ROLE OF BROWN RICE BIOACTIVES IN MODULATING LIPID METABOLISM AND ADIPOGENESIS: IMPLICATIONS FOR OBESITY MANAGEMENT

Anisa Handayani[1,2], Dian Handayani[3], and Widya Rahmawati[3]

[1]Master of Nutrition Science Program, Department of Nutrition, Faculty of Health Sciences, Universitas Brawijaya, Indonesia; [2]Department of Nutrition, Widya Cipta Husada Institute of Health Technology, Kepanjen, Malang, Indonesia; [3]Department of Nutrition, Faculty of Health Sciences, Universitas Brawijaya, Malang, Indonesia

Abstract. Obesity is a global public health issue with a steadily increasing prevalence. Based on the 2023 Indonesian Health Survey, the prevalence of obesity among adults (>18 years old) increased from 21.8% in 2018 to 23.4% in 2023. Globally, the World Obesity Atlas 2023 reported that 38% of the world's population is overweight or obese, and this figure is projected to reach 51% by 2035. Obesity contributes to various metabolic disorders such as insulin resistance, dyslipidemia, and inflammation. Nutritional interventions that can modulate these metabolic pathways, particularly those involving functional foods, are important strategies for managing obesity. This literature review aims to examine the potential of bioactive compounds in brown rice in regulating lipid metabolism and adipogenesis as a preventive and therapeutic strategy against obesity. This study employed a systematic literature review method by analyzing original experimental studies (*in vitro* and *in vivo*) published between 2020 and 2024. Articles were selected from reputable databases such as PubMed, ScienceDirect, and Scopus using keywords related to brown rice bioactive compounds (*eg*, γ-oryzanol, GABA, tocopherol, ferulic acid, phytosterols, polyphenols) and their roles in lipid metabolism and adipogenesis. Inclusion criteria focused on full-text, peer-reviewed studies examining the metabolic effects of these compounds on obesity-related parameters. Several bioactive compounds in brown rice - including γ-oryzanol, GABA, ferulic acid, phytosterols, and polyphenols - show anti-obesity potential through multiple mechanisms, such as inhibiting lipogenesis, enhancing lipolysis, promoting mitochondrial biogenesis and thermogenesis, improving insulin sensitivity, and reducing chronic inflammation in adipose

tissue. Germination and other processing methods have also been shown to increase the concentration and bioavailability of these compounds. Brown rice is a promising functional food rich in bioactive compounds with potential anti-obesity effects. These compounds play crucial roles in modulating lipid metabolism, reducing adipose tissue inflammation, and supporting metabolic health. The development of brown rice-based dietary interventions could serve as an effective, evidence-based strategy for obesity prevention and management.

Keywords: brown rice, bioactive compounds, obesity, lipid metabolism, adipogenesis

Correspondence: Anisa Handayani, Widya Cipta Husada Institute of Health Technology, Jl. Jendral Sudirman (Sidotopo) No. 11, Dilem Kepanjen, East Java 65163, Indonesia
Tel: +62 81249642209 E-mail: anisa.handayani55@gmail.com

INTRODUCTION

Obesity is a global public health issue with a prevalence that continues to rise year after year. Data from the 2023 Indonesian Health Survey (SKI) shows that the rate of obesity among adults (aged >18 years) increased from 21.8% in 2018 (Ministry of Health of the Republic of Indonesia, 2019) to 23.4% in 2023 (Ministry of Health of the Republic of Indonesia, 2024). Globally, according to the World Obesity Atlas 2023 released by the WHO, approximately 38% of the world's population is overweight or obese (World Obesity Federation, 2023). This figure is projected to rise to 51% by 2035, making obesity a serious challenge to global healthcare systems (World Obesity Federation, 2023). Obesity not only affects physical appearance but is also strongly associated with an increased risk of various non-communicable diseases such as heart disease, hypertension, dyslipidemia, and type 2 diabetes mellitus, all of which are components of metabolic syndrome (Yang *et al*, 2022).

Pathophysiologically, obesity is characterized by hypertrophy

and hyperplasia of adipocytes, leading to adipose tissue dysfunction and chronic low-grade inflammation (Petrick *et al*, 2020). Excessive fat accumulation triggers oxidative stress and mitochondrial dysfunction in adipocytes, exacerbating metabolic disturbances. Hypertrophic adipocytes exhibit impaired metabolic and endocrine functions, including reduced glucose uptake capacity, which ultimately contributes to insulin resistance (Khalil *et al*, 2022). Moreover, adipose tissue inflammation promotes macrophage recruitment and the production of pro-inflammatory cytokines such as TNF-α, IL-6, and MCP-1, which aggravate inflammation and metabolic dysregulation. The imbalanced interaction between adipocytes and immune cells further strengthens the link between obesity and systemic metabolic disorders (Sasiarini *et al*, 2024; Tanaka-Yachi *et al*, 2022). Therefore, nutritional interventions that can suppress inflammation and improve adipose function are considered essential strategies in obesity management.

Brown rice is a type of rice that has only undergone the removal of its outer husk, thus retaining its bran and germ layers, which are rich in nutrients and bioactive compounds (Wu *et al*, 2022). Unlike white rice that has undergone further polishing, brown rice contains various functional components such as γ-oryzanol, phenolic acids, flavonoids, phytosterols, tocotrienols, and γ-aminobutyric acid (GABA) (Munarko *et al*, 2022; Waewkum and Singthong, 2021; Wu *et al*, 2022). These constituents have been found to exert beneficial health effects, including antioxidant and anti-inflammatory activities, as well as metabolic effects that support obesity management (Munarko *et al*, 2022).

Previous studies have shown that the bioactive compounds in brown rice can help reduce body fat levels through various mechanisms, including enhancing fatty acid oxidation, reducing lipogenesis, and inhibiting adipocyte differentiation and proliferation (Pacifici *et al*, 2023; Tamura *et al*, 2020). Furthermore, components such as γ-oryzanol and tocotrienols play roles in modulating cholesterol levels, insulin sensitivity, and chronic low-grade inflammation commonly found in individuals

with obesity (Jung *et al*, 2015; Wu *et al*, 2022). Therefore, brown rice has the potential to be part of both preventive and therapeutic nutritional strategies in addressing obesity and related metabolic disorders.

Considering the increasing prevalence of obesity both globally and nationally, and the potential of bioactive compounds in brown rice to exert positive metabolic effects, this literature review is crucial. To date, there is still a limited number of studies that comprehensively examine the mechanisms and effectiveness of brown rice bioactive compounds in the context of obesity prevention and management. Hence, a structured scientific synthesis is needed to further explore the potential use of brown rice as part of a healthy dietary intervention. This review is also relevant in supporting the development of local food-based dietary recommendations in Indonesia - ones that are not only affordable and sustainable but also functionally valuable in reducing the risk of metabolic diseases such as obesity.

