Check for updates

The Journal of Phytopharmacology 2025; 14(6):536-542
Online at: www.phytopharmajournal.com

The Journal of Phytopharmacology
(Pharmacognosy and phytomedicine Research)

Phytochemical based nanoformulations: an advanced strategy for the management of metabolic syndrome

Sudhakar S, Suja Rani S*

Review Article

ISSN 2320-480X
JPHYTO 2025; 14(6): 536-542
November- December
Received: 07-10-2025
Accepted: 13-01-2026
Published: 30-01-2026
©2025, All rights reserved
doi: 10.31254/phyto.2025.14615

Sudhakar S
MVSc Scholar, Department of Veterinary Pharmacology and Toxicology, College of Veterinary and Animal Sciences Mannuthy, Thrissur-680651, Kerala, India

Suja Rani S
Associate Professor, Department of Veterinary Pharmacology and Toxicology, College of Veterinary and Animal Sciences Mannuthy, Thrissur-680651, Kerala, India

Correspondence:
Dr. Suja Rani S
Associate Professor, Department of Veterinary Pharmacology and Toxicology, College of Veterinary and Animal Sciences Mannuthy, Thrissur-680651, Kerala, India
Email: sujarani@kvasu.ac.in

ABSTRACT

Metabolic syndrome (MetS), a silent epidemic condition is characterized by a cluster of metabolic dysfunctions, including hypertension, central obesity, insulin resistance and atherogenic dyslipidemia, which collectively increase the risk of type 2 diabetes mellitus and cardiovascular diseases. The rising global prevalence of MetS and its association with increased morbidity and mortality have made it a significant public health concern. The complex pathophysiology of MetS, driven by the intricate interplay of metabolic, hormonal and inflammatory pathways, often results in partial therapeutic efficacy, treatment resistance and challenges in achieving sustained disease control. Recently, phytochemicals which are the bioactive compounds derived from plants have gained considerable attention for their therapeutic potential in managing MetS owing to their diverse pharmacological properties, such as anti-inflammatory, antioxidant and hypoglycemic effects. Phytochemicals like curcumin, resveratrol and epigallocatechin gallate have demonstrated efficacy in ameliorating metabolic derangements associated with MetS. However, their clinical application is often limited by poor bioavailability, rapid metabolism and low solubility. To address these limitations, nanoformulations of phytochemicals have been developed, leveraging advancements in nanotechnology to enhance their stability, solubility and bioavailability. Encapsulation in nanosystems, such as liposomes, polymeric nanoparticles, nanoemulsions and solid lipid nanoparticles, enables sustained release, targeted delivery and improved therapeutic efficacy while minimizing adverse effects. These nanoformulations facilitate precise delivery of active moieties to specific tissues or cellular targets, thereby optimizing therapeutic outcomes. This review highlights the potential of application of nanoformulated phytochemicals in the management of MetS, emphasizing their pharmacokinetic improvements and therapeutic benefits.

Keywords: Nanoformulations, Phytochemicals, Metabolic syndrome, Drug delivery systems, Nanotechnology, Nanocarriers.

INTRODUCTION

Metabolic syndrome (MetS) is a major health challenge, characterized by interconnected metabolic dysfunctions including insulin resistance, central obesity, atherogenic dyslipidemia and hypertension. These disturbances form a complex pathophysiological network, significantly increasing the risk of type 2 diabetes (T2D) by fivefold and cardiovascular diseases (CVD) by twofold, highlighting MetS as a key contributor to global morbidity and mortality [1]. Its rising prevalence, driven by sedentary lifestyles, poor diet, physical inactivity and genetic predispositions, underscores the need for effective management strategies.

Phytochemicals have attracted considerable attention for their potential in the prevention and management of MetS. They exhibit diverse pharmacological activities including antioxidant, anti-inflammatory and anticancer effects [2]. Flavonoids like quercetin contribute to cardiovascular protection and may aid diabetes management by modulating molecular pathways [3]. Their multifaceted activities make phytochemicals promising agents for targeting the complex pathophysiology of MetS.

However, clinical application is limited by poor bioavailability, low solubility and instability. Curcumin exemplifies these challenges, as poor solubility and rapid degradation necessitate high doses for efficacy [4]. Similar limitations affect other phytochemicals, highlighting the need for innovative delivery approaches.

Nanotechnology has emerged as a promising tool for addressing these challenges. Nanoformulations-based delivery systems enhance solubility, stability and bioavailability, while enabling controlled and targeted delivery These nanosystems improve permeability across biological barriers and improve their therapeutic efficacy [5]. The high surface area-to-volume ratio and customizable physical and chemical attributes to optimize drug loading and targeted delivery thereby broadening the scope of phytochemical applications in managing MetS [6].

This review explores the therapeutic potential of phytochemicals and their nanoformulations in MetS management, highlighting recent advances in nano formulation technologies and delivery strategies to improve health outcomes in this complex disorder.

Pathophysiology of Metabolic Syndrome

MetS represents a multifaceted cluster of interrelated metabolic abnormalities, primarily characterized by insulin resistance, central obesity, hypertension and dyslipidemia. Together, these factors substantially increase the risk of T2D and CVD. Insulin resistance, often aggravated by visceral fat accumulation, drives systemic metabolic disturbances, while hypertension and dyslipidemia create a pro-atherogenic environment that elevates cardiovascular risk. As illustrated in Figure 1, the interaction of these metabolic disturbances underpins the development and progression of MetS.

