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# Green Nanotechnology in the Development of Antioxidant-Rich Phytotherapeutics for Metabolic Syndrome

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**ABSTRACT**

Metabolic syndrome (MetS), a multifactorial disorder characterized by obesity, insulin resistance, hypertension, and dyslipidemia, has emerged as a global health challenge. Conventional therapeutic approaches often come with side effects and limited long-term efficacy. Phytotherapeutics, derived from medicinal plants and rich in natural antioxidants, offer a promising alternative for managing MetS. However, issues such as poor bioavailability, instability, and low solubility limit their clinical applicability. Green nanotechnology—a sustainable approach to nanomaterial synthesis using biological resources—offers a breakthrough in enhancing the delivery and efficacy of phytochemicals. This review provides an overview of the pathophysiology of metabolic syndrome and the limitations of traditional therapies. It further explores the integration of green nanotechnology in designing nanoformulations of antioxidant-rich phytotherapeutics. Special attention is given to the mechanisms, recent advancements, types of green nanoparticles, and their synergistic potential in managing oxidative stress and metabolic dysfunction. The article also discusses safety, regulatory challenges, and prospects of green nano-based phytotherapeutics in combating metabolic syndrome.

**Keywords:** Green nanotechnology; Phytotherapeutics; Metabolic syndrome; Antioxidants; Nanoformulations; Oxidative stress; Drug delivery; Herbal medicine

## INTRODUCTION

Metabolic syndrome (MetS) is an increasingly prevalent clinical condition characterized by a constellation of metabolic abnormalities, including abdominal obesity, elevated blood glucose levels, dyslipidemia (notably high triglycerides and low HDL cholesterol), and hypertension[1, 2]. These interconnected disorders not only compromise individual organ systems but synergistically increase the risk for life-threatening conditions such as cardiovascular disease, stroke, and type 2 diabetes mellitus.[3, 4] The global incidence of MetS has surged, correlating strongly with shifts in lifestyle behaviors marked by increased consumption of calorie-dense foods, reduced physical activity, and heightened exposure to environmental stressors[5, 6]. This epidemiological trend is particularly concerning in both developed and developing nations, where urbanization and sedentary habits are becoming more pervasive.

At the core of MetS pathogenesis lie several interwoven biological disruptions, most notably chronic low-grade inflammation, oxidative stress, insulin resistance, and mitochondrial dysfunction[6]. These processes create a vicious cycle where inflammatory cytokines, excessive reactive oxygen species (ROS), and dysfunctional cellular metabolism perpetuate each other, exacerbating metabolic derangements. While the clinical management of MetS often involves addressing each individual component—such as lowering blood pressure or blood sugar—the underlying systemic disturbances necessitate a more holistic therapeutic approach[5]. Additionally, certain populations, due to genetic predisposition or socioeconomic constraints, may face an elevated risk, further underscoring the need for accessible and effective interventions.

Traditional pharmacological therapies, including statins, antihypertensive agents, and oral hypoglycemics, remain foundational in MetS management. However, these medications are not without their drawbacks, often resulting in adverse effects, tolerance development, and financial burdens from prolonged use[7]. Consequently, there has been a surge in interest toward natural, plant-derived therapeutic agents known for their broad-spectrum biological activities, particularly their antioxidant and anti-inflammatory properties. Yet, a major limitation of phytotherapeutics is their poor bioavailability, rapid degradation in the gastrointestinal tract, and metabolic instability, which hinder their clinical utility [8]. In this context, green nanotechnology—leveraging biological systems like plant extracts to fabricate nanoparticles—has emerged as a promising strategy. This eco-friendly approach not only enhances the pharmacokinetic profiles of phytochemicals but also ensures sustainability and biocompatibility, making it a compelling frontier in the treatment of MetS.