MATERIALS AND METHODS

This paper employs a literature review method with a systematic approach, focusing on the analysis of experimental studies, both *in vivo* and *in vitro*, that examine the effects of bioactive compounds from brown rice on lipid metabolism and adipogenesis in the context of obesity management. This review does not involve direct experimentation; instead, it gathers, evaluates, and synthesizes findings from previous studies relevant to the topic.

The literature review process began with determining the topic and objectives of the review, followed by a comprehensive search for scientific articles using reputable electronic databases such as PubMed, ScienceDirect, and Scopus. The keywords used in the literature search included: "γ-oryzanol," "tocopherol," "ferulic acid," "lutein," "phytosterol," "phytic acid," "polyphenols," "zeaxanthin," "brown rice bioactives," "lipid metabolism," "adipogenesis," and "anti-obesity effect."

The inclusion criteria for article selection comprised original research conducted either *in vivo* or *in vitro*, with experimental designs assessing the effects of brown rice bioactive compounds (such as γ-oryzanol, tocopherol, lutein, ferulic acid, phytosterols, phytic acid, polyphenols, and zeaxanthin) on lipid metabolism and adipogenesis parameters. Selected articles had to be peer-reviewed, published between 2020 and 2024, and available in full text in either Indonesian or English.

Exclusion criteria included non-experimental articles such as reviews or editorials, studies irrelevant to lipid metabolism and adipogenesis, research that did not specifically assess the effects of bioactive compounds, and articles that were not accessible in full text.

The screening process was carried out systematically based on these inclusion and exclusion criteria. The selected articles were then further analyzed using a matrix synthesis approach, which involved mapping the main findings of each study - including the type of compound, research model (cellular or animal), mechanisms of action, and outcomes related to lipid metabolism and adipose tissue formation. Through this process, several key articles were identified that provide a comprehensive overview of the potential of brown rice bioactive compounds in addressing obesity through the modulation of lipid metabolism and adipogenesis.

RESULTS

Bioactive compound profiles in brown rice

Based on Table 1, numerous studies have revealed various bioactive compounds found in brown rice and how these compounds change through processes such as germination. These bioactive compounds include γ-oryzanol, GABA, tocopherol, lutein, ferulic acid, phytosterols, phytic acid, polyphenols, phenolics, and zeaxanthin, all of which are known to offer numerous health benefits, such as antioxidant effects,

Table 1

Review of bioactive compound profiles in brown rice: evidence from recent studies

No.	Reference	Study design	Subject characteristics	Intervention	Results	Conclusion
1.	Gong *et al* (2017)	Laboratory analysis (*in vitro* study)	Eight varieties of brown rice	Extraction and analysis of phytochemical content and antioxidant activity	Total phenolics: 72.45-120.13 mg GAE/100 g; 40.6-50.2% bound; Total flavonoids: 75.90-112.03 mg CE/100 g; 26.9-48.2% bound; trans-Ferulic acid: 161.42-374.81 μg/100 g; 96.4-99.2% in bound form; PSC (antioxidant activity): 18.29-40.33 mg vitamin C equiv/100 g; 67.2-77.2% bound	Brown rice contains significant amounts of phenolics and flavonoids, mainly in bound forms. Trans-ferulic acid is the predominant phenolic acid. Antioxidant activity is mostly contributed by bound compounds.
2.	Islam *et al* (2021)	Experimental validation study	Various rice products including brown rice, rice bran oil, rice germ, white rice, rice with large germ, and puffed rice	Method validation of phytosterol analysis using alkaline hydrolysis and trimethylsilyl derivatization coupled with GC-FID; applied to measure β-sitosterol, campesterol, and stigmasterol in rice products	Recoveries: 87.6-107.6%. Precision: RSD <4% (repeatability), <8% (reproducibility), HorRat ratio: 0.3-1.0. LOQ: 0.08-0.09 mg/100g. Total phytosterols: 18.88-1,375.47 mg/100g. β-sitosterol was dominant (58.4-63.6%). White rice had lowest content but is widely consumed.	The validated method is accurate, precise, and sensitive for analyzing phytosterols in rice products. Despite lower levels in white rice, its high consumption makes it a notable phytosterol source.

Table 1 (cont)

No.	Reference	Study design	Subject characteristics	Intervention	Results	Conclusion
3.	Ma *et al* (2023)	Experimental analysis	9 japonica rice cultivars (brown and white)	Analysis of polyphenol and flavonoid content, and antioxidant activity (DPPH, ABTS, OH, FRAP) in various japonica rice cultivars	Total phenolic content in brown rice: 241.98-296.76 mg GAE/100g; flavonoid: 225.30-276.80 mg RE/100g, which were 118.98-206.06% and 135-217% higher than in white rice. Antioxidant activity of brown rice was 1.68-2.85 times higher. p-Hydroxybenzoic acid was the predominant phenolic acid.	Brown japonica rice shows significantly higher antioxidant content and activity than white rice. The PZ21 (Yanfeng 47) variety had the strongest antioxidant performance, offering guidance for health food production.
4.	Lamberts and Delcour (2008)	Experimental laboratory analysis	5 raw rice cultivars with various degrees of milling (DOM <15% and >15%)	Measurement of color (b*), carotenoid content (β-carotene, lutein, zeaxanthin), and extinction (λ = 450 nm) before and after parboiling	Carotenoids (mainly β-carotene and lutein ~100 ng/g; zeaxanthin ~30 ng/g) were concentrated in the outer rice layers and nearly absent in inner endosperm. Carotenoids strongly correlated with yellow color and extinction values. Parboiling reduced carotenoids to trace levels.	Carotenoids in brown rice are primarily in the outer layers and significantly decrease after parboiling, contributing minimally to color in milled parboiled rice.

Table 1 (cont)

No.	Reference	Study design	Subject characteristics	Intervention	Results	Conclusion
5.	Ukpong *et al* (2023)	Experimental laboratory study	Rice cultivars: FARO 44, FARO 57, and NERICA-8; analyzed as non-germinated parboiled milled rice (NMR), brown rice (NBR), and germinated brown rice (GBR) germinated for 12, 24, and 36 hours	Rice samples were germinated at 35°C for 12, 24, and 36 hours; compared to non-germinated brown and milled rice	Germination reduced pasting properties (except breakdown viscosity) and significantly increased bioactive compounds and nutrients (eg, GABA, antioxidants, protein, vitamins, minerals) but decreased total carbohydrate, starch, and amylose. FARO 57 showed the highest improvements. Milling reduced all bioactives and nutrients.	Germination, especially for 36 hours, significantly enhances the nutritional and functional value of brown rice. FARO 57 was the most enriched cultivar post-germination.