The etiology of MetS is multifactorial, involving genetic susceptibility, epigenetic regulation, environmental exposures and lifestyle factors. While inherited traits shape individual predisposition, poor diet and sedentary behavior remain the strongest external drivers of its global rise [7,8]. Epigenetic mechanisms, including DNA methylation and histone modifications, mediate long-term effects of environmental inputs and can even produce heritable metabolic changes [9,10]. Early-life exposures, such as maternal obesity and adverse intrauterine conditions, further heighten susceptibility to metabolic disturbances later in life [7,11].

Chronic insulin resistance contributes to hyperglycemia, impaired lipid metabolism and ectopic fat deposition in the liver and skeletal muscle. In muscle, accumulation of intramyocellular lipids disrupts mitochondrial function [12] while in the liver, steatosis progresses to non-alcoholic fatty liver disease (NAFLD) and in severe cases to NASH, fibrosis and hepatocellular carcinoma[13,14]. These interlinked metabolic impairments ultimately magnify cardiovascular and systemic risks.

Chronic low-grade inflammation, which arises primarily from dysfunctional adipose tissue is also a hallmark of MetS. Excess adiposity alters the secretion profile of adipokines, increasing pro-inflammatory mediators such as leptin, Tumor Necrosis Factor-alpha (TNF-α), Interleukin-6 (IL-6), resistin and chemerin, while reducing protective adipokines like adiponectin [15]. This persistent inflammatory state contributes to progressive metabolic dysfunction and cardiometabolic complications.

Gut microbiota dysbiosis further amplifies this inflammatory milieu. Alterations in microbial composition disrupt intestinal homeostasis, compromise the gut barrier and degrade the mucus layer, thereby facilitating the systemic translocation of bacterial products such as lipopolysaccharide (LPS) often referred to as "leaky gut" [16,17]. Reduced microbial production of short-chain fatty acids impairs gut integrity, energy metabolism and hormone secretion (Glucagon-Like Peptide-1, Peptide YY) which favors adiposity and insulin resistance [18,19]. Moreover, bacterial translocation into adipose tissue perpetuates systemic low-grade inflammation and metabolic disruption, as explained in Figure 2 [20]. Diets rich in fat and refined carbohydrates further aggravate dysbiosis and intestinal permeability, accelerating the pathogenesis of MetS [17].

Phytochemicals in treatment of MetS

The management of MetS has increasingly incorporated phytochemicals, which offer diverse mechanisms targeting multiple aspects of the syndrome while minimizing side effects. By modulating physiological processes, phytochemicals aim to improve metabolic control and reduce the risk of associated CVD and T2D.

Phytochemicals exert therapeutic effects in MetS through antioxidant, anti-inflammatory and hypoglycemic properties. Curcumin, derived from turmeric, enhances insulin sensitivity, regulates lipid metabolism and reduces systemic inflammation [21]. Calebin A, a curcuminoid, supports weight management and improves lipid profiles[22]. Allicin, from garlic, improves glucose homeostasis, activates brown adipose tissue and reduces oxidative stress and inflammation [23,24].

Quercetin, a flavonoid in onions, exhibits anti-hyperglycemic and anti-hyperlipidemic effects while improving vascular function [25,26]. Berberine regulates peroxisome proliferator-activated receptor gamma (PPARγ) and adenosine monophosphate-activated protein kinase (AMPK) signaling, maintaining lipid and glucose homeostasis, enhancing insulin sensitivity and reducing inflammation [27,28]. Resveratrol mitigates adipose tissue inflammation, enhances antioxidant defenses and modulates pro-inflammatory cytokines via nuclear factor kappa-light-chain-enhancer of activated B cells (NF-κB) and Toll-like receptor (TLR) pathways [29,30].

Sulforaphane, from cruciferous vegetables, activates the nuclear factor erythroid 2–related factor 2 (Nrf2) pathway, reducing oxidative stress and improving glucose metabolism, while modulating bile acid and fatty acid metabolism to alleviate metabolic-associated fatty liver disease [31,32] Gingerol, particularly 6-gingerol, enhances mitochondrial function and inhibits triglyceride biosynthesis, thereby reducing cardiovascular risks [33–35].

Epigallocatechin gallate (EGCG), from green tea, inhibits adipogenesis, promotes adipocyte browning and improves energy metabolism, providing protection against T2D and cardiovascular complications [36,37]. Caffeine enhances insulin sensitivity and lipid profiles via gut microbiota and bile acid modulation [38]. Monacolin K, from red yeast rice, inhibits HMG-CoA reductase, reducing low-density lipoprotein (LDL) and triglycerides while increasing HDL. It also activates Sirtuin 1 (SIRT1) and AMPK pathways, promoting lipid catabolism and glucose regulation in MetS patients [39,40].

Limitations of Phytochemicals

Phytochemicals hold considerable therapeutic potential for managing MetS; however, their clinical application is limited by poor absorption, low solubility, environmental instability and extensive first-pass metabolism, all of which reduce bioavailability. Moreover, the lack of targeted delivery systems further compromises efficacy, while variability in bioactive concentrations, potential drug interactions and safety concerns at high doses present additional challenges. Overcoming these limitations requires advanced delivery systems, optimized formulations and standardized extraction techniques to enhance both therapeutic effectiveness and profiles.

A major challenge is poor water solubility, which restricts absorption and systemic availability, particularly for compounds such as curcumin [41], naringenin [42] and quercetin [43]. Poor chemical stability and rapid metabolic transformation further reduce efficacy, as seen with resveratrol [44], naringenin [42] and quercetin [43] which exhibit oral bioavailability below 5%.

