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Modulation of Adipose Tissue Inflammation by Flavonoids: Implications for Obesity-Induced Insulin Resistance

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ABSTRACT

Obesity-induced chronic low-grade inflammation of adipose tissue is a critical factor in the development of insulin resistance and metabolic syndrome. Adipose tissue inflammation is characterized by immune cell infiltration, particularly macrophages, and the secretion of pro-inflammatory cytokines such as TNF-α, IL-6, and MCP-1, which interfere with insulin signaling pathways. Flavonoids, a diverse group of polyphenolic compounds found in various fruits, vegetables, and plant-based foods, have gained significant attention for their anti-inflammatory and antioxidant properties. This review explores the mechanistic role of flavonoids in modulating adipose tissue inflammation and their therapeutic potential in improving insulin sensitivity in obese individuals. We highlight the molecular pathways influenced by flavonoids, including NF-κB, JNK, MAPKs, and AMPK signaling, and discuss their effects on macrophage polarization, adipokine regulation, oxidative stress, and insulin signaling. Evidence from in vitro studies, animal models, and clinical trials is presented to support the beneficial impact of flavonoids such as quercetin, epigallocatechin gallate (EGCG), luteolin, and apigenin. Despite promising preclinical data, challenges such as low bioavailability and interindividual variability in response remain to be addressed. Future research should focus on optimizing flavonoid formulations and identifying synergistic combinations to maximize their efficacy in metabolic disease prevention and management.

Keywords: Flavonoids; Adipose tissue inflammation; Insulin resistance; Obesity; Cytokines; Macrophage polarization; NF-κB; AMPK; Oxidative stress

INTRODUCTION

Obesity has emerged as a critical global health issue, affecting millions of individuals across both developed and developing countries[1]. It is strongly associated with a range of metabolic complications, including insulin resistance, type 2 diabetes mellitus (T2DM), cardiovascular diseases, non-alcoholic fatty liver disease (NAFLD), and various forms of cancer[2–4]. One of the most significant pathophysiological links between obesity and these metabolic disorders, particularly insulin resistance, is the presence of chronic low-grade inflammation in adipose tissue. This inflammatory state disrupts normal metabolic signaling and contributes to systemic insulin resistance[3, 5, 6]. In the context of obesity, the adipose tissue undergoes significant remodelling, characterized by an increase in adipocyte size (hypertrophy) and often, an inadequate supply of oxygen (hypoxia). These changes result in cellular stress and the release of various chemokines and cytokines, which, in turn, attract immune cells into the adipose tissue[6–8]. Among these, pro-inflammatory M1 macrophages are predominantly recruited and activated, leading to a sustained inflammatory response. These macrophages, along with hypertrophic adipocytes, secrete pro-inflammatory mediators such as tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and monocyte chemoattractant protein-1 (MCP-1). These factors disrupt insulin signaling pathways by inducing serine phosphorylation of insulin receptor substrate-1 (IRS-1), thereby impairing glucose uptake and utilization, which culminates in insulin resistance[9, 10]. Given the central role of inflammation and oxidative stress in obesity-induced insulin resistance, there is growing interest in natural compounds with anti-inflammatory and antioxidant properties[11, 12]. Among these, flavonoids—a diverse group of polyphenolic

compounds found abundantly in fruits, vegetables, tea, cocoa, and wine—have attracted considerable attention. Flavonoids possess a wide range of biological activities, including the ability to scavenge reactive oxygen species (ROS), inhibit pro-inflammatory gene expression, and modulate key signaling pathways involved in metabolism and immune responses[13–15]. Several experimental and clinical studies have demonstrated the beneficial effects of flavonoids on metabolic health. Flavonoids such as quercetin, epigallocatechin gallate (EGCG), hesperidin, and naringenin have been shown to reduce macrophage infiltration in adipose tissue, downregulate inflammatory cytokines, and improve insulin sensitivity[16–21]. Mechanistically, these compounds act through various molecular targets, including nuclear factor-kappa B (NF-κB), AMP-activated protein kinase (AMPK), and peroxisome proliferator-activated receptors (PPARs), which are integral to the regulation of inflammation, oxidative stress, and glucose homeostasis[22, 23]. This review aims to provide a comprehensive examination of the current evidence regarding the modulatory effects of flavonoids on adipose tissue inflammation. It explores how these naturally occurring bioactive compounds can potentially serve as therapeutic agents for the prevention and management of obesity-induced insulin resistance. By targeting the inflammatory pathways in adipose tissue, flavonoids may offer a promising adjunctive approach to current pharmacological and lifestyle interventions for obesity and its associated metabolic disorders.