## Pathophysiology of Metabolic Syndrome



The development of metabolic syndrome is driven by a multifactorial etiology involving a complex interplay between genetic susceptibility, environmental exposures, and lifestyle choices[9]. A sedentary lifestyle, excessive caloric intake, and diets rich in saturated fats and refined sugars act as primary environmental triggers. These factors converge to promote visceral adiposity, which serves as a central hub for metabolic dysregulation. Genetic polymorphisms related to insulin signaling pathways, lipid metabolism, and inflammatory mediators may predispose individuals to MetS, modulating how they respond to environmental insults[10]. Epigenetic modifications, such as DNA methylation and histone acetylation, also play roles in modulating gene expression patterns associated with metabolic homeostasis, further contributing to the syndrome's complexity[11].

Insulin resistance is a pivotal factor in the pathophysiology of MetS[2, 12, 13]. In this state, insulin's ability to promote glucose uptake in peripheral tissues like muscle and adipose is impaired, leading to hyperglycemia and compensatory hyperinsulinemia. Simultaneously, central obesity induces adipose tissue dysfunction, characterized by an imbalance in the secretion of adipokines such as adiponectin and leptin, and an upregulation of pro-inflammatory cytokines like TNF-α and IL-6 [5, 14]. These molecules promote a systemic inflammatory milieu that exacerbates insulin resistance and contributes to endothelial dysfunction, hypertension, and atherogenesis. Furthermore, hepatic lipid accumulation, or steatosis, often accompanies these changes, aggravating dyslipidemia and amplifying cardiovascular risk[14].

Oxidative stress and mitochondrial dysfunction form additional pathological pillars in MetS[15, 16]. The excessive generation of ROS disrupts cellular integrity by damaging proteins, lipids, and nucleic acids. Mitochondrial dysfunction, either as a cause or consequence of oxidative stress, impairs ATP production and lipid metabolism, contributing further to insulin resistance and metabolic inefficiency[17]. These intertwined mechanisms collectively sustain the pathological state of MetS, making it a self-reinforcing disorder. Consequently, therapeutic strategies aimed at reducing oxidative stress, restoring mitochondrial function, and modulating inflammatory responses have gained traction in MetS research. Antioxidant therapies, particularly those derived from natural sources, are being intensively investigated for their potential to break this pathological cycle.

## Antioxidant-Rich Phytotherapeutics for MetS

Phytochemicals derived from medicinal plants offer a treasure trove of bioactive compounds with potent antioxidant and anti-inflammatory properties[18, 19]. These include polyphenols, flavonoids, alkaloids, terpenoids, and tannins—compounds that play a crucial role in neutralizing ROS and modulating inflammatory signaling pathways. Curcumin, the active compound in turmeric, is known for its ability to suppress nuclear factor-kappa B (NF-κB), a key regulator of inflammation, while also improving lipid profiles and enhancing insulin sensitivity[18]. Similarly, resveratrol, found in grape skins, activates sirtuins and AMP-activated protein kinase (AMPK), which enhances mitochondrial biogenesis and reduces oxidative damage[20]. Quercetin, abundant in onions and apples, and EGCG from green tea have also demonstrated antihypertensive, anti-obesity, and glucose-regulating effects[21, 22].

Despite their demonstrated efficacy in preclinical and some clinical studies, the practical application of these phytochemicals is significantly hindered by pharmacokinetic limitations. Most antioxidant phytochemicals have poor water solubility, are unstable in acidic gastrointestinal environments, and undergo rapid hepatic metabolism, resulting in low systemic bioavailability.

For instance, curcumin exhibits excellent in vitro activity but less than 1% oral bioavailability in vivo. These challenges necessitate the development of novel delivery systems capable of protecting these compounds during digestion and ensuring their efficient absorption and sustained release.

Enhancing their therapeutic index through improved bioavailability remains a key focus of current research.earch.

