive components to maximize their health benefits via microbiome modulation (Table 1)[10].

CHALLENGES AND LIMITATIONS WITH RESPECT TO DIETARY FIBRES AND POLYPHENOLS

Polyphenols are reactive compounds. Their stability and composition depend heavily on postharvest and processing conditions. When plant tissues are broken down, polyphenols become susceptible to enzymatic and oxidative reactions. These reactions are driven by polyphenol oxidases, peroxidases, glycosidases, and esterases. Such changes can modify the native phenolic profile and lead to the formation of pigments. Enzymatic oxidation causes unwanted browning in fresh foods and promotes desirable color and flavor development in products like coffee, tea, cocoa, and dried fruits. In fermented drinks, anthocyanins undergo further changes thus forming pigments such as pyranoanthocyanins, ethyl-bridged adducts, and portisins which affect color stability. Flavanol oxidation creates dimers and yellow pigments, some of which show improved bioactivity[6]Poor stability and bioavailability of polyphenols

A major limitation in using polyphenols in functional foods or nutraceutical formulations is their poor stability and low bioavailability. Most polyphenolic compounds are sensitive to environmental stressors such as heat, light, oxygen exposure, and pH changes. These factors lead to degradation or structural changes which reduce the effectiveness of polyphenols over time during storage or processing. Ensuring consistent effectiveness in final products is therefore challenging, especially when these compounds are included in complex food matrices[6].

pH factor

pH is a key factor in polyphenol stability. Many of these compounds are more resistant to degradation in acidic conditions. Neutral or alkaline environments usually speed up their breakdown[7,8]. Anthocyanins clearly show this behavior. At low pH values they mainly exist as stable red flavylium cations. However, at higher pH they change into colorless or degraded forms. This change causes noticeable color shifts and lowers their functional activity[9,13]. This pH-dependent behavior creates important challenges in making beverages, dairy products, and other foods where pH is hard to control[10].

Temperature

The stability of polyphenols in foods and nutraceutical systems depends on a mix of environmental and compositional factors. Temperature is one of the most important factors as increased heat speeds up important degradation processes like hydrolysis, oxidative breakdown, and epimerization. These reactions collectively contribute to the loss of structural integrity and functional activity of polyphenols[11]. Cold storage conditions approximately at 4° C markedly decelerate these processes and are therefore widely recommended for preserving phenolic quality during handling and processing[12]. Within the broad polyphenol family anthocyanins are particularly heat-labile thus displaying rapid pigment fading and reduced bioactivity under thermal stress while phenolic acids and flavonoid glycosides generally demonstrate higher thermal tolerance, retaining their stability for longer periods[14] .

Interaction with other food components

Interactions with other components within the food matrix also modulate the behavior and longevity of dietary polyphenols[15]. Naturally occurring sugars such as glucose, fructose and sucrose have been shown to confer a certain degree of protection by lowering oxygen solubility, binding pro-oxidant metal ions and scavenging reactive radical species, although comprehensive quantitative data remain limited[16]. Ascorbic acid presents a notable dual effect while it can enhance the stability of catechins in beverages such as green tea. It often promotes the degradation of anthocyanins significantly by
shortening their half-lives[17].

Light & oxygen

Exposure to light and oxygen further impacts polyphenol stability particularly for anthocyanin-rich systems[18]. Light-induced reactions can trigger photodegradation while oxygen supports both non-enzymatic oxidation and enzymatic pathways catalyzed by polyphenol oxidase. These processes contribute to pigment bleaching, browning, and the overall decline of phenolic content[19].

Metal ions & other chemical agents:

Metal ions and different chemical agents used in processing have a strong impact on behaviour of polyphenols when oxidized. For instance, Fe^{2+} can lower antioxidant capacity or even cause pro-oxidant effects in certain situations. In contrast, ions like Cu^{2+} and Mn^{2+} can either improve or reduce polyphenol activity depending on the pH and the composition of the surrounding matrix[12,21]. Other additives used in food processing including nitrites, Sulphur dioxide, and certain enzymes may also weaken the structure of polyphenols which can speed up their breakdown. These factors highlight the need for careful processing and storage conditions to keep the functional quality of polyphenolic compounds. Other additives used in food processing including nitrites, Sulphur dioxide, and certain enzymes may also weaken the structure of polyphenols which can speed up their breakdown. These factors highlight the need for careful processing and storage conditions to keep the functional quality of polyphenolic compounds.