Stability concerns also affect several phytochemicals. Compounds such as allicin [45], EGCG [46] and sulforaphane [47,48] are prone to degradation under heat, pH variations and oxidation. Addressing these issues through innovative drug delivery systems is essential to enhance bioavailability, stability and overall therapeutic potential, thereby realizing the full clinical utility of phytochemicals in managing MetS.

Nanoformulations of Phytobioactives

Phytobioactives such as curcumin, quercetin, berberine, allicin and sulforaphane are widely recognized for their therapeutic potential, yet their clinical use remains restricted by poor solubility, low bioavailability and instability. To address these challenges, nanoformulation technologies including solid lipid nanoparticles (SLNs), liposomes, niosomes and polymeric nanoparticles (PNPs) have emerged as effective strategies. These carriers improve solubility, stability and absorption, while also enabling controlled and sustained release. By enhancing pharmacokinetics and facilitating targeted delivery, nanoformulations hold promise in managing MetS-related conditions such as diabetes, dyslipidemia, obesity and fatty liver, as highlighted in Figure 3.

Nano-based systems offer unique advantages owing to their high surface area, ability to cross biological barriers and potential for sustained release. Among them, nanoemulsions form stable dispersions that improve solubility, absorption and biological activities, while nanoemulgels extend these benefits to topical, oral and ocular applications [49,50]. Lipid-based systems such as phytosomes and SLNs further enhance stability and uptake; phytosomes achieve this by binding bioactives to phospholipids, whereas SLNs encapsulate hydrophobic compounds for controlled release and scalability [51,52].

Other versatile systems include self-nanoemulsifying drug delivery systems (SNEDDS), which form oil-in-water emulsions in gastrointestinal fluids to enhance absorption and reduce toxicity [53]. PNPs protect sensitive compounds and ensure targeted, controlled release [54] while nanogels combine hydrogel and nanoemulsion properties to provide high permeability, sustained release and non-invasive delivery [50].

More advanced carriers such as dendrimers and nanosponges further expand the scope of phytochemical delivery. Dendrimers, with their branched architecture, enhance solubility, stability and targeted release [55]. Nanosponges, often cyclodextrin-based, encapsulate hydrophobic compounds like curcumin and resveratrol in stable, cross-linked networks, offering improved therapeutic efficacy and safety [56,57].

Nanomaterials in Metabolic Syndrome

Nanoformulations of bioactive compounds have emerged as a pioneering strategy to enhance the therapeutic efficacy of natural compounds in managing MetS, a complex condition characterized by obesity, hypertension, dyslipidemia and insulin resistance. MetS poses a significant global health burden, contributing to the rising prevalence of CVD, T2D and NAFLD [58]. Despite the pharmacological potential of bioactives such as curcumin, EGCG, resveratrol and berberine, their clinical application is limited by poor bioavailability, low aqueous solubility and chemical instability [4]. Nanoformulations offer solutions through enhanced surface area-to-volume ratio, targeted delivery, sustained and controlled release and improved bioavailability, thereby optimizing pharmacokinetic and pharmacodynamic properties for effective MetS management [5,49].Curcumin, a polyphenol from *Curcuma longa*, exhibits anti-inflammatory and antioxidant properties but suffers from poor pharmacokinetics. Turmeric derived nanovesicles enhancing lipolysis and inhibiting lipogenesis [59]. PLGA nanoparticles improve cardiovascular function and normalize blood pressure in diet-induced MetS models at lower doses than unformulated curcumin [60], while SNEDDS enhance curcumin bioavailability, improving lipid profile modulation in diabetic models [5].

EGCG, a potent antioxidant from *Camellia sinensis*, benefits from liposomal and metal-based nanoparticles, enhancing its bioavailability and antioxidative property. These formulations mitigate oxidative stress, improve cardiovascular outcomes via Nrf2/HO-1 activation and regulate intercellular adhesion molecule-1 (ICAM-1) [61]. Resveratrol, encapsulated in oxidized starch-lysozyme nanocarriers, targets the liver, reduces triglyceride accumulation and improves insulin sensitivity through the AMPK/SIRT1/ Sterol regulatory element-binding protein-1c (SREBP-1c) pathway [62]. Nanoemulsions, liposomes and starch-based nanoparticles further enhance resveratrol's solubility, stability and bioavailability [63].

Ginsenosides from *Panax ginseng* formulated in SNEDDS and liposomes improve solubility and bioavailability while modulating phosphoinositide 3-kinase/protein kinase B (PI3K/Akt) and AMPK–c-Jun N-terminal kinase (JNK) signaling pathways to regulate glucose homeostasis and lipid metabolism [64]. Quercetin, with antioxidant and anti-inflammatory effects, has been incorporated into SNEDDS and iron oxide nanoparticles, improving solubility, bioavailability, cardiovascular function and glycemic control [25,65].

Overall, nanoformulations represent a transformative advancement in MetS management. By improving bioavailability, stability and targeted delivery, nanotechnology overcomes limitations of conventional formulations and amplifies therapeutic efficacy. Nanovesicles, nanoparticles, nanoemulsions and liposomal carriers optimize pharmacokinetic and pharmacodynamic profiles, promoting improved lipid profile modulation, glucose homeostasis, oxidative stress reduction and cardiovascular health. As research in this field progresses, the development of innovative nanoformulations hold significant promise for advancing MetS therapeutics and enabling new clinical interventions in this multifactorial disorder.