One promising avenue to overcome these limitations is incorporating phytochemicals into nanocarrier systems, particularly those developed through green nanotechnology[25, 26]. This approach utilizes natural reducing and capping agents often derived from the same plant sources to synthesize biocompatible nanoparticles that encapsulate the active compounds. These nanoformulations improve solubility, enhance stability, prolong circulation time, and enable targeted delivery to tissues affected by metabolic dysfunction. Several studies have shown that nanoparticle-mediated delivery of phytochemicals like curcumin and quercetin results in significantly greater bioavailability and therapeutic outcomes in experimental models of MetS[27]. Thus, integrating nanotechnology with phytotherapy represents a transformative strategy in harnessing the full potential of antioxidant-rich botanicals for the effective management of metabolic syndrome.

## Green Nanotechnology: Principles and Applications

Green nanotechnology is an emerging interdisciplinary field that integrates principles of sustainability with nanoscience to minimize environmental hazards and health risks[28]. It involves the use of eco-friendly methods for the synthesis of nanomaterials, aiming to reduce the dependency on toxic chemicals, high-energy processes, and hazardous waste generation[28]. This approach aligns with the principles of green chemistry and sustainability, promoting safer manufacturing processes that are both efficient and environmentally responsible. By employing biological systems such as plant extracts, algae, or microorganisms, green nanotechnology enables the synthesis of nanoparticles in mild conditions, often at ambient temperatures and pressures, without the need for synthetic stabilizers or toxic reducing agents[25].



In phytomedicine, green nanotechnology plays a transformative role by offering novel drug delivery systems that improve the pharmacokinetic and pharmacodynamic profiles of plant-based bioactive compounds[29]. Phytochemical-rich plant extracts act as reducing and capping agents during nanoparticle synthesis, producing biocompatible and stable formulations. These nanoparticles can encapsulate, protect, and deliver natural therapeutic agents more effectively, enhancing their solubility, bioavailability, and targeted delivery. For instance, gold and silver nanoparticles synthesized using green methods have demonstrated excellent stability, surface functionalization potential, and therapeutic compatibility, particularly in chronic metabolic conditions[29]. This approach ensures that bioactive molecules retain their efficacy while being delivered in a controlled, sustained-release manner to specific tissues or cells. Furthermore, the application of green nanotechnology significantly reduces the environmental impact traditionally associated with nanoparticle synthesis. By avoiding hazardous solvents, surfactants, and other chemical additives, this method prevents the release of toxic by-products and minimizes energy consumption[30]. Nanoparticles such as gold (AuNPs), silver (AgNPs), zinc oxide (ZnO NPs), lipid-based carriers, and polymeric systems synthesized through green methods offer an array of benefits, including improved safety profiles and biodegradability. As the demand for safer, cleaner, and more effective drug delivery systems grows, green nanotechnology holds immense promise for the sustainable development of next-generation therapeutics, especially in natural and plant-derived medicines[31].

## Integration of Green Nanotechnology with Phytotherapeutics

The integration of green nanotechnology with phytotherapeutics marks a significant advancement in enhancing the therapeutic efficacy and delivery of natural products[32]. Phytochemicals, known for their potent antioxidant, anti-inflammatory, and metabolic regulatory effects, often suffer from poor solubility, instability, and low bioavailability in conventional formulations. Green nanotechnology offers an elegant solution by encapsulating these compounds into biocompatible nanoparticles synthesized through environmentally safe methods[32, 33]. This combination not only improves the pharmacological profiles of phytochemicals but also enables targeted and controlled drug release, minimizing systemic toxicity and improving patient outcomes in chronic conditions such as metabolic syndrome (MetS). For example, curcumin, a polyphenol with extensive anti-inflammatory and antioxidant properties, has shown enhanced bioactivity when loaded into green-synthesized gold nanoparticles[34, 35]. These nanoformulations exhibit improved cellular uptake and reactive oxygen species (ROS) scavenging, especially in diabetic models. Similarly, liposomal formulations of resveratrol synthesized using soybean lecithin have demonstrated increased stability and bioavailability, resulting in improved insulin sensitivity in obese mice. Another promising approach involves the use of green ZnO nanoparticles combined with quercetin, a flavonoid with lipid-lowering and anti-inflammatory effects.[20] This formulation has shown superior therapeutic outcomes compared to free quercetin alone, indicating the potential of these systems to significantly enhance disease management through synergistic actions.