APPLICATIONS OF POLYPHENOL AND DIETARY FIBERS

The combination of polyphenols and dietary fiber represents one of the most promising approaches in nutrition science, functional foods, and nutraceuticals[14]. Their synergistic use offers numerous benefits across applications in functional foods, gut health, and delivery technologies[22].

Applications in functional foods

Polyphenol-fiber conjugates, especially those from fruit and vegetable by-products in the form of pomace flours, have been incorporated into bakery items, snacks, and beverages to improve their antioxidant capacity and gut bioactivity[23]. These complexes enhance properties like water-holding capacity, texture, and oxidative stability, promoting sensory quality and health claims[24]. Fortified fibers with polyphenols mainly increase SCFA production and hence help improve cardiometabolic health and reduce inflammation[25].Gut microbiota and health benefits

The synergistic utilization of polyphenols and fibers stimulates the growth of beneficial gut bacteria, increases microbiome diversity, and enhances the production of SCFAs[26]. These changes contribute to gut integrity, immune function, prevention of metabolic disorders, diabetes, and inflammatory bowel disease by optimizing gut microbiota composition and barrier function[11].

Technological and industrial applications

The valorization of agro-food by-products, such as grape and apple pomace, citrus peels, cereal bran, and husks, represents a contribution to food-industry sustainability due to polyphenol-dietary fiber complexes[10]. Such ingredients improve the stability and shelf life of foods, enhance their sensory properties, and may act as natural clean-label antioxidants/color stabilizers, reducing the reliance on synthetic additive[20].

Sources and sustainability

Commonly, by-products like grape and apple pomace, mango and citrus peels, cocoa and coffee residuals, or cereal bran and husks are used in formulations due to their high content of bound polyphenols and dietary fibers[27]. For such purposes, these materials are fully in line with the circular economy and sustainability theme within the food industry because important classes of bioactive compounds can be valorized and reduce waste[28].

Functional food formulations

Bakery products like Pomace flours from apple or grape enriched with polyphenol-fiber conjugates have been added to bread, cookies, and crackers[27]. Beverages and meal replacers featuring mango and citrus peels or cereal bran with bound polyphenols are turned into fiber-rich powders that can enhance the gut health, sensory appeal, and shelf stability of smoothies and shakes[10].Both the by-products of cocoa and coffee, and fruit fiber are mixed into energy bars, snacking bites, or extruded products for polyphenol-fiber synergy with prebiotic and antioxidant features[20].

Nanotechnology-Based Formulations

Synbiotic formulations with polyphenol-fiber structures, together with probiotics, offer new gut health concepts and targeted colonic delivery[29]. Fiber-based nanocarriers and nanoparticles are some of the applications of nanotechnology in improving polyphenol stability, bioavailability, and controlled release in the gastrointestinal tract. These developments have the potential for targeting obesity, diabetes, disorders of the gut-brain axis, and chemoprevention of colorectal cancer[23]. Dietary fibers such as PHGG (Partially hydrolysed guar gum) resistant starches, β-glucans, or pectin are used as matrix materials to encapsulate standardized polyphenol extracts, for instance aronia and sambucus, for targeted colonic release[30]. These can be prepared by compression-coating, employing pH-dependent polymers, or using enzymatically degradable matrices. Synbiotic blends are designed as a combination of dietary fiber PHGG, probiotics, and polyphenol-rich extract either in powder or capsule form to help gut health[31].

Polysaccharide Nanoparticles: The nanocarriers based on fibers like pectin or guar gum nanoparticles encapsulating polyphenol extracts help in overcoming poor solubility and, thereby, bioavailability issues while ensuring controlled release at the colon[32–34]. Protein-fiber nanocomposites: Systems based on zein protein and fiber have encapsulated multiple polyphenols, stabilized actives, and providing advanced delivery for food or pharmaceutical applications (Table 2). Applications might include oral and mucosal dosage forms for inflammatory bowel diseases[35,36].