Adipose Tissue Inflammation in Obesity

Pathophysiological Changes: Obesity is characterized by the excessive accumulation of adipose tissue, which triggers significant pathophysiological changes, particularly in adipocyte function and immune cell recruitment[5, 6]. As adipocytes expand in response to increased lipid storage, they undergo stress and begin to secrete a range of chemokines, notably monocyte chemoattractant protein-1 (MCP-1). MCP-1 serves as a potent signal that attracts circulating monocytes into the adipose tissue, where they differentiate into macrophages[24–26]. These recruited macrophages predominantly adopt a pro-inflammatory M1 phenotype, distinguished by their production of cytokines such as tumor necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6). The presence of these cytokines promotes a chronic low-grade inflammatory environment within the adipose tissue[8]. One of the critical consequences of this inflammation is the disruption of insulin receptor signaling. TNF-α and IL-6 interfere with insulin action by inducing serine phosphorylation of insulin receptor substrate (IRS) proteins, particularly IRS-1, which impairs downstream insulin signaling and contributes to systemic insulin resistance—a key feature of obesity-associated metabolic syndrome[8].

Inflammatory Signaling Pathways: The chronic inflammatory state observed in obesity is largely mediated by several key intracellular signaling pathways within adipose tissue[27]. Among these, the nuclear factor kappa B (NF-κB) pathway plays a central role. Upon activation by inflammatory stimuli, NF-κB translocate to the nucleus and initiates the transcription of a wide range of pro-inflammatory genes, including those encoding TNF-α, IL-6, and other chemokines. In parallel, the c-Jun N-terminal kinase (JNK) pathway is activated by various stress signals, including free fatty acids and cytokines[28]. JNK phosphorylates IRS-1 on serine residues, further inhibiting insulin signaling and exacerbating insulin resistance. Another critical pathway is the mitogen-activated protein kinase (MAPK) pathway, which enhances the production of cytokines and perpetuates inflammation. Additionally, activation of the NOD-like receptor protein 3 (NLRP3) inflammasome within adipose macrophages results in the maturation and secretion of interleukin-1β (IL-1β), a potent pro-inflammatory cytokine. This inflammasome-driven response is a key component of metabolic inflammation and further links innate immunity to metabolic dysfunction in obesity[29, 30].

Flavonoids: Classification and Sources

Flavonoids, a diverse group of polyphenolic compounds naturally occurring in plants, are classified into several distinct subclasses based on their chemical structure and functional groups[12, 31, 32]. Each subclass has unique biological activities and is predominantly found in specific types of fruits, vegetables, and beverages. Flavonols, such as quercetin and kaempferol, are commonly found in onions, apples, and leafy vegetables[16, 33]. These compounds are widely recognized for their potent antioxidant and anti-inflammatory properties, which contribute to their role in disease prevention, particularly in cardiovascular and metabolic disorders. Flavones, another subclass, include apigenin and luteolin, found primarily in parsley, celery, and various herbs[34–36]. These compounds have shown promising anti-carcinogenic and anti-inflammatory effects, making them subjects of interest in cancer and chronic inflammation research.

Flavanones, including hesperidin and naringenin, are abundant in citrus fruits like oranges and grapefruits[19–21]. These flavonoids are known for their antioxidant and lipid-lowering properties, and they have demonstrated potential in improving cardiovascular health and metabolic function. Flavanols, such as epigallocatechin gallate (EGCG) and catechins, are richly present in green tea and cocoa[17, 37, 38]. These compounds exhibit strong antioxidant activity and have been linked to improved brain function, fat metabolism, and a reduced risk of heart disease. Furthermore, anthocyanins, which include cyanidin and delphinidin, are responsible for the red, purple, and blue pigments in berries such as blueberries, blackberries, and raspberries. These flavonoids possess significant free radical-scavenging abilities and have shown potential in enhancing cognitive function and reducing inflammation in chronic diseases.