Table 1 (cont)

No.	Reference	Study design	Subject characteristics	Intervention	Results	Conclusion
6.	Waewkum and Singthong (2021)	Experimental study analyzing physicochemical, functional properties and bioactive compounds	Four Thai indigenous pigmented brown rice varieties: Hom Mali (HR), Red Hom Mali (RHR), Riceberry (RBR), and Homnil (HNR)	Analysis of physicochemical characteristics, bioactive compounds, and glycemic index in pigmented brown rice flours	All flours had high carbohydrate, protein, vitamins, and minerals. RHR had highest amylose content, lowest rapid available glucose (RAG) and glycemic index (GI). Pasting properties slightly changed when heated. Good water/oil absorption, swelling, solubility, emulsion, and foaming properties. High syneresis at low temperature storage. High phenolic, flavonoids, and antioxidant activities especially in RHR. Morphology showed polyhedral shape with size variation.	Thai pigmented brown rice flours, especially RHR, are nutritionally rich with good functional properties and high antioxidant bioactives, suggesting potential as functional food ingredients.
7.	Munarko *et al* (2022)	Experimental study	Five Indonesian brown rice varieties, germinated up to 120 hours with samples taken every 24 hours	Soaking and germination for 0-120 hours; measurements every 24 hours	Germination increased GABA content, highest in Inpari 43 (126.55 mg/100g after 120 hours). Phenolic content, antioxidant capacity, and γ-oryzanol changed; fatty acid profile remained unchanged. Pasting properties significantly altered (peak viscosity, final viscosity, breakdown, setback).	Germination modifies brown rice properties by increasing GABA and altering pasting behavior, useful for developing functional rice-based foods.

Table 1 (cont)

No.	Reference	Study design	Subject characteristics	Intervention	Results	Conclusion
8.	Wu *et al* (2022)	Experimental study	Paddy rice and brown rice germinated for 18 to 72 hours	Germination of rice in two forms: paddy rice (GP) and brown rice (GBR) over 18-72 hours	GABA content and phytase activity were lower in GP than GBR; phytic acid higher in GP. GP had higher total γ-oryzanol, free and total phenolics, free and total flavonoids, and higher antioxidant activities (DPPH and T-AOC) than GBR during germination.	Germinating rice as paddy rice increases γ-oryzanol, phenolics, flavonoids, and antioxidant capacity but reduces GABA content compared to germinating brown rice. This informs germination method choices and wholegrain food development.

ABTS: 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid); CE: Catechin equivalents; DOM: degree of milling; DPPH: 2,2-diphenyl-1-picrylhydrazyl; FA: ferulic acid; FRAP: ferric reducing antioxidant power assay; g: gram; GABA: gamma-aminobutyric acid; GAE: gallic acid equivalents; GBR: germinated brown rice; GC-FID: gas chromatography-flame ionization detector; GI: glycemic index; GP: glutathione peroxidase; HorRat ratio: a ratio used to assess the reproducibility of an analytical method; LOQ: limit of quantification; mg: milligram; NBR: non-germinated brown rice; ng: nanogram; NMR: non-germinated parboiled milled rice; OH: hydroxyl radical scavenging activity assay; PSC: Peroxyl radical scavenging capacity; RE: rutin equivalents; RSD: relative standard deviation; RAG: rapid available glucose; T-AOC: total antioxidant capacity; vitamin C equiv: Vitamin C equivalents; μg: microgram

protection against oxidative stress, and potential use in functional food development. The following is a review of research findings discussing these bioactive contents and their implications for the nutritional and functional value of brown rice.

Gong *et al* (2017) conducted an *in vitro* analysis on eight varieties of brown rice aiming to identify varieties with the highest potential health benefits based on their bioactive compound profiles. The study found that total phenolics ranged from 72.45 to 120.13 mg gallic acid equivalent (GAE)/100 g, with 40.6-50.2% in bound form. Total flavonoids measured were between 75.90 and 112.03 mg catechin equivalent (CE)/100 g, of which 26.9-48.2% were bound. Notably, trans-ferulic acid was identified as the predominant phenolic acid, present at 161.42–374.81 μg/100 g, with an overwhelming majority (96.4-99.2%) in bound form. The antioxidant activity, measured as peroxyl radical scavenging capacity (PSC), ranged from 18.29 to 40.33 mg vitamin C equivalent/100 g, with 67.2-77.2% contributed by bound compounds. This study highlights the important role of trans-ferulic acid as a key bioactive compound in brown rice, significantly contributing to its antioxidant capacity.

Meanwhile, Munarko *et al* (2022) investigated five Indonesian brown rice varieties during germination up to 120 hours and found that germination significantly increased levels of GABA, phenolic compounds, antioxidant capacity, and γ-oryzanol - without affecting the fatty acid profile. The Inpari 43 variety showed the highest GABA content (126.55 mg/100g of brown rice after 120 hours. In addition, rice paste viscosity changed significantly, potentially affecting culinary properties and product applications. These findings indicate that germination can significantly enhance the nutraceutical quality and functional value of brown rice.

Furthermore, Wu *et al* (2022) compared the effects of germination in paddy rice (GP) and brown rice (GBR) on various bioactive compounds. The results showed that GP produced higher levels of γ-oryzanol,

phenolics, flavonoids, and antioxidant activity than GBR. Conversely, GBR exhibited higher GABA content and phytase activity. These findings are important as they show that the initial physical form of rice during germination (paddy *vs* brown) can influence the profile of bioactive compounds, thus informing the selection of appropriate germination strategies for functional food development.

Islam *et al* (2021) focused on validating a method for analyzing phytosterols in various rice products, including brown rice, white rice, rice bran oil, and sprouts, using alkaline hydrolysis and after trimethylsilyl (TMS) derivatization combined with gas chromatography-flame ionization detector (GC-FID). The results showed that β-sitosterol was the dominant phytosterol and its content was higher in brown rice compared to white rice. The method proved to be valid and reliable for phytosterol quantification and confirmed that brown rice is a good source of phytosterols, especially in relation to cholesterol-lowering benefits.

Ma *et al* (2022) conducted a comparative study on nine japonica rice cultivars, both white and brown, aiming to evaluate total polyphenol content (TPC), flavonoid content (TFC), and antioxidant capacity using various assays including 2,2-diphenyl-1-picrylhydrazyl (DPPH), 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), hydroxyl radical (OH), and ferric reducing antioxidant power (FRAP). The findings showed that brown rice had 1.7 to 2.8 times higher antioxidant capacity compared to white rice. Among all varieties, the PZ21 cultivar showed the highest antioxidant capacity. This study highlights the importance of considering rice variety and processing type for developing functional foods rich in bioactive compounds.

In a study by Lamberts and Delcour (2008), carotenoid content, particularly β-carotene and lutein, was analyzed across five rice cultivars with different milling degrees and parboiling treatments. Carotenoids were found mainly in the outer layers of the rice grain, so milling and parboiling significantly reduced their levels to trace amounts. The study

shows that brown rice, which is not fully milled, retains better carotenoid content compared to white or parboiled rice, albeit still in relatively low amounts.