Limitation of Nanoformulation

Nanoformulations of phytochemicals enhance stability, bioavailability and pharmacokinetics, offering promising strategies for managing MetS. However, clinical translation faces challenges including low absorption rates due to their large molecular sizes, which significantly reduces their therapeutic efficacy. Although nanotechnological approaches like polymeric and solid lipid nanoparticles have improved solubility and enabled controlled release, challenges such as potential toxicity, physicochemical instability and large-scale production constraints persist [66,67].

Nanoemulsions, solid lipid nanoparticles and SNEDDS have shown to improved therapeutic efficacy of compounds like curcumin, resveratrol and quercetin. However, comprehensive toxicity evaluations and clinical trials are essential to ensure their long-term safety and efficacy. Additionally, the preparation methods, choice of polymers and synthesis techniques significantly influence the physicochemical properties and therapeutic outcomes of nanoformulations, thereby necessitating rigorous standardization and validation [68,69].

Safety and toxicity concerns are critical in nanoformulations, particularly due to the unique physicochemical properties, such as size and surface charge, which influence their biological interactions and toxicity profiles. While natural polymers like chitosan show promise in mitigating these adverse effects, their systemic impacts and biocompatibility require thorough investigation. Even though several studies have demonstrated the efficacy of nanoformulations in reducing MetS markers of insulin resistance and oxidative stress, further research is necessary to confirm their long-term safety and minimize potential cytotoxicity [5].

Scalability and regulatory hurdles further complicate the application of these nanoformulations. Large scale production is constrained by financial and technical challenges, as well as the need to maintain stability and bioactivity during manufacturing. Regulatory agencies, including the Food and Drug Administration (FDA), require extensive data on biocompatibility, stability and clinical efficacy, which can be resource intensive and time consuming to generate [70]. Despite these limitations, nanoformulations hold significant potential in addressing insulin resistance, oxidative stress and chronic inflammation and overcoming these barriers is crucial for their therapeutic translation.

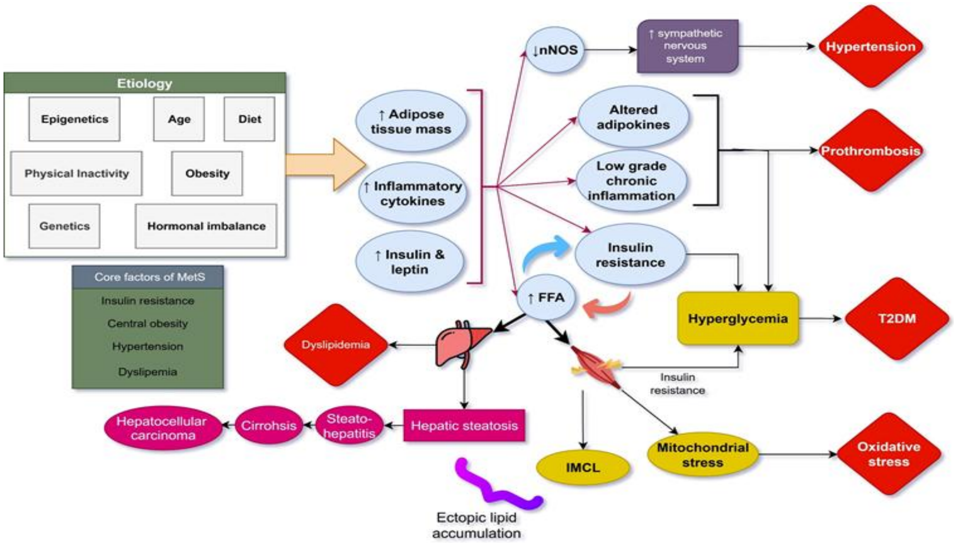

Figure 1: Overview of the pathophysiology of metabolic syndrome (MetS). **Abbreviations:** FFA – Free Fatty Acids; ins – inducible Nitric Oxide Synthase; T2DM – Type 2 Diabetes Mellitus; IMCL – Intramyocellular Lipid

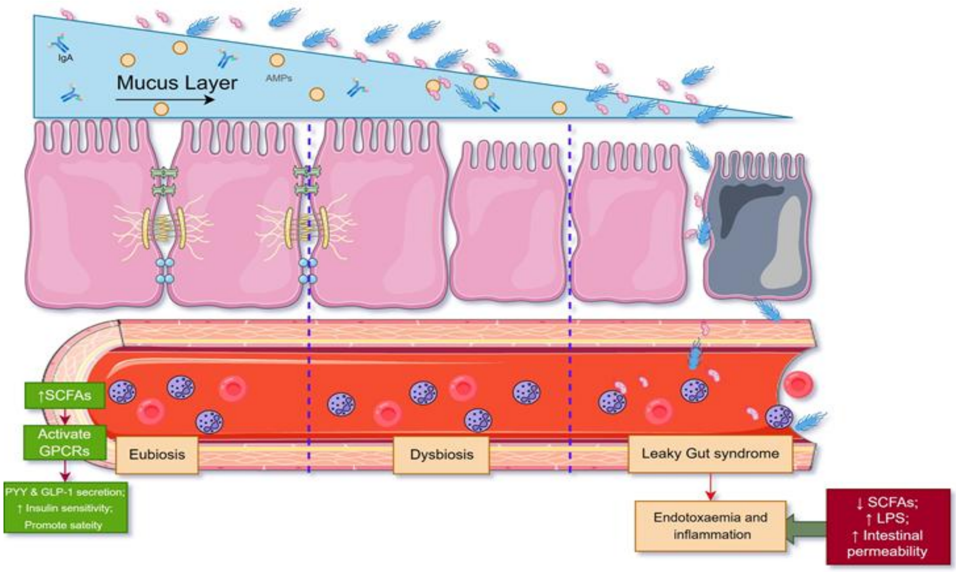

Figure 2: Dysbiosis and their impact on metabolic dysfunction. **Abbreviations:** SCFAs – Short-Chain Fatty Acids; GPCRs – G Protein-Coupled Receptors; PYY – Peptide YY; GLP-1 – Glucagon-Like Peptide-1; IgA – Immunoglobulin A; AMPs – Antimicrobial Peptides; LPS – Lipopolysaccharides