These integrated nano-phytotherapeutic systems also protect delicate bioactive compounds from premature degradation in the gastrointestinal tract or bloodstream, allowing them to reach their site of action intact. Moreover, they promote better interaction with cellular membranes, improving drug absorption and therapeutic response. Targeted delivery ensures that the compounds exert their effects where needed, reducing off-target effects and enhancing treatment specificity. As a result, green nanotechnology not only maximizes the efficacy of natural compounds but also opens new pathways for the development of next-generation herbal medicines with optimized therapeutic outcomes in metabolic and other chronic disorders.

## Mechanisms of Action in MetS Management

Green nano-phytotherapeutics function through multiple biochemical and molecular pathways, making them highly effective in managing metabolic syndrome (MetS), a multifactorial condition characterized by insulin resistance, dyslipidemia, hypertension, and obesity[36]. One of the primary mechanisms of action involves potent antioxidant activity. Many phytochemicals used in green nanotechnology are rich in flavonoids, polyphenols, and other antioxidants that neutralize reactive oxygen species (ROS) and reduce oxidative stress. Nanocarriers further amplify this effect by ensuring the sustained and targeted delivery of these compounds, thereby maintaining redox balance within the body, protecting cellular components from oxidative damage, and mitigating disease progression[37, 38].

Anti-inflammatory action is another crucial mechanism through which green nano-phytotherapeutics exert beneficial effects in MetS[36]. These formulations often inhibit key inflammatory mediators such as nuclear factor kappa B (NF-κB) and pro-inflammatory cytokines like TNF-α and IL-6. By suppressing these signaling pathways, they reduce chronic low-grade inflammation—a hallmark of metabolic disorders. In addition, nanoparticles can increase the bioactivity and cell permeability of phytochemicals, ensuring a greater therapeutic impact at lower doses[39]. This reduces the risk of side effects and enables more precise control over metabolic pathways that are dysregulated in conditions like insulin resistance and adipose tissue inflammation. Moreover, these therapeutic systems contribute to lipid modulation, glycemic control, and mitochondrial function restoration. Nano-encapsulated phytochemicals enhance the expression of insulin receptors, glucose transporters, and key enzymes involved in lipid metabolism, thereby improving insulin sensitivity and reducing blood glucose and LDL-cholesterol levels[26]. They also support mitochondrial biogenesis and repair, addressing mitochondrial dysfunction often observed in patients with MetS. Collectively, these multifaceted mechanisms allow green nano-phytotherapeutics to target the root causes and systemic effects of metabolic syndrome, offering a comprehensive and natural alternative to conventional pharmacotherapy.

## Safety, Regulatory, and Translational Considerations

Despite its numerous advantages, green nanotechnology in phytomedicine faces critical safety and regulatory challenges that must be addressed before widespread clinical use. One major concern is the toxicological evaluation of nanoparticles, particularly their long-term accumulation in tissues and potential unforeseen effects. Although green synthesis reduces chemical toxicity, the biological behavior of nanoparticles—such as their biodistribution, metabolism, and excretion—needs thorough investigation. Preclinical studies often do not mimic the complexity of human physiology, underscoring the need for robust in vivo and long-term studies that evaluate chronic exposure and tissue-specific toxicity of nano-herbal formulations.

Another challenge lies in standardization and reproducibility. Plant extracts used for green synthesis often vary in composition depending on the source, season, and processing methods, leading to batch-to-batch inconsistency in nanoparticle synthesis. This variability affects the size, shape, and functional properties of the nanoparticles, complicating quality control and regulatory approval. Furthermore, existing regulatory frameworks do not fully account for the complexities of nano-herbal products, and there is a lack of harmonized guidelines globally. Regulatory bodies such as the FDA and EMA are only beginning to outline frameworks for nanomedicine, making it imperative for researchers and developers to engage proactively in establishing safety, efficacy, and manufacturing standards for green nanoformulations.