Ukpong *et al* (2023) evaluated the effect of germination duration (12, 24, and 36 hours) on the nutritional content, bioactive compounds, and physicochemical properties of three Nigerian rice cultivars (FARO 44, FARO 57, and NERICA-8). Results showed that germination increased GABA, vitamin E, zinc, fiber, protein, and antioxidant activity. On the other hand, starch content and some viscosity parameters decreased. FARO 57 germinated for 36 hours showed the most optimal results in terms of nutritional value and functional properties. This study underscores the crucial role of germination duration in maximizing the health potential of brown rice.

Finally, Waewkum and Singthong (2021) investigated the functional properties and bioactive compound content of flour from four pigmented Thai brown rice varieties: Hom Mali (HR), Red Hom Mali (RHR), Riceberry (RBR), and Homnil (HNR). All varieties showed high carbohydrate, protein, vitamin, and mineral content. Among them, RHR had the lowest amylose content, highest bioactive compounds, and lowest glycemic index (GI), making it an excellent candidate for functional foods. This research emphasizes the advantages of pigmented brown rice, particularly the RHR variety, as a nutritious and low-GI food alternative.

Brown rice contains a variety of important bioactive compounds that make it a functional food with broad health benefits. Key compounds found in brown rice include γ-oryzanol, GABA, and tocopherol (vitamin E), which act as powerful antioxidants and support nervous system and cardiovascular health (Munarko *et al*, 2022; Ukpong *et al*, 2023; Wu *et al*, 2022). In addition, brown rice is rich in lutein and zeaxanthin, two carotenoids important for eye health (Lamberts and Delcour, 2008).

The ferulic acid and polyphenol (including phenolic) contents in brown rice provide protection against oxidative stress and inflammation,

contributing to its high antioxidant activity (Ma *et al*, 2022; Gong *et al*, 2017). Brown rice also contains phytosterols such as β-sitosterol, which can help lower blood cholesterol levels (Islam *et al*, 2021). However, it also contains phytic acid, which serves as a natural antioxidant but may inhibit the absorption of certain minerals if consumed in excess (Wu *et al*, 2022).

Overall, the combination of bioactive compounds - γ-oryzanol, GABA, tocopherol, lutein, ferulic acid, phytosterols, phytic acid, polyphenols, phenolics, and zeaxanthin - makes brown rice a rich nutritional source with significant potential for the development of functional food products that support holistic health.

Effects of bioactive compound of brown rice on anti-obesity mechanism

Based on Table 2, various bioactive compounds in brown rice have been identified to exert significant metabolic effects on the prevention and management of obesity. Compounds such as γ-oryzanol, GABA, tocopherol, lutein, ferulic acid, phytosterol, phytic acid, polyphenols, phenolics, and zeaxanthin exhibit diverse mechanisms of action supporting lipid metabolism regulation, inflammation reduction, enhanced insulin sensitivity, and thermogenesis activation. These studies utilize both *in vitro* and *in vivo* approaches in various animal and human models, highlighting the substantial potential of brown rice as a functional food for metabolic disorder interventions.

γ-Oryzanol is a bioactive compound proven to have anti-obesity effects through various molecular mechanisms. In an *in vitro* study on 3T3-L1 preadipocytes, γ-oryzanol enhanced adipocyte differentiation and glucose uptake by activating the PPAR-γ and mTORC1 pathways and promoting GLUT4 translocation (Jung *et al*, 2015). In animal models, supplementation with 0.5% γ-oryzanol in a high-sugar and high-fat diet for 30 weeks in Wistar rats increased PPAR-γ expression and decreased

Table 2

Effects of bioactive compound of brown rice on anti-obesity mechanism

Compound	Metabolic effect	Experimental model	Effective dose	Treatment duration	Anti-obesity mechanism	Reference
γ-Oryzanol	Increases adipocyte differentiation and glucose uptake	3T3-L1 preadipocytes (*in vitro*)	Not specified	Not specified	γ-Oryzanol activates *PPAR*-γ and mTORC1 signaling pathways and enhances GLUT4 translocation to improve glucose uptake.	Jung *et al* (2015)
	Increases *PPAR*-γ expression while inflammation and oxidative stress are reduced	Wistar rats on high sugar-fat diet	0.5% in diet	30 weeks	γ-Oryzanol modulates adipose tissue inflammation and oxidative stress through activation of *PPAR*-γ.	Francis-queti-Ferron *et al* (2021b)
	Reduces features of metabolic syndrome and hepatic inflammation	Wistar rats on high sugar-fat diet	0.5% in diet	30 weeks	γ-Oryzanol prevents the development of NAFLD by exerting anti-inflammatory and antioxidant effects.	Francis-queti-Ferron *et al* (2022)
	Reduces adipocyte hypertrophy and macrophage infiltration	Sprague-Dawley rats (HFHFr diet)	Not specified	12 weeks	γ-Oryzanol reduces the M1/M2 macrophage ratio and attenuates inflammation in adipose tissue.	Sasiarini *et al* (2024)
	Reduces renal inflammation and oxidative stress	Wistar rats (HSF diet)	Not specified	10 weeks (after 20-week HSF diet)	γ-Oryzanol downregulates RAGE expression and modulates the AGEs/RAGE axis to reduce inflammation.	Francisqueti-Ferron *et al* (2021a)

Table 2 (cont)

Compound	Metabolic effect	Experimental model	Effective dose	Treatment duration	Anti-obesity mechanism	Reference
GABA	Reduces body weight gain, adipogenesis, lipogenesis, adipocyte size, and fasting glucose; improves lipid profile and enhances PKA signaling and UCP1 browning	C57BL/6J mice (HFD-induced) and 3T3-L1 adipocytes	Not specified	Not specified	GABA regulates lipid metabolism, enhances lipolysis, and promotes the browning of fat tissue via the PKA signaling pathway.	Jin *et al* (2024a)
	Reduces leptin levels, hepatic triglycerides, and expression of *SREBP-1, ACC,* and FAS; increases *UCP1, PGC-1α*, and fatty acid oxidation; provides protection against NAFLD	Male C57BL/6J mice (HFD-induced)	Not specified	Not specified	GABA enhances thermogenesis and lipid metabolism, reduces lipogenesis, and supports the function of liver and adipose tissue.	Weera-watanakorn *et al* (2023)
	Reduces body weight and inflammation; increases thermogenic gene expression and abundance of *Akkermansia* and *Bacteroidetes*; reduces *Firmicutes*	Obese mice (HFD-induced)	Not specified	Not specified	GABA promotes beiging of adipose tissue by modulating gut microbiota and reduces the risk of metabolic disorders.	Ma *et al* (2023)

Table 2 (cont)