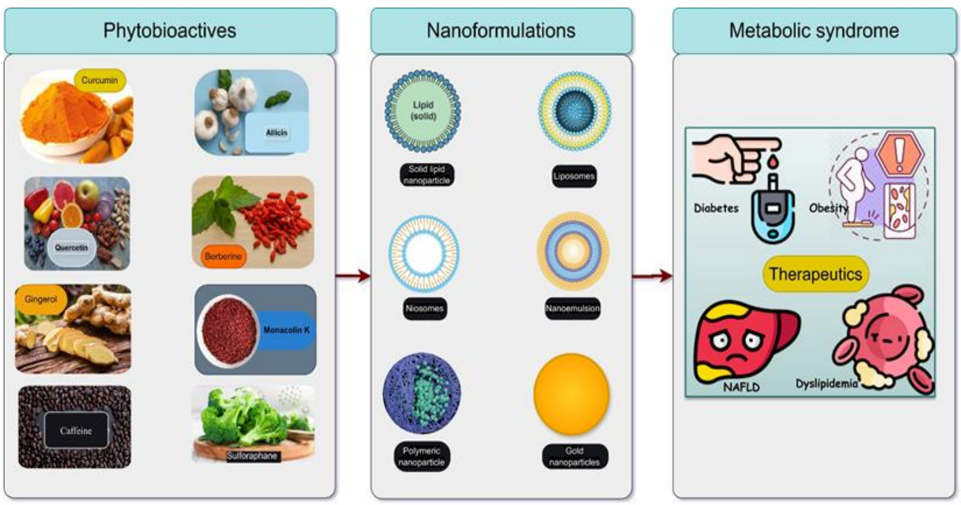

Figure 3: Therapeutic strategy of phytobioactives and its nanoformulation in metabolic syndrome and its associated disorders

CONCLUSION

Nanoformulations of phytochemicals marks a paradigmatic shift in MetS management, circumventing the key limitations of conventional therapies, such as poor bioavailability, rapid degradation and limited therapeutic efficacy. By leveraging advanced nanotechnology, these formulations enhance the solubility, stability and targeted delivery of bioactive compounds, thereby amplifying their therapeutic potential. Preclinical studies using nanoparticles, liposomes, nanoemulsions and solid lipid nanoparticles have demonstrated that targeted drug delivery leads to improved pharmacokinetics, sustained drug release and reduced side effects compared to traditional approaches. However, translating these advancements into clinical practice faces challenges due to concerns regarding toxicity, scalability and regulatory compliance. Overcoming these hurdles requires innovative strategies, biocompatible materials and rigorous clinical evaluations. Continued research efforts focusing on personalized medicine and scalable production strategies will be crucial in transforming these promising nanoformulations into clinically viable therapies, ultimately enhancing patient outcomes and mitigating the global burden of MetS.

Conflict of interest

The authors declared no conflict of interest.

Financial Support

None declared.