Translational efforts from laboratory to clinical settings are also limited due to scalability issues and the high costs associated with clinical trials. Only a few green nano-phytotherapeutics have entered clinical evaluation for metabolic disorders, primarily due to the lack of funding, infrastructure, and clear regulatory pathways. Bridging this gap requires a multidisciplinary approach involving toxicologists, pharmacologists, regulatory experts, and industry partners to design comprehensive pipelines for product development. Future success will depend on scalable synthesis methods, validated characterization techniques, and clear clinical endpoints, ensuring that these sustainable, effective formulations can be safely delivered to patients.

## Challenges and Future Perspectives

The application of green nanotechnology in phytomedicine, especially for metabolic disorders, faces several key challenges that currently hinder its full potential. First among them is the lack of standardized synthesis protocols. Due to the variability in plant extract composition and the influence of synthesis conditions on nanoparticle characteristics, reproducibility remains a significant issue. Moreover, there is a paucity of detailed in vivo data and human clinical trials to validate the safety and efficacy of these green nanoformulations. Most studies are still confined to in vitro or small animal models, which cannot fully replicate human metabolic complexity or predict long-term outcomes in diverse patient populations.

Another challenge lies in the complex pharmacokinetics and pharmacodynamics of nano-herbals. The interaction of phytochemicals with nanocarriers alters their absorption, distribution, metabolism, and excretion, necessitating advanced modeling to understand their behavior in the human body. This complexity makes it difficult to predict therapeutic efficacy, optimal dosing, and potential drug interactions. Moreover, many herbal products are used in combinations, further complicating the formulation and evaluation process. Without comprehensive pharmacological data, regulatory bodies may remain hesitant to approve such formulations, delaying their clinical translation. Addressing these issues requires extensive multidisciplinary research, incorporating nanotechnology, systems biology, pharmacology, and clinical sciences.

Looking forward, the future of green nano-phytotherapeutics appears promising, particularly with emerging innovations such as artificial intelligence (AI)-driven nanodesign and smart delivery systems. AI and machine learning tools can optimize nanoparticle design based on desired therapeutic outcomes, patient-specific data, and pharmacological profiles. Hybrid nanosystems that co-deliver multiple phytochemicals may allow for synergistic effects and broader therapeutic coverage. Furthermore, stimuli-responsive delivery systems—such as those activated by glucose levels or inflammatory markers—offer precise, on-demand drug release. The integration of these systems into functional foods and nutraceuticals could revolutionize chronic disease management by offering safe, accessible, and personalized interventions for metabolic syndrome and related disorders.

## CONCLUSION

Green nanotechnology holds immense promise in revolutionizing the delivery of antioxidant-rich phytotherapeutics for metabolic syndrome. By overcoming the limitations of conventional phytomedicine, green nanoformulations enhance bioavailability, stability, and targeted action of plant-derived compounds. As the field matures, interdisciplinary collaboration, robust clinical trials, and regulatory innovation will be essential for translating these advances into effective, sustainable therapies for MetS.