Isoflavones, primarily found in soy products, include genistein and daidzein. These compounds are unique due to their phytoestrogenic properties, allowing them to modulate estrogen receptors and influence hormone-related processes in the human body[39, 40]. Isoflavones have gained attention for their potential in managing menopausal symptoms, preventing hormone-related cancers, and improving bone health. Collectively, flavonoids exert a broad spectrum of beneficial effects including anti-inflammatory, antioxidant, and insulin-sensitizing activities. These properties make them valuable in the prevention and management of numerous chronic conditions such as diabetes, obesity, cardiovascular diseases, and certain types of cancers. Regular dietary intake of flavonoid-rich foods is therefore encouraged to support overall health and mitigate disease risk.

Mechanisms of Flavonoid Action on Adipose Tissue Inflammation

Suppression of Pro-Inflammatory Cytokine: Flavonoids play a significant role in suppressing pro-inflammatory cytokines through the inhibition of key signaling pathways such as nuclear factor-kappa B (NF-κB) and c-Jun N-terminal kinase (JNK)[41–43]. These pathways are crucial for the transcription of inflammatory mediators, including tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and monocyte chemoattractant protein-1 (MCP-1), particularly in adipocytes and macrophages. By downregulating these pathways, flavonoids reduce the expression and release of these cytokines. For instance, quercetin, a widely studied flavonoid, has demonstrated the ability to suppress macrophage activation and inhibit the production of pro-inflammatory cytokines, thereby contributing to reduced inflammation and improved metabolic health.

Modulation of Macrophage Polarization: Flavonoids influence macrophage polarization by shifting the balance from the M1 pro-inflammatory phenotype toward the M2 anti-inflammatory phenotype. This polarization switch is essential in reducing chronic inflammation and enhancing tissue repair mechanisms. Epigallocatechin gallate (EGCG), a potent flavonoid found in green tea, is known to promote the expression of M2-associated markers such as arginase-1 (Arg1) and interleukin-10 (IL-10)[17, 37]. This modulation not only suppresses inflammation but also improves insulin sensitivity and fosters an anti-inflammatory microenvironment in adipose tissues. The shift toward M2 macrophages under the influence of flavonoids highlights their therapeutic potential in managing metabolic disorders such as obesity and type 2 diabetes.

Antioxidant Activity and Reduction of Oxidative Stress: Flavonoids exhibit powerful antioxidant properties that contribute to the reduction of oxidative stress, a key contributor to insulin resistance and metabolic dysfunction[44]. These compounds neutralize reactive oxygen species (ROS), which are harmful byproducts of cellular metabolism that can damage proteins, lipids, and DNA[45]. Moreover, flavonoids activate the nuclear factor erythroid 2–related factor 2 (Nrf2) signaling pathway, which enhances the expression of endogenous antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx). By boosting the body's antioxidant defense system and minimizing ROS levels, flavonoids protect tissues from oxidative damage and improve insulin signaling pathways, thereby supporting metabolic homeostasis[9].

Improvement of Insulin Signaling: Flavonoids contribute to the enhancement of insulin signaling by mitigating inflammation and oxidative stress, which are known disruptors of insulin receptor function[29, 46]. These compounds help in restoring the normal activity of the insulin receptor and the phosphorylation of insulin receptor substrates 1 and 2 (IRS-1/2), which are critical for the downstream signaling cascade. Furthermore, flavonoids promote the translocation of glucose transporter type 4 (GLUT4) to the cell membrane, facilitating efficient glucose uptake in muscle and adipose tissues. By improving these key aspects of insulin signaling, flavonoids aid in maintaining glucose homeostasis and preventing insulin resistance, especially in metabolic disease contexts.

Regulation of Adipokine Secretion: Flavonoids also regulate the secretion of adipokines—hormones secreted by adipose tissue that influence metabolic processes[47]. They enhance the production of adiponectin, a beneficial adipokine that improves insulin sensitivity, has anti-inflammatory effects, and supports lipid metabolism. Simultaneously, flavonoids inhibit the secretion of leptin and resistin, which are often elevated in obesity and associated with insulin resistance and inflammation. This balanced modulation of adipokines contributes to improved metabolic outcomes, including better insulin responsiveness and lipid homeostasis[47]. Through these regulatory effects on adipokine secretion, flavonoids offer promising therapeutic benefits in addressing obesity-related metabolic dysfunctions and promoting overall endocrine balance.

Challenges and Future Directions

Bioavailability Issues: Flavonoids are known to undergo extensive metabolism in the human body, which often leads to low systemic availability and limits their therapeutic potential. This bioavailability challenge has prompted researchers to explore various strategies to enhance flavonoid absorption and efficacy. Approaches such as nano formulations, co-administration with other polyphenols, and the development of synthetic analogs have shown promise in improving the stability and delivery of flavonoids, thereby potentially increasing their bioactive concentrations in the body.