ORCID ID

Sudhakar S: https://orcid.org/0009-0000-0600-7340

Suja Rani S: https://orcid.org/0000-0002-8618-7798

REFERENCES

1. Alberti KGMM, Eckel RH, Grundy SM, Zimmet PZ, Cleeman JI, Donato KA, et al. Harmonizing the Metabolic Syndrome. Circulation. 2009;120(16):1640-5.
2. Dagdag O, Kim H, Haldhar R, Daoudi W, Berdimurodov E. Phytochemicals/Plant Extracts: Preparation, Characterization, and Properties. In: Phytochemistry in Corrosion Science. CRC Press; 2024.
3. Liu RH. Potential Synergy of Phytochemicals in Cancer Prevention: Mechanism of Action. The Journal of Nutrition. 2004;134(12):3479S–3485S.
4. Anand P, Kunnumakkara AB, Newman RA, Aggarwal BB. Bioavailability of Curcumin: Problems and Promises. Molecular Pharmaceutics. 2007;4(6):807-18.
5. Taghipour YD, Hajialyani M, Naseri R, Hesari M, Mohammadi P, Stefanucci A, et al. Nanoformulations of natural products for management of metabolic syndrome. International Journal of Nanomedicine. 2019;14:5303-21.
6. Khan I, Saeed K, Khan I. Nanoparticles: Properties, applications and toxicities. Arabian Journal of Chemistry. 2019;12(7):908-31.
7. Gonzalez-Bulnes A, Astiz S, Ovilo C, Garcia-Contreras C, Vazquez-Gomez M. Nature and Nurture in the Early-Life Origins of Metabolic Syndrome. Current Pharmaceutical Biotechnology. 2016;17(7):573-86.
8. Patial R, Batta I, Thakur M, Sobti RC, Agrawal DK. Etiology, Pathophysiology, and Treatment Strategies in the Prevention and Management of Metabolic Syndrome. Archives of Internal Medicine Research. 2024;7(4):273-83.
9. Carson C, Lawson HA. Epigenetics of metabolic syndrome. Physiological Genomics. 2018;50(11):947-55.
10. Kuneš J, Vaněčková I, Mikulášková B, Behuliak M, Maletínská L, Zicha J. Epigenetics and a new look on metabolic syndrome. Physiological Research. 2015;64(5):611-20.
11. Smith CJ, Ryckman KK. Epigenetic and developmental influences on the risk of obesity, diabetes, and metabolic syndrome. Diabetes, Metabolic Syndrome and Obesity. 2015;8:295-302.
12. Tamura Y, Kakehi S, Takeno K. Intracellular lipid accumulation and insulin sensitivity in muscle and liver: Fighting against "intracellular obesity." The Journal of Physical Fitness and Sports Medicine. 2014;3(5):501-5.
13. Ghazanfar H, Javed N, Qasim A, Zacharia GS, Ghazanfar A, Jyala A, et al. Metabolic Dysfunction-Associated Steatohepatitis and Progression to Hepatocellular Carcinoma: A Literature Review. Cancers. 2024;16(6):1214.
14. Neuschwander-Tetri BA. Chapter 9 - Fatty Liver and Nonalcoholic Steatohepatitis. In: Friedman LS, Martin P, editors. Handbook of Liver Disease (Fourth Edition). Elsevier; 2018. p. 121-9.
15. Engin A. Reappraisal of Adipose Tissue Inflammation in Obesity. In: Engin AB, Engin A, editors. Obesity and Lipotoxicity. Cham: Springer International Publishing; 2024. p. 297-327.
16. Bischoff SC, Barbara G, Buurman W, Ockhuizen T, Schulzke JD, Serino M, et al. Intestinal permeability - a new target for disease prevention and therapy. BMC Gastroenterology. 2014;14:189.
17. Chae YR, Lee YR, Kim YS, Park HY. Diet-Induced Gut Dysbiosis and Leaky Gut Syndrome. Journal of Microbiology and Biotechnology. 2024;34(4):747-56.
18. Ikeda T, Nishida A, Yamano M, Kimura I. Short-chain fatty acid receptors and gut microbiota as therapeutic targets in metabolic, immune, and neurological diseases. Pharmacology & Therapeutics. 2022;239:108273.
19. Rasouli-Saravani A, Jahankhani K, Moradi S, Gorgani M, Shafaghat Z, Mirsanei Z, et al. Role of microbiota short-chain fatty acids in the pathogenesis of autoimmune diseases. Biomedicine & Pharmacotherapy. 2023;162:114620.
20. May KS, den Hartigh LJ. Gut Microbial-Derived Short Chain Fatty Acids: Impact on Adipose Tissue Physiology. Nutrients. 2023;15(2):272.
21. Zeng Y, Luo Y, Wang L, Zhang K, Peng J, Fan G. Therapeutic Effect of Curcumin on Metabolic Diseases: Evidence from Clinical Studies. International Journal of Molecular Sciences. 2023;24(4):3323.
22. Majeed M, Nagabhushanam K, Devarajan TV, Saklecha S, Reddy SVK, Mundkur L. A minor metabolite from Curcuma longa effective against metabolic syndrome: results from a randomized, double-blind, placebo-controlled clinical study. Food & Function. 2023;14(10):4722-33.
23. Buendia ASA, Rojas JGJ, García-Arroyo F, Trejo OEA, Sánchez-Muñoz F, Argüello-García R, et al. Antioxidant and anti-inflammatory effects of allicin in the kidney of an experimental model of metabolic syndrome. PeerJ. 2023;11:e16132.
24. Wang M. The pathology of type 2 diabetes mellitus and relevant treatments. Theoretical and Natural Science. 2023;22:1-6.
25. Ahmed OAA, Azhar AS, Tarkhan MM, Balamash KS, El-Bassossy HM. Antiglycation Activities and Common Mechanisms Mediating Vasculoprotective Effect of Quercetin and Chrysin in Metabolic Syndrome. Evidence-Based Complementary and Alternative Medicine. 2020;2020:3439624.
26. Hosseini A, Razavi BM, Banach M, Hosseinzadeh H. Quercetin and metabolic syndrome: A review. Phytotherapy Research. 2021;35(10):5352-64.
27. Cheng X, Hu Y, Kuang J, Guo X, Cao H, Wu H, et al. Berberine alleviates high-energy and low-protein diet-induced fatty liver hemorrhagic syndrome in laying hens:

insights from microbiome and metabolomics. Poultry Science. 2024;103(8):103968.
28. Och A, Och M, Nowak R, Podgórska D, Podgórski R. Berberine, a Herbal Metabolite in the Metabolic Syndrome: The Risk Factors, Course, and Consequences of the Disease. Molecules. 2022;27(4):1351.
29. Batista-Jorge GC, Barcala-Jorge AS, Lelis DF, Santos DE, Jorge AH, Monteiro-Junior RS, et al. Resveratrol Effects on Metabolic Syndrome Features: A Systematic Review and Meta-Analysis. Endocrines. 2024;5(2):225-43.
30. Ghahremani H, Bahramzadeh A, Bolandnazar K, Emamgholipor S, Hosseini H, Meshkani R. Resveratrol as a potential protective compound against metabolic inflammation. Acta Biochimica Iranica. 2023.
31. Ma S, Pang X, Tian S, Sun J, Hu Q, Li X, et al. The protective effects of sulforaphane on high-fat diet-induced metabolic associated fatty liver disease in mice via mediating the FXR/LXRα pathway. Food & Function. 2022;13(24):12966-82.
32. Patel B, Mann GE, Chapple SJ. Concerted redox modulation by sulforaphane alleviates diabetes and cardiometabolic syndrome. Free Radical Biology and Medicine. 2018;122:150-60.
33. Alipour A, Baradaran Rahimi V, Askari VR. Promising influences of gingerols against metabolic syndrome: A mechanistic review. BioFactors. 2022;48(5):993-1004.
34. Salaramoli S, Mehri S, Yarmohammadi F, Hashemy SI, Hosseinzadeh H. The effects of ginger and its constituents in the prevention of metabolic syndrome: A review. Iranian Journal of Basic Medical Sciences. 2022;25(6):664-74.
35. Xia Q, Lu F, Chen Y, Li J, Huang Z, Fang K, et al. 6-Gingerol regulates triglyceride and cholesterol biosynthesis to improve hepatic steatosis in MAFLD by activating the AMPK-SREBPs signaling pathway. Biomedicine & Pharmacotherapy. 2024;170:116060.
36. Mielgo-Ayuso J, Barrenechea L, Alcorta P, Larrarte E, Margareto J, Labayen I. Effects of dietary supplementation with epigallocatechin-3-gallate on weight loss, energy homeostasis, cardiometabolic risk factors and liver function in obese women: randomised, double-blind, placebo-controlled clinical trial. British Journal of Nutrition. 2014;111(7):1263-71.
37. Ntamo Y, Jack B, Ziqubu K, Mazibuko-Mbeje SE, Nkambule BB, Nyambuya TM, et al. Epigallocatechin gallate as a nutraceutical to potentially target the metabolic syndrome: novel insights into therapeutic effects beyond its antioxidant and anti-inflammatory properties. Critical Reviews in Food Science and Nutrition. 2024;64(1):87-109.
38. Chen L, Wang XJ, Chen JX, Yang JC, Ling L, Cai XB, et al. Caffeine ameliorates the metabolic syndrome in diet-induced obese mice through regulating the gut microbiota and serum metabolism. Diabetology & Metabolic Syndrome. 2023;15(1):37.
39. Esposito T, Allocca S, Adelfi L. Effects of Monacolin K of Red Rice and Glucomannan, Combined with a Low Calorie Diet, in Treatment of Dyslipidemia and Hypertension. Biology and Medicine. 2015;7(5).
40. Mazza A, Lenti S, Schiavon L, Di Giacomo E, Tomasi M, Manunta R, et al. Effect of Monacolin K and COQ10 supplementation in hypertensive and hypercholesterolemic subjects with metabolic syndrome. Biomedicine & Pharmacotherapy. 2018;105:992-6.
41. Suresh K, Nangia A. Curcumin: pharmaceutical solids as a platform to improve solubility and bioavailability. CrystEngComm. 2018;20(24):3277-96.
42. Ribeiro MH, Lage P. Naringin: Advances on Resources, Biosynthesis Pathway, Bioavailability, Bioactivity, and Pharmacology. In: Xiao J, editor. Handbook of Dietary Flavonoids. Cham: Springer International Publishing; 2023. p. 1-50.
43. Cai X, Fang Z, Dou J, Yu A, Zhai G. Bioavailability of Quercetin: Problems and Promises. Current Medicinal Chemistry. 2013;20(20):2572-82.
44. Amri A, Chaumeil JC, Sfar S, Charrueau C. Administration of resveratrol: What formulation solutions to bioavailability limitations? Journal of Controlled Release. 2012;158(2):182-93.
45. Lu Q, Lu PM, Piao JH, Xu XL, Chen J, Zhu L, et al. Preparation and physicochemical characteristics of an allicin nanoliposome and its release behavior. LWT - Food Science and Technology. 2014;57(2):686-95.
46. Pan Q, Xie L, Cai P, Wu D, Zhu H, Xu L, et al. Acid-Resistant Nano-antioxidants Based on Epigallocatechin Gallate Alleviate Acute Intestinal and Kidney Inflammation. ACS Applied Materials & Interfaces. 2024;16(35):46090-101.
47. Karroum R, Üçışık MH. Efficacy and safety of sulforaphane-loaded emulsomes as tested on MCF7 and MCF10A cells. Turkish Journal of Biochemistry. 2024;49(5):629-36.
48. Yepes-Molina L, Pérez-Jiménez MI, Martínez-Esparza M, Teruel JA, Ruiz-Alcaraz AJ, García-Peñarrubia P, et al. Membrane Vesicles for Nanoencapsulated Sulforaphane Increased Their Anti-Inflammatory Role on an In Vitro Human Macrophage Model. International Journal of Molecular Sciences. 2022;23(4):1940.
49. Zuccari G, Alfei S. Development of Phytochemical Delivery Systems by Nano-Suspension and Nano-Emulsion Techniques. International Journal of Molecular Sciences. 2023;24(12):9824.
50. Anto S, Tamizharasi S, Prabha T, Gocika G, Punitha S, Thirumaran J, et al. Nanoemulgel as an innovative platform for phytomolecules. Annals of Phytomedicine: An International Journal. 2023;12(2).
51. Pathak A, Faijan M, Adil Tahseen M. Phytosomes as Novel Drug Delivery Methods. International Journal of Innovative Science and Research Technology (IJISRT). 2024:116-23.
52. Tang CH, Chen HL, Dong JR. Solid Lipid Nanoparticles (SLNs) and Nanostructured Lipid Carriers (NLCs) as Food-Grade Nanovehicles for Hydrophobic Nutraceuticals or Bioactives. Applied Sciences. 2023;13(3):1726.
53. Nur'Aini L, Priani SE, Aryani R. Optimasi Formula SNEDDS (Self Nanoemulsifying Drug Delivery System) Minyak Atsiri Bawang Putih. Bandung Conference Series: Pharmacy. 2024;4(2):831-8.
54. Hnamte M, Pulikkal AK. Biocompatible polymeric nanoparticles as carriers for anticancer phytochemicals. European Polymer Journal. 2024;202:112637.
55. Popat RR, Chaudhari HS. Chapter 15 - Dendrimer: A new carrier for herbal medicine. In: Thomas S, Oyedeji AO, Oluwafemi OS, Jaquilin PJR, editors. Nanotechnology in Herbal Medicine. Woodhead Publishing; 2023. p. 405-23.
56. Pyrak B, Gubica T, Rogacka-Pyrak K. Cyclodextrin nanosponges as bioenhancers of phytochemicals. Prospects in Pharmaceutical Sciences. 2024;22(3):170-7.
57. Sengupta P, Das A, Datta D, Dewanjee S, Khanam J, Ghosal K. Novel super porous nanosponge-based drug delivery system synthesized from cyclodextrin/polymer for anti-fungal medication. Reactive and Functional Polymers. 2024;196:105830.
58. Grundy SM, Cleeman JI, Daniels SR, Donato KA, Eckel RH, Franklin BA, et al. Diagnosis and management of the metabolic syndrome: an American Heart Association/National Heart, Lung, and Blood Institute scientific statement: Executive Summary. Critical Pathways in Cardiology. 2005;4(4):198-203.
59. Wang J, Zhang T, Gu R, Ke Y, Zhang S, Su X, et al. Development and Evaluation of Reconstructed Nanovesicles from Turmeric for Multifaceted Obesity Intervention. ACS Nano. 2024;18(34):23117-35.