## REFERENCES


1. Islam, Md.S., Wei, P., Suzauddula, M., Nime, I., Feroz, F., Acharjee, M., Pan, F.: The interplay of factors in metabolic syndrome: understanding its roots and complexity. Mol. Med. 30, 279 (2024). https://doi.org/10.1186/s10020-024-01019-y
2. Chopra, A.K.: Metabolic Syndrome or Insulin Resistance: Evolution, Controversies and Association With Cardiovascular Disease Risk. Indian J. Clin. Cardiol. 1, 77–85 (2020). https://doi.org/10.1177/2632463620935030
3. Ansari, P., Akther, S., Hannan, J.M.A., Seidel, V., Nujat, N.J., Abdel-Wahab, Y.H.A.: Pharmacologically Active Phytomolecules Isolated from Traditional Antidiabetic Plants and Their Therapeutic Role for the Management of Diabetes Mellitus. Molecules. 27, 4278 (2022). https://doi.org/10.3390/molecules27134278
4. Chan, Y., Ng, S.W., Tan, J.Z.X., Gupta, G., Negi, P., Thangavelu, L., Balusamy, S.R., Perumalsamy, H., Yap, W.H., Singh, S.K., Caruso, V., Dua, K., Chellappan, D.K.: Natural products in the management of obesity: Fundamental mechanisms and pharmacotherapy. South Afr. J. Bot. 143, 176–197 (2021). https://doi.org/10.1016/j.sajb.2021.07.026
5. Uti, D.E., Atangwho, I.J., Eyong, E.U., Umoru, G.U., Egbung, G.E., Rotimi, S.O., Nna, V.U.: African walnuts (Tetracarpidium conophorum) modulate hepatic lipid accumulation in obesity via reciprocal actions on HMG-CoA reductase and paraoxonase. Endocr. Metab. Immune Disord.-Drug Targets Former. Curr. Drug Targets-Immune Endocr. Metab. Disord. 20, 365–379 (2020)
6. 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. Obes. Med. 54, 100585 (2025). https://doi.org/10.1016/j.obmed.2025.100585
7. Annett, S., Moore, G., Robson, T.: Obesity and Cancer Metastasis: Molecular and Translational Perspectives. Cancers. 12, 3798 (2020). https://doi.org/10.3390/cancers12123798
8. Alum, E.U.: Climate change and its impact on the bioactive compound profile of medicinal plants: implications for global health. Plant Signal. Behav. 19, 2419683 (2024). https://doi.org/10.1080/15592324.2024.2419683
9. Patial, R., Batta, I., Thakur, M., Sobti, R.C., Agrawal, D.K.: Etiology, Pathophysiology, and Treatment Strategies in the Prevention and Management of Metabolic Syndrome. Arch. Intern. Med. Res. 7, 273–283 (2024). https://doi.org/10.26502/aimr.0184
10. Islam, Md.S., Wei, P., Suzauddula, M., Nime, I., Feroz, F., Acharjee, M., Pan, F.: The interplay of factors in metabolic syndrome: understanding its roots and complexity. Mol. Med. 30, 279 (2024). https://doi.org/10.1186/s10020-024-01019-y
11. Lee, H.-T., Oh, S., Ro, D.H., Yoo, H., Kwon, Y.-W.: The Key Role of DNA Methylation and Histone Acetylation in Epigenetics of Atherosclerosis. J. Lipid Atheroscler. 9, 419–434 (2020). https://doi.org/10.12997/jla.2020.9.3.419
12. Kodama, K., Toda, K., Morinaga, S., Yamada, S., Butte, A.J.: Anti-CD44 Antibody Treatment Lowers Hyperglycemia and Improves Insulin Resistance, Adipose Inflammation, and Hepatic Steatosis in Diet-Induced Obese Mice. Diabetes. 64, 867–875 (2015). https://doi.org/10.2337/db14-0149
13. MacDonald-Ramos, K., Monroy, A., Bobadilla-Bravo, M., Cerbón, M.: Silymarin Reduced Insulin Resistance in Non-Diabetic Women with Obesity. Int. J. Mol. Sci. 25, 2050 (2024). https://doi.org/10.3390/ijms25042050
14. Umoru, G.U., Atangwho, I.J., David-Oku, E., Uti, D.E., Agwupuye, E.I., Obeten, U.N., Maitra, S., Subramaniyan, V., Wong, L.S., Aljarba, N.H., Kumarasamy, V.: Tetracarpidium conophorum nuts (African walnuts) up-regulated adiponectin and PPAR-γ expressions with reciprocal suppression of TNF-α gene in obesity. J. Cell. Mol. Med. 28, e70086 (2024). https://doi.org/10.1111/jcmm.70086
15. Roy, P.K., Islam, J., Lalhlenmawia, H.: Prospects of potential adipokines as therapeutic agents in obesity-linked atherogenic dyslipidemia and insulin resistance. Egypt. Heart J. 75, 24 (2023). https://doi.org/10.1186/s43044-023-00352-7
16. Suren Garg, S., Kushwaha, K., Dubey, R., Gupta, J.: Association between obesity, inflammation and insulin resistance: Insights into signaling pathways and therapeutic interventions. Diabetes Res. Clin. Pract. 200, 110691 (2023). https://doi.org/10.1016/j.diabres.2023.110691