Compound	Metabolic effect	Experimental model	Effective dose	Treatment duration	Anti-obesity mechanism	Reference
	Improves insulin tolerance and liver glycogen storage; reduces blood glucose, lipid levels, and HbA1c; increases glucose infusion rate (GIR) and expression of *FoxO1, Irs2, Akt2,* and *Pepck*	Type 2 diabetic rats (parents and offspring)	Not specified	6 months (parents), 4 months (offspring)	GABA improves liver insulin signaling and gluconeogenesis pathways to enhance glucose metabolism.	Hosseini Dastgerdi *et al* (2021)
Tocopherol	Reduces body weight and pro-inflammatory gene expression (*IL-1β, IL-6, iNOS*)	*in vivo* (C57BL/6J mice); *in vitro* (3T3-L1, RAW264.7)	800 mg/kg diet	16 weeks	Tocopherol decreases inflammation *in vitro*, though its effects on adipose tissue inflammation *in vivo* are unclear.	Kiyose *et al* (2021)
	Reduces fat accumulation and adipocyte hypertrophy; increases *UCP1* and *PGC-1α* expression	*in vitro* (brown adipocytes); *in vivo* (HFD mice)	Not specified; preincubation and diet supplementation	16 weeks	Tocopherol prevents thermogenic dysfunction by suppressing *ERK1/2* signaling and inflammation.	Tanaka-Yachi *et al* (2022)
	Reduces insulin resistance as indicated by HOMA-IR	Human randomized controlled trial (non-diabetic obese subjects)	800 IU/day	8 weeks	Tocopherol improves insulin sensitivity, aiding glucose regulation.	Marfianti and Miladiyah (2021)

Table 2 (cont)

Compound	Metabolic effect	Experimental model	Effective dose	Treatment duration	Anti-obesity mechanism	Reference
	Reduces reactive oxygen species (ROS); improves insulin signaling; decreases plasma glucose and insulin levels	*in vivo* (hyperthyroid rat model)	Not specified	Not specified	Tocopherol reduces oxidative stress and inhibits activation of the JNK signaling pathway.	Fasciolo *et al* (2022)
Lutein	Reduces lipid accumulation in differentiated 3T3-L1 cells and abdominal adipose tissue through a SIRT1-mediated pathway	*in vivo* and *in vitro* experiments	Male Sprague-Dawley rats, differentiated 3T3-L1 cells	Lutein supplementation (25 mg/kg body weight in rats, 40 μM lutein in 3T3-L1 cells)	Lutein decreases body weight, abdominal fat ratio, and size of large adipocytes in rats fed a high-fat diet; it activates SIRT1 and increases *FoxO1*, *ATGL*, and *HSL* expression while decreasing *SREBP-1*, *FAS*, and *ACC* expression. The combined treatment of lutein and Ex527 suppresses these effects.	Wang *et al* (2021)
	Reduces high-fat diet-induced obesity, fatty liver, and glucose intolerance in C57BL/6J mice	*in vivo* experiment	C57BL/6J mice on a high-fat diet (60% kcal fat)	Lutein (300 and 500 μM), Orlistat (30 mg/kg body weight), combination of lutein and orlistat	Lutein reduces epididymal and abdominal adipose tissue weight, lowers serum cholesterol and LDL cholesterol, prevents increases in triglycerides and liver cholesterol, reduces elevated blood glucose caused by a high-fat diet, and decreases expression of *CEBP-α*, *PPAR-γ*, and *FAS*.	Gopal *et al* (2023)

Table 2 (cont)

Compound	Metabolic effect	Experimental model	Effective dose	Treatment duration	Anti-obesity mechanism	Reference
	Decrease in body fat percentage, preservation of fat-free mass, reduction in visceral fat, total cholesterol, and LDL-cholesterol	Middle-aged obese individuals (45-65 years)	20 mg/day	10 weeks	Lutein improves body composition and lipid profile during calorie restriction.	Hajiza-deh-Shara-fabad *et al* (2021)
	Reduces oxidative stress, inflammation, and apoptosis caused by alcohol exposure, alleviating reproductive damage in male rats	Animal model study	Male rats exposed to excessive alcohol (12 ml/(kg body weight) for 12 weeks	Lutein supplementation (12, 24, 48 mg/(kg body weight)	High-dose lutein supplementation (48 mg/kg body weight per day) increases sperm quality, testosterone levels, and antioxidant markers (*GSH-Px*), reduces malondialdehyde and inflammatory markers (*IL-6, TNF-α*), and downregulates pro-apoptotic biomarkers (*Bax, Cytc, caspase-3*).	Zhang *et al* (2022)
Ferulic acid	Prevents NAFLD and enhances fatty acid oxidation and energy expenditure	*In vivo* (C57BL/6 mice high-fat diet)	100 mg/kg/day	Not specified	Ferulic acid activates *PPARα*, leading to increased fatty acid oxidation and energy expenditure.	Luo *et al* (2022)
	Reduces body weight and improves both glucose and lipid profiles	*In vivo* (C57BL/6J mice high-fat diet)	5 g/kg diet	Not specified	Ferulic acid maintains the self-renewal capacity of embryonic stem cells and adipose-derived mesenchymal stem cells.	Cho and Park (2020)

Table 2 (cont)

Compound	Metabolic effect	Experimental model	Effective dose	Treatment duration	Anti-obesity mechanism	Reference
	Reduces blood lipids and increases antioxidant activity and adiponectin levels	*In vivo* (Sprague-Dawley rats)	50-250 mg/kg; optimal 200 mg/kg	14 weeks	Ferulic acid modulates *HMG-CoA* reductase activity and adiponectin levels, affecting cholesterol metabolism and insulin sensitivity.	Mumtaz Begum and Ramamurthy (2021)
	Suppresses body weight gain, reduces white adipose tissue, blood glucose, hepatic fat, and inflammation (*IL-6, TNF-α*)	*In vivo* (C57BL/6J mice, high-fat diet)	0.5% (w/w) in diet	6 weeks	Ferulic acid provides antioxidant effects, suppresses oxidative stress, inhibits pro-inflammatory cytokines, and improves insulin sensitivity.	Wang *et al* (2018)
	Enhances lipid metabolism and antioxidant capacity	*In vivo* (Piglets)	0.05% and 0.45% diet	Not specified	Ferulic acid induces antioxidant enzyme production and improves lipid profiles.	Wang *et al* (2020)
Phytosterols	Reduces body mass index, waist circumference, total cholesterol, LDL, and blood pressure	Cross-sectional (912 adults)	Daily dietary intake	Not applicable	Phytosterols shows a negative association with metabolic risk parameters, indicating protective effects.	Li *et al* (2018)
	Provides cytoprotective and antioxidant effects	*In vitro* (nerve cells)	Natural content in oils	Not specified	Phytosterols protects cells from death induced by oxidative stress.	Zarrouk *et al* (2019)

Table 2 (cont)