Interindividual Variability: The metabolism and efficacy of flavonoids can vary significantly among individuals due to several factors. Genetic polymorphisms can affect enzymes involved in flavonoid metabolism, while variations in gut microbiota composition influence the biotransformation and absorption of these compounds.

Additionally, individual dietary habits play a crucial role in determining the extent to which flavonoids are absorbed and utilized, highlighting the need for personalized approaches in flavonoid-based interventions.

Need for Long-term Clinical Studies: Despite promising findings from in vitro and animal studies, there remains a significant gap in long-term human clinical data on flavonoid supplementation. More randomized controlled trials using standardized flavonoid preparations are essential to establish effective dosing regimens and to thoroughly assess the long-term safety profiles of these compounds. Such studies will provide a more robust foundation for integrating flavonoids into therapeutic and preventive health strategies.

CONCLUSION

Flavonoids offer a promising dietary and therapeutic approach for modulating adipose tissue inflammation and improving insulin resistance in obesity. Through their multifaceted actions—suppressing pro-inflammatory cytokines, enhancing antioxidant defense, modulating immune cell polarization, and restoring insulin signaling—flavonoids contribute to metabolic homeostasis. Continued research into optimized delivery systems, bioavailability enhancement, and well-designed clinical trials will pave the way for the integration of flavonoids into strategies for managing metabolic diseases.

REFERENCES

1. Alum, E.U.: Metabolic memory in obesity: Can early-life interventions reverse lifelong risks? Obesity Medicine. 55, 100610 (2025). https://doi.org/10.1016/j.obmed.2025.100610
2. Powell-Wiley, T.M., Poirier, C.P., Burke, V.C.L.E., Després, J.-P., Gordon-Larsen, P., Lavie, C.J., Lear, S.A., Ndumele, C.E., Neeland, I.J., Sanders, P., St-Onge, M.-P.: Obesity and Cardiovascular Disease. Circulation. 143, e984–e1010 (2021). https://doi.org/10.1161/CIR.0000000000000973
3. Aloo, S.O., Barathikannan, K., Oh, D.-H.: Polyphenol-rich fermented hempseed ethanol extracts improve obesity, oxidative stress, and neural health in high-glucose diet-induced *Caenorhabditis elegans*. Food Chemistry: X. 21, 101233 (2024). https://doi.org/10.1016/j.fochx.2024.101233
4. Alum, E.U.: Optimizing patient education for sustainable self-management in type 2 diabetes. Discov Public Health. 22, 44 (2025). https://doi.org/10.1186/s12982-025-00445-5
5. Achari, A.E., Jain, S.K.: Adiponectin, a Therapeutic Target for Obesity, Diabetes, and Endothelial Dysfunction. Int J Mol Sci. 18, 1321 (2017). https://doi.org/10.3390/ijms18061321
6. Basu, T., Selman, A., Reddy, A.P., Reddy, P.H.: Current Status of Obesity: Protective Role of Catechins. Antioxidants (Basel). 12, 474 (2023). https://doi.org/10.3390/antiox12020474
7. Ashour, M.M., Mabrouk, M., Aboelnasr, M.A., Beherei, H.H., Tohamy, K.M., Das, D.B.: Anti-Obesity Drug Delivery Systems: Recent Progress and Challenges. Pharmaceutics. 15, 2635 (2023). https://doi.org/10.3390/pharmaceutics15112635
8. Uti, D.E., Atangwho, I.J., Omang, W.A., Alum, E.U., Obeten, U.N., Udeozor, P.A., Agada, S.A., Bawa, I., Ogbu, C.O.: Cytokines as key players in obesity low grade inflammation and related complications. Obesity Medicine. 54, 100585 (2025). https://doi.org/10.1016/j.obmed.2025.100585
9. Udeozor, P.A., Ibiam, U.A., Uti, D.E., Umoru, G.U., Onwe, E.N., Mbonu, F.O., Omang, W.A., Ijoganu, S.I., Anaga, C.O., Mbah, J.O., Nwadum, S.K.: Antioxidant and Anti-Anemic Effects of Ethanol Leaf Extracts of Mucuna poggei and Telfairia occidentalis in Phenyl-Hydrazine-Induced Anemia in Wistar Albino Rats. Ibnosina Journal of Medicine and Biomedical Sciences. 14, 116–126 (2022). https://doi.org/10.1055/s-0042-1756684
10. Huang, P., Fan, X., Yu, H., Zhang, K., Li, H., Wang, Y., Xue, F.: Glucose metabolic reprogramming and its therapeutic potential in obesity-associated endometrial cancer. Journal of Translational Medicine. 21, 94 (2023). https://doi.org/10.1186/s12967-022-03851-4
11. Zheng, X., Zhang, X., Zeng, F.: Biological Functions and Health Benefits of Flavonoids in Fruits and Vegetables: A Contemporary Review. Foods. 14, 155 (2025). https://doi.org/10.3390/foods14020155
12. Zhou, M., Konigsberg, W.H., Hao, C., Pan, Y., Sun, J., Wang, X.: Bioactivity and mechanisms of flavonoids in decreasing insulin resistance. J Enzyme Inhib Med Chem. 38, 2199168. https://doi.org/10.1080/14756366.2023.2199168
13. Ahn-Jarvis, J.H., Parihar, A., Doseff, A.I.: Dietary Flavonoids for Immunoregulation and Cancer: Food Design for Targeting Disease. Antioxidants. 8, 202 (2019). https://doi.org/10.3390/antiox8070202
14. AL-Ishaq, R.K., Abotaleb, M., Kubatka, P., Kajo, K., Büsselberg, D.: Flavonoids and Their Anti-Diabetic Effects: Cellular Mechanisms and Effects to Improve Blood Sugar Levels. Biomolecules. 9, 430 (2019). https://doi.org/10.3390/biom9090430
15. Alum, E.U.: Role of phytochemicals in cardiovascular disease management: Insights into mechanisms, efficacy, and clinical application. Phytomedicine Plus. 5, 100695 (2025). https://doi.org/10.1016/j.phyplu.2024.100695
16. Alharbi, H.O.A., Alshebremi, M., Babiker, A.Y., Rahmani, A.H.: The Role of Quercetin, a Flavonoid in the Management of Pathogenesis Through Regulation of Oxidative Stress, Inflammation, and Biological Activities. Biomolecules. 15, 151 (2025). https://doi.org/10.3390/biom15010151