17. Barber, T.M., Kyrou, I., Randeva, H.S., Weickert, M.O.: Mechanisms of Insulin Resistance at the Crossroad of Obesity with Associated Metabolic Abnormalities and Cognitive Dysfunction. Int. J. Mol. Sci. 22, 546 (2021). https://doi.org/10.3390/ijms22020546
18. 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. Nat. Prod. Commun. 20, 1934578X251323393 (2025). https://doi.org/10.1177/1934578X251323393
19. 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
20. 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. Off. Publ. Fed. Am. Soc. Exp. Biol. 34, 4527–4539 (2020). https://doi.org/10.1096/fj.201902222R
21. Chiang, M.-C., Tsai, T.-Y., Wang, C.-J.: The Potential Benefits of Quercetin for Brain Health: A Review of Anti-Inflammatory and Neuroprotective Mechanisms. Int. J. Mol. Sci. 24, 6328 (2023). https://doi.org/10.3390/ijms24076328
22. Markowska, J., Kasprzak-Drozd, K., Niziński, P., Dragan, M., Kondracka, A., Gondek, E., Oniszczuk, T., Oniszczuk, A.: Quercetin: A Promising Candidate for the Management of Metabolic Dysfunction-Associated Steatotic Liver Disease (MASLD). Molecules. 29, 5245 (2024). https://doi.org/10.3390/molecules29225245
23. Aqil, F., Munagala, R., Jeyabalan, J., Vadhanam, M.V.: Bioavailability of phytochemicals and its enhancement by drug delivery systems. Cancer Lett. 334, 133–141 (2013). https://doi.org/10.1016/j.canlet.2013.02.032
24. Uti, D.E., Atangwho, I.J., Alum, E.U., Ntaobeten, E., Obeten, U.N., Bawa, I., Agada, S.A., Ukam, C.I.-O., Egbung, G.E.: Antioxidants in cancer therapy mitigating lipid peroxidation without compromising treatment through nanotechnology. Discov. Nano. 20, 70 (2025). https://doi.org/10.1186/s11671-025-04248-0
25. Magadani, R., Ndinteh, D.T., Roux, S., Nangah, L.P., Atangwho, I.J., Uti, D.E., Alum, E.U., Egba, S.I.: Cytotoxic Effects Of Lecaniodiscus Cupanioides (Planch.) Extract and Triterpenoids-derived Gold Nanoparticles On MCF-7 Breast Cancer Cell Lines. Anticancer Agents Med. Chem. (2025). https://doi.org/10.2174/0118715206325529241004064307
26. Uti, D.E., Alum, E.U., Atangwho, I.J., Ugwu, O.P.-C., Egbung, G.E., Aja, P.M.: Lipid-based nano-carriers for the delivery of anti-obesity natural compounds: advances in targeted delivery and precision therapeutics. J. Nanobiotechnology. 23, 336 (2025). https://doi.org/10.1186/s12951-025-03412-z
27. Nurcahyanti, A.D.R., Cokro, F., Wulanjati, M.P., Mahmoud, M.F., Wink, M., Sobeh, M.: Curcuminoids for Metabolic Syndrome: Meta-Analysis Evidences Toward Personalized Prevention and Treatment Management. Front. Nutr. 9, 891339 (2022). https://doi.org/10.3389/fnut.2022.891339
28. Pathak, J., Xavier, K.A.M., Ngasotter, S., Goswami, A., Hazarika, U., Saikia, R.: Sustainable Nanotechnology for Green Environment. In: Waste Derived Carbon Nanomaterials. Volume 1. pp. 17–39. American Chemical Society (2025)
29. Elayaperumal, S., Sivamani, Y., Agarwal, P., Srivastava, N.: Plant-based nanotherapeutics: A new frontier in disease management and prevention. Nano TransMed. 4, 100086 (2025). https://doi.org/10.1016/j.ntm.2025.100086
30. kazemi, S., Hosseingholian, A., Gohari, S.D., Feirahi, F., Moammeri, F., Mesbahian, G., Moghaddam, Z.S., Ren, Q.: Recent advances in green synthesized nanoparticles: from production to application. Mater. Today Sustain. 24, 100500 (2023). https://doi.org/10.1016/j.mtsust.2023.100500
31. Paiva-Santos, A.C., Herdade, A.M., Guerra, C., Peixoto, D., Pereira-Silva, M., Zeinali, M., Mascarenhas-Melo, F., Paranhos, A., Veiga, F.: Plant-mediated green synthesis of metal-based nanoparticles for dermopharmaceutical and cosmetic applications. Int. J. Pharm. 597, 120311 (2021). https://doi.org/10.1016/j.ijpharm.2021.120311
32. Herdiana, Y.: Nanoparticles of natural product-derived medicines: Beyond the pandemic. Heliyon. 11, e42739 (2025). https://doi.org/10.1016/j.heliyon.2025.e42739
33. Jalili, A., Bagherifar, R., Nokhodchi, A., Conway, B., Javadzadeh, Y.: Current Advances in Nanotechnology-Mediated Delivery of Herbal and Plant-Derived Medicines. Adv. Pharm. Bull. 13, 712–722 (2023). https://doi.org/10.34172/apb.2023.087
34. Karthikeyan, A., Senthil, N., Min, T.: Nanocurcumin: A Promising Candidate for Therapeutic Applications. Front. Pharmacol. 11, (2020). https://doi.org/10.3389/fphar.2020.00487
35. Moetlediwa, M.T., Ramashia, R., Pheiffer, C., Titinchi, S.J.J., Mazibuko-Mbeje, S.E., Jack, B.U.: Therapeutic Effects of Curcumin Derivatives against Obesity and Associated Metabolic Complications: A Review of In Vitro and In Vivo Studies. Int. J. Mol. Sci. 24, 14366 (2023). https://doi.org/10.3390/ijms241814366