Compound	Metabolic effect	Experimental model	Effective dose	Treatment duration	Anti-obesity mechanism	Reference
Phytic acid	Reduces liver triglycerides with effects dependent on diet and microbiota	*In vivo* (Sprague-Dawley rats)	1.02% sodium phytic acid	12 days	Phytic acid reduces lipogenesis and alters gut microbiota composition, especially when combined with a low-fat diet.	Okazaki and Katayama (2020)
	Reduces lipogenesis, inflammation, and metabolic-associated steatohepatitis	*In vivo* (mice, high-fat diet)	Not specified	Not specified	Phytic acid inhibits the *mTOR-SREBP1* pathway, reducing lipid synthesis.	Xu *et al* (2024)
Polyphenol	Reduces adipogenesis and promotes browning of white adipose tissue	*In vitro* (3T3-L1 cells)	Not specified	Not specified	Polyphenol activates *uncoupling protein 1* (*UCP1*) and *AMP-activated protein kinase (AMPK)*, promoting thermogenesis and energy expenditure.	Pacifici *et al* (2023)
	Reduces body fat and promotes browning	*In vivo* (C57BL/6J mice); *in vitro*	Daily intake	Not specified	Polyphenol activates the *FGF21-PGC1α-UCP1* pathway, enhancing brown fat function.	Tamura *et al* (2020)
	Stimulates browning of adipocytes and lipolysis	*In vitro* (3T3-L1 cells)	Not specified	Not specified	Polyphenol stimulates the *β3-adrenergic receptor/AMPK* pathway, activating *UCP1* and mitochondrial activity.	Kong *et al* (2022)

Table 2 (cont)

Compound	Metabolic effect	Experimental model	Effective dose	Treatment duration	Anti-obesity mechanism	Reference
Phenolics	Reduces adiposity and improves overall metabolism	*In vivo* (C57BL/6J mice, high-fat diet)	50 and 100 mg GAE/ kg	14 weeks	Phenolics increases energy expenditure and reduces inflammation systemically.	Moura *et al* (2021)
Zeaxanthin	Reduces body weight, triglycerides, glucose, total cholesterol, and nitric oxide; increases insulin levels and catalase activity	*in vivo* (male Wistar rats induced by high-fat diet)	Zeaxanthin and exercise (dose not specified)	5 weeks (after 12 weeks of HFD induction)	The combination of zeaxanthin supplementation and exercise more effectively reduces metabolic disturbances caused by a high-fat diet.	Al-thepyani *et al* (2022)
	Promotes browning and mitochondrial biogenesis; reduces lipid accumulation	*in vitro* (3T3-L1 adipocytes)	Zeaxanthin (dose not specified)	Not specified	Zeaxanthin increases expression of browning markers (*Cd137, Tbx1, Sirt1*) and stimulates mitochondrial respiration via the PKA signaling pathway.	Zhao *et al* (2021)
	Reduces body weight, fat mass, adipocyte hypertrophy, and hepatic lipid content; enhances glucose and lipid metabolism	*in vivo* (C57BL6/N mice on high-fat diet)	Zeaxanthin (dose not specified)	Not specified	Zeaxanthin activates β3-adrenergic receptors, promotes thermogenesis in inguinal fat, and modulates gut microbiota composition.	Xie *et al* (2021)

Table 2 (cont)

Compound	Metabolic effect	Experimental model	Effective dose	Treatment duration	Anti-obesity mechanism	Reference
	Reduces fasting blood glucose and improves insulin sensitivity and lipid profile	*in vivo* (HFD-induced obese mice)	Zeaxanthin (dose not specified)	Not specified	Zeaxanthin activates the PI3K/Akt signaling pathway, enhances lipid metabolism, repairs damage in liver and pancreas, and improves microbiota diversity.	Jin *et al* (2024b)

ACC: acetyl-CoA carboxylase; AGEs: advanced glycation end-products; Akt2: RAC-beta serine/threonine-protein kinase gene; AMPK: AMP-activated protein kinase; ATGL: adipose triglyceride lipase; CEBP-α: CCAAT/enhancer-binding protein alpha; Cytc: cytochrome c; ERK1/2: extracellular signal-regulated kinases ½; FAS: fatty acid synthase; FGF21: fibroblast growth factor 21; FoxO1: Forkhead box protein O1; g/kg: grams per kilogram; GABA: gamma-aminobutyric acid; GAE: gallic acid equivalents; GLUT4: glucose transporter type 4; GSH-Px: glutathione peroxidase; HbA1c: glycated hemoglobin A1c; HFD: high-fat diet; HFHFr: high-fat high-fructose; HMG-CoA: 3-hydroxy-3-methyl-glutaryl-coenzyme A; HOMA-IR: homeostatic model assessment for insulin resistance; HSF: high sugar-fat; HSL: hormone-sensitive lipase; IL-1β: interleukin-1 beta; IL-6: interleukin-6; iNOS: inducible nitric oxide synthase; *Irs2*: insulin receptor substrate 2 gene; JNK: c-Jun N-terminal kinase; kcal: kilocalorie; kg: kilogram; LCD: low-calorie diet; LDL: low-calorie diet; mg: milligram; mg/kg: milligrams per kilogram; ml: milliliter; mTORC1: mechanistic target of rapamycin complex 1; NAFLD: Non-alcoholic fatty liver disease; *Pepck*: Phosphoenolpyruvate carboxykinase gene; PI3K/Akt: phosphoinositide 3-kinase / protein kinase B signaling pathway; PGC-1α: peroxisome proliferator-activated receptor gamma coactivator 1-alpha; PKA: protein kinase A; *PPAR*-γ: peroxisome proliferator-activated receptor gamma; PPARα: peroxisome proliferator-activated receptor alpha; RAGE: receptor for advanced glycation end-products; SIRT1: sirtuin 1; SREBP-1: sterol regulatory element-binding protein; TNF-α: tumor necrosis factor-alpha; UCP1: uncoupling protein 1; w/w: weight by weight; μM: micromoles

inflammation and oxidative stress in adipose tissue (Francisqueti-Ferron *et al*, 2021b), while also preventing the development of non-alcoholic fatty liver disease (NAFLD) through anti-inflammatory and antioxidant effects (Francisqueti-Ferron *et al*, 2022).

The anti-obesity effect of γ-oryzanol was also observed in Sprague-Dawley rats fed a high-fat, high-fructose diet, where γ-oryzanol reduced adipocyte hypertrophy and macrophage infiltration by decreasing the M1/M2 macrophage ratio, indicating its ability to mitigate adipose tissue inflammation (Sasiarini *et al*, 2024). Additionally, γ-oryzanol reduced renal inflammation and oxidative stress in HSF-diet rats by suppressing RAGE expression and modulating the AGEs/RAGE pathway, which is linked to obesity-related metabolic complications (Francisqueti-Ferron *et al*, 2021a).

GABA exhibits anti-obesity effects via multiple mechanisms targeting adipose tissue, lipid metabolism, and the endocrine system. In obese C57BL/6J mice fed a high-fat diet (HFD) and in 3T3-L1 adipocytes, GABA reduced body weight, inhibited adipogenesis and lipogenesis, decreased adipocyte size, and enhanced lipolysis and protein kinase A signaling, which triggered browning of white adipose tissue through UCP1 expression (Jin *et al*, 2024a). GABA also reduced leptin levels, hepatic triglycerides, and the expression of lipogenic genes such as *SREBP-1*, *ACC*, and *FAS*. Conversely, it increased the expression of UCP1, PGC-1α, and fatty acid oxidation, supporting thermogenesis and protecting the liver from NAFLD development (Weerawatanakorn *et al*, 2023).