17. Andreu Fernández, V., Almeida Toledano, L., Pizarro Lozano, N., Navarro Tapia, E., Gómez Roig, M.D., De la Torre Fornell, R., García Algar, Ó.: Bioavailability of Epigallocatechin Gallate Administered with Different Nutritional Strategies in Healthy Volunteers. Antioxidants (Basel). 9, 440 (2020). https://doi.org/10.3390/antiox9050440
18. Mokra, D., Joskova, M., Mokry, J.: Therapeutic Effects of Green Tea Polyphenol (–)-Epigallocatechin-3-Gallate (EGCG) in Relation to Molecular Pathways Controlling Inflammation, Oxidative Stress, and Apoptosis. Int J Mol Sci. 24, 340 (2022). https://doi.org/10.3390/ijms24010340
19. Nouri, Z., Fakhri, S., El-Senduny, F.F., Sanadgol, N., Abd-ElGhani, G.E., Farzaei, M.H., Chen, J.-T.: On the Neuroprotective Effects of Naringenin: Pharmacological Targets, Signaling Pathways, Molecular Mechanisms, and Clinical Perspective. Biomolecules. 9, 690 (2019). https://doi.org/10.3390/biom9110690
20. Vásquez-Reyes, S., Bernal-Gámez, M., Domínguez-Chávez, J., Mondragón-Vásquez, K., Sánchez-Tapia, M., Ordaz, G., Granados-Portillo, O., Coutiño-Hernández, D., Barrera-Gómez, P., Torres, N., Tovar, A.R.: The Effects of Novel Co-Amorphous Naringenin and Fisetin Compounds on a Diet-Induced Obesity Murine Model. Nutrients. 16, 4425 (2024). https://doi.org/10.3390/nu16244425
21. Zhu, Y., Guo, X., Li, S., Wu, Y., Zhu, F., Qin, C., Zhang, Q., Yang, Y.: Naringenin ameliorates amyloid-β pathology and neuroinflammation in Alzheimer's disease. Commun Biol. 7, 912 (2024). https://doi.org/10.1038/s42003-024-06615-6
22. Christofides, A., Konstantinidou, E., Jani, C., Boussiotis, V.A.: The role of Peroxisome Proliferator-Activated Receptors (PPAR) in immune responses. Metabolism. 114, 154338 (2021). https://doi.org/10.1016/j.metabol.2020.154338
23. Li, Y., Pan, Y., Zhao, X., Wu, S., Li, F., Wang, Y., Liu, B., Zhang, Y., Gao, X., Wang, Y., Zhou, H.: Peroxisome proliferator-activated receptors: A key link between lipid metabolism and cancer progression. Clinical Nutrition. 43, 332–345 (2024). https://doi.org/10.1016/j.clnu.2023.12.005
24. Abdillah, A.M., Yun, J.W.: Capsaicin induces ATP-dependent thermogenesis via the activation of TRPV1/β3-AR/α1-AR in 3T3-L1 adipocytes and mouse model. Archives of Biochemistry and Biophysics. 755, 109975 (2024). https://doi.org/10.1016/j.abb.2024.109975
25. Colson, C., Batrow, P.-L., Gautier, N., Rochet, N., Ailhaud, G., Peiretti, F., Amri, E.-Z.: The Rosmarinus Bioactive Compound Carnosic Acid Is a Novel PPAR Antagonist That Inhibits the Browning of White Adipocytes. Cells. 9, 2433 (2020). https://doi.org/10.3390/cells9112433