36. Nouri, Z., Hajialyani, M., Izadi, Z., Bahramsoltani, R., Farzaei, M.H., Abdollahi, M.: Nanophytomedicines for the Prevention of Metabolic Syndrome: A Pharmacological and Biopharmaceutical Review. Front. Bioeng. Biotechnol. 8, 425 (2020). https://doi.org/10.3389/fbioe.2020.00425
37. Dash, P., Piras, A.M., Dash, M.: Cell membrane coated nanocarriers - an efficient biomimetic platform for targeted therapy. J. Controlled Release. 327, 546–570 (2020). https://doi.org/10.1016/j.jconrel.2020.09.012
38. Gressler, S., Hipfinger, C., Part, F., Pavlicek, A., Zafiu, C., Giese, B.: A systematic review of nanocarriers used in medicine and beyond — definition and categorization framework. J. Nanobiotechnology. 23, 90 (2025). https://doi.org/10.1186/s12951-025-03113-7
39. Peng, Y., Ao, M., Dong, B., Jiang, Y., Yu, L., Chen, Z., Hu, C., Xu, R.: Anti-Inflammatory Effects of Curcumin in the Inflammatory Diseases: Status, Limitations and Countermeasures. Drug Des. Devel. Ther. 15, 4503–4525 (2021). https://doi.org/10.2147/DDDT.S327378



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