Furthermore, GABA plays a role in modulating gut microbiota, supporting adipose tissue beiging mechanisms, and reducing inflammation and the risk of metabolic disorders. Obese mice given GABA showed increased proportions of beneficial bacteria such as *Akkermansia* and *Bacteroidetes*, and a decrease in *Firmicutes*, which are known to be associated with healthier energy metabolism (Ma *et al*, 2023). In a type 2 diabetic mouse model, GABA improved insulin tolerance, lowered blood glucose,

improved lipid profiles, and enhanced expression of genes involved in insulin signaling and hepatic gluconeogenesis, such as *FoxO1, Irs2*, and *Akt2* (Hosseini Dastgerdi *et al*, 2021). These findings suggest that GABA is not only effective in obesity control but also in improving insulin sensitivity and overall metabolic health.

Tocopherol, the active form of vitamin E, shows multiple metabolic benefits in combating obesity via anti-inflammatory, antioxidant, and insulin-sensitizing mechanisms. In obese animal models (C57BL/6J mice) and cell cultures (3T3-L1, RAW264.7), supplementation with tocopherol at 800 mg/kg diet for 16 weeks reduced body weight and suppressed the expression of proinflammatory genes such as IL-1β, IL-6, and iNOS, although its direct effect on adipose tissue *in vivo* is not fully understood (Kiyose *et al*, 2021). In addition, *in vitro* studies in brown adipocytes and *in vivo* in HFD mice showed that tocopherol could inhibit adipocyte hypertrophy and increase thermogenic gene expression (UCP1, PGC-1α), possibly by inhibiting the ERK1/2 pathway and inflammation (Tanaka-Yachi *et al*, 2022).

In a clinical trial in non-diabetic obese subjects, vitamin E supplementation at 800 IU/day for 8 weeks significantly reduced insulin resistance as measured by HOMA-IR (Marfianti and Miladiyah, 2021). These effects are supported by findings in a hyperthyroid mouse model where tocopherol reduced oxidative stress, improved insulin signaling, and lowered plasma glucose and insulin levels by inhibiting JNK activation (Fasciolo *et al*, 2022). Overall, tocopherol has potential as an adjunct agent in obesity management by targeting inflammation, oxidative stress, and metabolic dysfunction.

Lutein, a carotenoid with strong antioxidant properties, shows anti-obesity potential through modulation of lipid metabolism, inflammation, and oxidative stress (Wang *et al*, 2021). In Sprague-Dawley rats and 3T3-L1 adipocytes, lutein supplementation (25 mg/kg body weight in rats; 40 μM in cell cultures) reduced fat accumulation, abdominal fat ratio, and

large adipocyte size. These effects were mediated by activation of the SIRT1 pathway, enhancing expression of *FoxO1*, *ATGL*, and *HSL*, while suppressing *SREBP-1*, *FAS*, and *ACC*. The use of Ex527, a SIRT1 inhibitor, abolished these effects, confirming the central role of SIRT1 in lutein's mechanism (Wang *et al*, 2021). In C57BL/6J mice fed a high-fat diet, lutein (300-500 μM) significantly reduced epididymal and abdominal fat weight, serum cholesterol and low-density lipoprotein cholesterol (LDL-C) levels, and prevented increases in triglycerides and blood glucose. Lutein also suppressed the expression of adipogenic genes such as *CEBP-α*, *PPAR-γ*, and *FAS* (Gopal *et al*, 2023).

In a randomized controlled trial involving 48 middle-aged obese individuals, supplementation with lutein (20 mg/day) combined with a low-calorie diet for 10 weeks resulted in a significant decrease in body fat percentage and visceral fat, along with improved lipid profile, including a significant reduction in total cholesterol and LDL-cholesterol levels. The lutein group also preserved fat-free mass during calorie restriction compared to placebo, although no significant differences were found in glucose homeostasis parameters or appetite sensations (Hajizadeh-Sharafabad *et al*, 2021). In addition to metabolic effects, a study in male rats with reproductive damage due to chronic alcohol intake showed that lutein (up to 48 mg/kg body weight improved sperm quality and testosterone levels, and reduced oxidative stress and inflammation by increasing glutathione peroxidase (GSH-Px) and reducing IL-6, TNF-α, and expression of apoptotic proteins such as Bax, Cytc, and caspase-3 (Zhang *et al*, 2022). These findings confirm lutein's wide-ranging systemic benefits in mitigating the effects of obesity and oxidative stress-related comorbidities.

Ferulic acid has potential as an anti-obesity and metabolic protective compound through various biological mechanisms. In high-fat-diet-fed C57BL/6 mice, ferulic acid prevented NAFLD by enhancing fatty acid oxidation and energy expenditure via PPARα activation (Luo *et*

al, 2022). The compound also reduced body weight and improved glucose and lipid profiles, potentially through the maintenance of embryonic stem cell (ESC) and adipose-derived mesenchymal stem cell (ADMSC) rejuvenation capacity (Cho and Park, 2020). In Sprague-Dawley rats, ferulic acid reduced blood lipid levels, increased antioxidant status, and adiponectin levels by modulating HMG-CoA reductase enzyme activity (Mumtaz Begum and Ramamurthy, 2021). In a 6-week study on high-fat diet-induced obese C57BL/6J mice, dietary supplementation with ferulic acid (0.5% w/w) significantly reduced body weight gain, white adipose tissue mass, blood glucose levels, hepatic fat accumulation, and inflammatory cytokines (IL-6 and TNF-α), suggesting ferulic acid's potential to suppress obesity and related metabolic syndromes (Wang *et al*, 2018). Additionally, studies in piglets showed that ferulic acid supplementation improved lipid metabolism and antioxidant capacity by inducing antioxidant enzymes and improving lipid profiles (Wang *et al*, 2020).

Phytosterols are known for their metabolic benefits and protective effects against oxidative stress. In a cross-sectional study of 912 adults, dietary phytosterol intake showed an inverse relationship with several metabolic parameters such as body mass index (BMI), waist circumference, total cholesterol, LDL cholesterol, and blood pressure, indicating their potential role in preventing metabolic syndrome (Li *et al*, 2018). *In vitro* research on neuronal cells showed that phytosterols naturally present in vegetable oils have cytoprotective and antioxidant properties, capable of protecting cells from oxidative stress-induced death (Zarrouk *et al*, 2019).

Phytic acid has demonstrated positive effects on lipid metabolism and inflammation. In a study using Sprague-Dawley rats, supplementation with 1.02% sodium phytic acid for 12 days reduced hepatic triglyceride levels, inhibited lipogenesis, and modulated gut microbiota composition, particularly in rats fed a low-fat diet (Okazaki and Katayama, 2020). Moreover, in a high-fat diet-induced mouse model, phytic acid was shown

to reduce lipogenesis, inflammation, and the incidence of metabolic dysfunction-associated steatohepatitis (MASH) through the inhibition of the mTOR–SREBP1 pathway (Xu *et al*, 2024).