CASE STUDIES

Evidence from randomized controlled trials and meta-analyses consistently shows that combining polyphenols with dietary fiber offers synergistic health benefits. A meta-analysis of 46 (Random Clinical Trials) RCTs involving 2,494 participants found that polyphenol-rich whole foods, which naturally contain fiber, significantly reduced systolic and diastolic blood pressure by around 3.7 mmHg and 1.4 mmHg, respectively. These foods also improved lipid levels, including reductions in triglycerides and total cholesterol. Similar effects were observed when both whole-food and extract-based interventions were analyzed together, although there was noticeable variability between studies. Most of the trials used whole food matrices, highlighting the importance of the natural polyphenol–fiber complex rather than isolated compounds[37][38]

A randomized controlled crossover clinical pilot study was conducted to evaluate the effects of a high-polyphenol, high-fiber, minimally processed meal, in the presence and absence of aerobic exercise, on the metabolism of healthy adults in their mid-life and older years. A traditional high-fat, high-carbohydrate meal, the same meal designed as plant-based high fat, high carbohydrate with increased fiber and polyphenols, and plant-based high fat, high carbohydrate with increased fiber and polyphenols and the addition of aerobic exercise after 30 minutes were used in the study protocol. Meanwhile, postprandial blood samples were taken up to six hours to measure triglycerides, glucose, insulin, and metabolic lipoprotein indexes, and the EE% for postprandial aerobic exercise was adjusted to 25% from the total ME% derived from a test meal. The novel high-fiber and high-polyphenol test meal resulted in attenuated postprandial responses on triglyceride and metabolic lipoprotein concentrations; postprandial aerobic exercise supplementation resulted in additional attenuation on postprandial response to traditional high-fiber and high-fat test meal concentrations. Thus, the study outcomes were conclusive to the effect that a high-polyphenol and high-fiber test meal positively modulates postprandial metabolic responses, and postprandial aerobic exercises have additional benefits on attenuating potential risks from cardiometabolic responses[39].

The influences of polyphenolic and fermentable fiber blend combinations on the human gut microbiome profile regarding its functional potential have also been elucidated in a pre-clinical in vitro human fecal inoculum study. Here, the bacterial growth patterns in relation to the metabolites produced and the evaluation of the antioxidants produced by the bacterial flora in the fermented mixture have been examined. In the study, the human fecal inoculum mixture has been obtained from 30 normal volunteers. Both polyphenolic blend and fiber blend combinations independently have a positive modulation in the levels of beneficial bacteria such as Ruminococcus bromii, Bifidobacterium spp., Lactobacillus spp., and Dorea spp. Nevertheless, it was shown that regarding beneficial effects, fiber in combination with polyphenols had broader beneficial effects, increasing total SCFAs, decreasing indole, and ammonia in contrast to controls. Improved antioxidant potential was detected only in media with polyphenols, while overall metabolic enhancements were detected in a combination of them. The findings indicate that, first and foremost, in terms of beneficial effects, combining polyphenols with fibers improves microbial composition, metabolic activities, and antioxidant potential in contrast to each single component used separately[40].

Current clinical and preclinical evidence highlights that the synergy of dietary fibers and polyphenols increases their inflammatory, metabolic, and gut microbiota-related benefits (Table 3). These findings point out the significance of whole-food matrices in increasing the efficacy of dietary interventions for cardiometabolic health.

CONCLUSION

This review emphasizes the synergistic relationship between polyphenols and dietary fibers and describes how their combined effects are on the gut health and their therapeutic outcomes. As polyphenols provide anti-inflammatory, antioxidants, cardioprotective and neuroprotective benefits, it also has some limitations such as poor stability and low bioavailability. On the other hand, dietary fibers act as prebiotics which stimulate beneficial gut bacteria and further facilitate the production of SCFAs, which is essential for immune reaction and intestinal integrity. Combination of polyphenols and dietary fibers form synbiotic systems in which fibers provide protection to polyphenols from degradation and further enable their slow release in the colon. In the gut, while enhancing the production of SCFAs, the fermentation of fiber releases bioactive phenolic metabolites, mainly butyrate which strengthens the intestinal barrier and further reduces inflammation. This synergy facilitates a healthy gut microbiome, improves metabolic and immune responses, and increases microbial diversity. This review also highlights challenges faced by polyphenols such as poor stability that occur under heat, light, oxygen, and pH variation. It also emphasizes application such as functional foods, nutraceuticals, cosmetic formulations, and gut-targeted therapies. Using the agro-food by products such as fruit peels and cereal bran makes this approach cost-effective and sustainable. Certain clinical trials were also conducted using this synergy. Lastly, the paper concludes that polyphenol dietary fiber synergy provides strong potential for disease prevention, industrial innovation and gut health enhancement.