26. Li, Z., Zhang, Z., Ke, L., Sun, Y., Li, W., Feng, X., Zhu, W., Chen, S.: Resveratrol promotes white adipocytes browning and improves metabolic disorders in Sirt1-dependent manner in mice. FASEB J. 34, 4527–4539 (2020). https://doi.org/10.1096/fj.201902222R
27. Kawai, T., Autieri, M.V., Scalia, R.: Adipose tissue inflammation and metabolic dysfunction in obesity. Am J Physiol Cell Physiol. 320, C375–C391 (2021). https://doi.org/10.1152/ajpcell.00379.2020
28. Yung, J.H.M., Giacca, A.: Role of c-Jun N-terminal Kinase (JNK) in Obesity and Type 2 Diabetes. Cells. 9, 706 (2020). https://doi.org/10.3390/cells9030706
29. Feng, J., Lu, S., Ou, B., Liu, Q., Dai, J., Ji, C., Zhou, H., Huang, H., Ma, Y.: The Role of JNk Signaling Pathway in Obesity-Driven Insulin Resistance. DMSO. Volume 13, 1399–1406 (2020). https://doi.org/10.2147/DMSO.S236127
30. Min, R.W.M., Aung, F.W.M., Liu, B., Arya, A., Win, S.: Mechanism and Therapeutic Targets of c-Jun-N-Terminal Kinases Activation in Nonalcoholic Fatty Liver Disease. Biomedicines. 10, 2035 (2022). https://doi.org/10.3390/biomedicines10082035
31. Ziqubu, K., Mazibuko-Mbeje, S.E., Dludla, P.V.: Regulation of adipokine and batokine secretion by dietary flavonoids, as a prospective therapeutic approach for obesity and its metabolic complications. Biochimie. 230, 95–113 (2025). https://doi.org/10.1016/j.biochi.2024.11.007
32. Alum, E.U., Ugwu, O.P.C.: Beyond Nutrients: Exploring the Potential of Phytochemicals for Human Health. IAA JAS. 10, 1–7 (2023). https://doi.org/10.59298/IAAJAS/2023/4.1.3211
33. Chen, A.Y., Chen, Y.C.: A review of the dietary flavonoid, kaempferol on human health and cancer chemoprevention. Food Chem. 138, 2099–2107 (2013). https://doi.org/10.1016/j.foodchem.2012.11.139
34. Allemailem, K.S., Almatroudi, A., Alharbi, H.O.A., AlSuhaymi, N., Alsugoor, M.H., Aldakheel, F.M., Khan, A.A., Rahmani, A.H.: Apigenin: A Bioflavonoid with a Promising Role in Disease Prevention and Treatment. Biomedicines. 12, 1353 (2024). https://doi.org/10.3390/biomedicines12061353
35. Naponelli, V., Rocchetti, M.T., Mangieri, D.: Apigenin: Molecular Mechanisms and Therapeutic Potential against Cancer Spreading. International Journal of Molecular Sciences. 25, 5569 (2024). https://doi.org/10.3390/ijms25105569
36. Salehi, B., Venditti, A., Sharifi-Rad, M., Kręgiel, D., Sharifi-Rad, J., Durazzo, A., Lucarini, M., Santini, A., Souto, E.B., Novellino, E., Antolak, H., Azzini, E., Setzer, W.N., Martins, N.: The Therapeutic Potential of Apigenin. Int J Mol Sci. 20, 1305 (2019). https://doi.org/10.3390/ijms20061305