Polyphenols play a significant role in regulating adipogenesis and enhancing the metabolic activity of adipose tissue. Several studies have shown that polyphenols can inhibit adipogenesis and induce the browning process in white adipose tissue (WAT), as observed in 3T3-L1 cells through the activation of UCP1 and AMPK (Pacifici *et al*, 2023). Additionally, daily consumption of polyphenols has been proven to reduce body fat and promote browning in C57BL/6J mice and *in vitro* models, mediated via the FGF21–PGC1α–UCP1 pathway (Tamura *et al*, 2020). Another study on 3T3-L1 cells demonstrated that polyphenols stimulate lipolysis and enhance mitochondrial activity via activation of the β3-adrenergic receptor/AMPK pathway and UCP1 (Kong *et al*, 2022).

Phenolic compounds have also been shown to effectively reduce adiposity and improve metabolism in high-fat diet-induced C57BL/6J mice. Administration of phenolics at doses of 50 and 100 mg GAE/kg for 14 weeks resulted in increased energy expenditure and reduced inflammation, contributing to overall improvements in metabolic profiles (Moura *et al*, 2021).

Zeaxanthin, a xanthophyll carotenoid with high antioxidant activity, has shown multiple metabolic benefits in the context of obesity. In an *in vivo* study using male Wistar rats induced with a high-fat diet, a five-week intervention combining zeaxanthin supplementation and physical exercise significantly reduced body weight, triglyceride levels, glucose, total cholesterol, and nitric oxide (NO), while increasing insulin levels and the activity of the antioxidant enzyme catalase. The synergistic effect of zeaxanthin and exercise was more effective than either intervention alone in mitigating high-fat diet-induced metabolic disorders (Al-thepyani *et al*, 2022). Additionally, in a high-fat diet-

induced C57BL/6N mouse model, zeaxanthin reduced body weight, fat mass, adipocyte hypertrophy, and hepatic lipid accumulation while improving glucose and lipid metabolism through β3-adrenergic receptor activation, increased inguinal fat thermogenesis, and modulation of gut microbiota (Zhao *et al*, 2021).

At the cellular level, an *in vitro* study on 3T3-L1 adipocytes showed that zeaxanthin enhances browning and mitochondrial biogenesis, as indicated by increased expression of browning markers such as Cd137, Tbx1, and Sirt1, and stimulation of mitochondrial respiration via the PKA pathway (Xie *et al*, 2021). Another study on diet-induced obese mice demonstrated that zeaxanthin improved lipid profiles and insulin sensitivity, reduced fasting glucose levels, and supported liver and pancreatic function through activation of the PI3K/Akt pathway and increased gut microbiota diversity (Jin *et al*, 2024b). These findings indicate that zeaxanthin not only acts as an antioxidant but also serves as a metabolic modulator working through various molecular pathways. The combined effects of these compounds strengthen the potential of brown rice as a functional food to prevent obesity and related metabolic disorders.

DISCUSSION

The findings from various studies compiled in Tables 1 and 2 indicate that brown rice is a food source rich in bioactive compounds with great potential in promoting health, particularly in the context of obesity prevention and management. These compounds include γ-oryzanol, GABA, tocopherol, lutein, ferulic acid, phytosterols, phytic acid, polyphenols, phenolics, and zeaxanthin, each of which has its own mechanism of action.

Nutritional and bioactive advantages of brown rice

Several studies emphasize that the bioactive compound content in brown rice not only surpasses that of white rice, but can also be enhanced through the process of germination (sprouting). For example, studies by Munarko *et al* (2022) and Ukpong *et al* (2023) showed that germination significantly increases levels of GABA, phenolic compounds, and antioxidant capacity. This process also affects functional characteristics such as viscosity and digestibility, which are important in the formulation of functional food products.

In addition, higher levels of phytosterols such as β-sitosterol in brown rice (Islam *et al*, 2021) have been shown to help reduce cholesterol levels. Carotenoids such as lutein and zeaxanthin, found in the outer layers of rice (Lamberts and Delcour, 2008), also support eye health. These findings reinforce the position of brown rice as a superior functional food ingredient nutritionally compared to white or parboiled rice.

Role of bioactive compounds in anti-obesity mechanisms

The studies summarized in Table 2 highlight the specific biological mechanisms through which the bioactive compounds in brown rice suppress the development of obesity. For instance, γ-oryzanol has been shown to act at the molecular level by activating the PPAR-γ, mTORC1, and GLUT4 pathways, as well as reducing inflammation and oxidative stress in adipose tissue and metabolic organs such as the liver and kidneys (Francisqueti-Ferron *et al*, 2021b; Francisqueti-Ferron *et al*, 2022; Sasiarini *et al*, 2024).

Likewise, GABA plays an important role in the browning of adipose tissue, reducing lipogenesis, and increasing lipolysis through upregulation of genes such as UCP1 and PGC-1α. GABA has also shown a positive impact on gut microbiota profiles, which are known to contribute to energy metabolism and the body's inflammatory status (Ma *et al*, 2023).

Clinical implications and functional food product development

Collectively, these results affirm that the consumption of brown rice - particularly when germinated - may provide protective effects against various components of metabolic syndrome, including obesity, insulin resistance, and systemic inflammation. Given the current high prevalence of obesity and metabolic diseases, brown rice holds potential for further development as a scientifically backed dietary intervention.

Furthermore, variations in bioactive effects based on processing methods and rice varieties (Wu *et al*, 2022; Ma *et al*, 2022) suggest that the formulation of functional food products from brown rice should be carefully tailored, taking into account food technology, consumer preferences, and the desired nutraceutical content.

In conclusion, brown rice is a functional food enriched with a variety of bioactive compounds, including γ-oryzanol, GABA, tocopherol, lutein, ferulic acid, phytosterols, phytic acid, polyphenols, phenolics, and zeaxanthin; all of which contribute to its strong antioxidant properties and its ability to counteract oxidative stress. Scientific evidence has demonstrated that these compounds not only enhance the nutritional and functional value of brown rice -especially when optimized through processes like germination - but also exert significant anti-obesity effects through mechanisms such as inhibition of lipogenesis, stimulation of lipolysis, reduction of inflammation in adipose tissue, and promotion of thermogenesis via the activation of brown adipose tissue–related genes (*eg*, UCP1 and PGC-1α). Moreover, these bioactives support insulin sensitivity, mitigate oxidative damage, and protect vital organs from obesity-related metabolic complications. Taken together, these findings highlight the potential of brown rice as a scientifically grounded, health-promoting dietary intervention for the prevention and management of obesity and related metabolic disorders.

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CONFLICT OF INTEREST DISCLOSURE

All authors declare that they have no conflict of interest related to this article.

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