60. du Preez R, Pahl J, Arora M, Ravi Kumar MNV, Brown L, Panchal SK. Low-Dose Curcumin Nanoparticles Normalise Blood Pressure in Male Wistar Rats with Diet-Induced Metabolic Syndrome. Nutrients. 2019;11(7):1542.
61. Hong Z, Xu Y, Yin JF, Jin J, Jiang Y, Du Q. Improving the effectiveness of (-)-epigallocatechin gallate (EGCG) against rabbit atherosclerosis by EGCG-loaded nanoparticles prepared from chitosan and polyaspartic acid. Journal of Agricultural and Food Chemistry. 2014;62(52):12603-9.
62. Teng W, Zhao L, Yang S, Zhang C, Liu M, Luo J, et al. The hepatic-targeted, resveratrol loaded nanoparticles for relief of high fat diet-induced nonalcoholic fatty liver disease. Journal of Controlled Release. 2019;307:139-49.
63. Ahmad M, Gani A. Development of novel functional snacks containing nano-encapsulated resveratrol with anti-diabetic, anti-obesity and antioxidant properties. Food Chemistry. 2021;352:129323.
64. Khattab A, Ahmed-Farid OA, Nasr Sawsan A. Enhanced brain biodistribution of Ginsenoside Rg1 based self-nanoemulsifying drug delivery system to ameliorate metabolic syndromes and keep homeostatic balance. Journal of Drug Delivery Science and Technology. 2021;61:102276.
65. Shatilo V, Antonyuk-Shcheglova I, Naskalova S, Bondarenko O, Monastyrov M, Prikhna T. Positive effects of Quercetin, Iron Oxide Nanoparticles and Ascorbic Acid composition in the treatment of women with metabolic syndrome. Ageing and Longevity. 2023;4(1):8-15.
66. Rahat I, Yadav P, Singhal A, Fareed M, Purushothaman JR, Aslam M, et al. Polymer lipid hybrid nanoparticles for phytochemical delivery: challenges, progress, and future prospects. Beilstein Journal of Nanotechnology. 2024;15(1):1473-97.
67. Rao NS, Balaji P. Phytonano particles for the Treatment of Type 2 Diabetes Mellitus: A Review. Journal of Advanced Zoology. 2023;44(4):357-73.
68. Hu F, Sun DS, Wang KL, Shang DY. Nanomedicine of Plant Origin for the Treatment of Metabolic Disorders. Frontiers in Bioengineering and Biotechnology. 2022;9.
69. Nouri Z, Hajialyani M, Izadi Z, Bahramsoltani R, Farzaei MH, Abdollahi M. Nanophytomedicines for the Prevention of Metabolic Syndrome: A Pharmacological and Biopharmaceutical Review. Frontiers in Bioengineering and Biotechnology. 2020;8.
70. Yücel Ç, Şeker Karatoprak G. Chapter 3 - Nanotechnology and phytonutrients. In: Khan H, Akkol EK, Daglia M, editors. The Role of Phytonutrients in Metabolic Disorders. Academic Press; 2022. p. 67-102.

HOW TO CITE THIS ARTICLE

Sudhakar S, Rani SS. Phytochemical based nanoformulations: an advanced strategy for the management of metabolic syndrome. J Phytopharmacol 2025; 14(6):536-542. doi: 10.31254/phyto.2025.14615

Creative Commons (CC) License-

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY 4.0) license. This license permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. (http://creativecommons.org/licenses/by/4.0/).