37. James, A., Wang, K., Wang, Y.: Therapeutic Activity of Green Tea Epigallocatechin-3-Gallate on Metabolic Diseases and Non-Alcoholic Fatty Liver Diseases: The Current Updates. Nutrients. 15, 3022 (2023). https://doi.org/10.3390/nu15133022
38. Legeay, S., Rodier, M., Fillon, L., Faure, S., Clere, N.: Epigallocatechin Gallate: A Review of Its Beneficial Properties to Prevent Metabolic Syndrome. Nutrients. 7, 5443–5468 (2015). https://doi.org/10.3390/nu7075230
39. de la Parra, C., Castillo-Pichardo, L., Cruz-Collazo, A., Cubano, L., Redis, R., Calin, G.A., Dharmawardhane, S.: Soy Isoflavone Genistein-Mediated Downregulation of miR-155 Contributes to the Anticancer Effects of Genistein. Nutr Cancer. 68, 154–164 (2016). https://doi.org/10.1080/01635581.2016.1115104
40. Sharifi-Rad, J., Quispe, C., Imran, M., Rauf, A., Nadeem, M., Gondal, T.A., Ahmad, B., Atif, M., Mubarak, M.S., Sytar, O., Zhilina, O.M., Garsiya, E.R., Smeriglio, A., Trombetta, D., Pons, D.G., Martorell, M., Cardoso, S.M., Razis, A.F.A., Sunusi, U., Kamal, R.M., Rotariu, L.S., Butnariu, M., Docea, A.O., Calina, D.: Genistein: An Integrative Overview of Its Mode of Action, Pharmacological Properties, and Health Benefits. Oxidative Medicine and Cellular Longevity. 2021, 3268136 (2021). https://doi.org/10.1155/2021/3268136
41. Cao, H.: Adipocytokines in Obesity and Metabolic Disease. J Endocrinol. 220, T47–T59 (2014). https://doi.org/10.1530/JOE-13-0339
42. Naiyila, X., Li, J., Huang, Y., Chen, B., Zhu, M., Li, J., Chen, Z., Yang, L., Ai, J., Wei, Q., Liu, L., Cao, D.: A Novel Insight into the Immune-Related Interaction of Inflammatory Cytokines in Benign Prostatic Hyperplasia. Journal of Clinical Medicine. 12, 1821 (2023). https://doi.org/10.3390/jcm12051821
43. Shi, C., Zhu, L., Chen, X., Gu, N., Chen, L., Zhu, L., Yang, L., Pang, L., Guo, X., Ji, C., Zhang, C.: IL-6 and TNF-α Induced Obesity-Related Inflammatory Response Through Transcriptional Regulation of miR-146b. J Interferon Cytokine Res. 34, 342–348 (2014). https://doi.org/10.1089/jir.2013.0078
44. Alum, E.U., Nwuruku, A.O. and Edwin, N. Targeting oxidative stress in cancer management: The role of antioxidant phytochemicals. KJHS. 4, 1–10 (2024). https://doi.org/10.59568/KJHS-2024-4-2-01
45. Zhou, M., Konigsberg, W.H., Hao, C., Pan, Y., Sun, J., Wang, X.: Bioactivity and mechanisms of flavonoids in decreasing insulin resistance. J Enzyme Inhib Med Chem. 38, 2199168. https://doi.org/10.1080/14756366.2023.2199168
46. Martínez Báez, A., Ayala, G., Pedroza-Saavedra, A., González-Sánchez, H.M., Chihu Amparan, L.: Phosphorylation Codes in IRS-1 and IRS-2 Are Associated with the Activation/Inhibition of Insulin Canonical Signaling Pathways. Current Issues in Molecular Biology. 46, 634–649 (2024). https://doi.org/10.3390/cimb46010041
47. Uti, D.E., Atangwho, I.J., Alum, E.U., Egba, S.I., Ugwu, O.P.-C., Ikechukwu, G.C.: Natural Antidiabetic Agents: Current Evidence and Development Pathways from Medicinal Plants to Clinical use. Natural Product Communications. 20, 1934578X251323393 (2025). https://doi.org/10.1177/1934578X251323393

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