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TABLE 1: INTERACTIONS AND OUTCOME OF POLYPHENOLS

Polyphenol Type	Dietary Fiber Type	Interaction Mechanism	Microbial Action	Physiological Outcome	Ref
Ferulic acid	Arabinoxylan	Ester linkage	Microbial este	Antioxidant release, gut barrier support	**14–17**

			rasecleavage		
Proanthocyanidins	Cellulose	Hydrogen bonding	Colonic fermentation	Increased SCFA production	**15, 16**
Catechins	Pectin	Hydrophobic interaction	Bifidobacterium metabolism	Anti-inflammatory effect	**10, 20**
Tannins	Insoluble fiber	Complex formation	Slow colonic release	Reduced gut inflammation	**14, 21**

TABLE 2: ADVANCED NANO-ENABLED APPLICATIONS OF POLYPHENOLS.

Formulation	**Polyphenol Examples**	**Fiber Correlation**	**Ref.**
Nano Sunscreens	Green tea polyphenols (EGCG), resveratrol, curcumin.	Electrospun nanofibers of chitosan polyphenol composites used as UV-protective films for biodegradable skin-safe delivery.	**41**
Barrier Creams	Tannic acid	Tannic acid-polymer nanofibers strengthen skin barrier and reduce trans epidermal water loss.	**42**
Anti-Acne Products	Quercetin, curcumin, catechins	Electrospun cellulose or silk fibroin nanofibers with quercetin release polyphenols locally at acne sites.	**43**
Nano Moisturizers	Grape seed polyphenols, ferulic acid	Polyphenol-loaded nano-emulsions within nanofiber mats enhance sustained hydration and ceramide replenishment.	**44**
Anti-Aging Formulations	Resveratrol, soy isoflavones, epigallocatechin gallate (EGCG)	Electropun collagen–polyphenol nanofibers mimic an extracellular matrix, enabling deeper penetration and anti-aging action.	**44**

TABLE 3: SUMMARY OF CLINICAL AND PRECLINICAL STUDIES DEMONSTRATING POLYPHENOL–DIETARY FIBER SYNERGY

Study Type	**Polyphenol–Fiber Source**	**Study Population / Model**	**Key Outcomes Observed**	**Ref.**
Meta-analysis of RCTs (46 trials)	Polyphenol-rich whole foods (natural fiber matrix)	2,494 human participants	↓ Systolic BP (~3.7 mmHg), ↓ Diastolic BP (~1.4 mmHg), ↓triglycerides, ↓ total cholesterol; stronger effects with whole-food matrices	**37**
Randomized, controlled, double-blind, crossover clinical trial	Blackcurrant polyphenol extract combined with fruit pulp (dietary fiber)	Healthy adult human participants (UK population)	↓ Postprandial glucose and insulin responses, favorable modulation of GIP and C-peptide, improved	**38**

			glycaemic regulation; combined polyphenol–fiber drink more effective than pulp alone or placebo	
Randomized, controlled, crossover clinical pilot study	High-polyphenol, high-fiber, minimally processed plant-based meal	10 healthy middle-aged and older adults	↓ Postprandial triglycerides and metabolic lipoprotein responses; additional improvements when combined with postprandial aerobic exercise; improved postprandial metabolic regulation and reduced cardiometabolic risk markers	**39**
Preclinical in vitro fermentation study	Polyphenol blend (blueberry, cranberry, green tea, cocoa) combined with fermentable fiber blend (high-amylose maize starch, galacto-oligosaccharides, inulin)	In vitro gut fermentation model using pooled human fecal inoculum from 30 healthy volunteers	↑ Beneficial gut taxa (Ruminococcus bromii, Bifidobacterium, Lactobacillus, Dorea spp.), ↑ total short-chain fatty acids, ↓ indole and ammonia, ↑ antioxidant capacity; additive gut microbiota and metabolic benefits with combined polyphenol–fiber blends	**40**

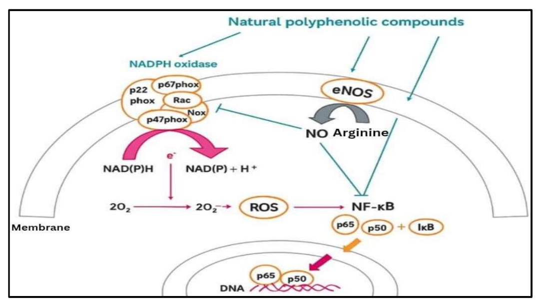

Fig 1: Mechanistic Pathways of Polyphenol