NEWPORT INTERNATIONAL JOURNAL OF SCIENTIFIC AND EXPERIMENTAL SCIENCES (NIJSES)

Volume 7 Issue 2 Page 72-77, 2026

ONLINE ISSN:2992-5819 PRINT ISSN:2992-6149

Open Access

https://doi.org/10.59298/NIJSES/2026/72.7277

Nanotechnology Approaches for Targeting Inflamed White Adipose Tissue: Implications for Insulin Resistance and Metabolic Syndrome

Serunjogi Ruth

Department of Clinical Pharmacy Kampala International University Uganda
Email: ruth.serunjogi@studwc.kiu.ac.ug

ABSTRACT

Nanotechnology has emerged as a transformative approach to targeting metabolic disorders, particularly insulin resistance (IR) and metabolic syndrome (MetS), by addressing the underlying chronic inflammation in white adipose tissue (WAT). In obesity, WAT undergoes hypertrophy and dysregulation, leading to an infiltration of immune cells such as macrophages, which secrete pro-inflammatory cytokines, thereby exacerbating IR and contributing to the development of MetS. Traditional therapies, including insulin sensitizers, face limitations due to systemic side effects and suboptimal targeting of inflamed adipose tissue. Nanotechnology, with its ability to deliver therapeutic agents precisely to WAT, offers a solution to these challenges. This review explores the role of nanomaterials, including nanoparticles (NPs), nanostructured lipid carriers (NLCs), and nanosensors, in targeting inflamed adipocytes. Nanoparticles can be designed to encapsulate anti-inflammatory agents, modulate immune responses, and restore insulin sensitivity in adipose tissue. We provide an in-depth overview of various nanotechnology-based strategies for targeting WAT inflammation, including the development of functionalized nanocarriers that improve drug delivery specificity and minimize adverse effects. Furthermore, we examine the potential for clinical translation of these approaches and address the challenges, such as biocompatibility, targeting efficiency, and scalability. Ultimately, nanotechnology holds promise in providing more effective, personalized treatments for individuals suffering from IR and MetS, addressing the root causes of these disorders at the cellular level.

Keywords: Nanotechnology; White adipose tissue; Insulin resistance; Metabolic syndrome; Nanoparticles

INTRODUCTION

The global prevalence of obesity, insulin resistance (IR), and metabolic syndrome (MetS) has reached alarming levels, constituting significant public health challenges[1–4]. These interconnected conditions are associated with an increased risk of developing type 2 diabetes, cardiovascular diseases, and other metabolic disorders. Central to the development of IR and MetS is chronic low-grade inflammation in white adipose tissue (WAT), which is thought to contribute to impaired insulin signaling and metabolic dysfunction.[1, 5–7]

WAT, which was once considered a passive energy store, is now recognized as an active endocrine organ that secretes a variety of hormones and cytokines that regulate metabolic processes. In healthy individuals, WAT maintains metabolic homeostasis through the release of adipokines such as leptin, adiponectin, and resistin, which play key roles in energy balance and insulin sensitivity[8, 9]. However, in obesity, the expansion of WAT leads to alterations in adipocyte function, resulting in an inflammatory response. Adipocytes undergo hypertrophy and cellular stress, leading to hypoxia and apoptosis. These cellular changes recruit immune cells, primarily macrophages, to infiltrate the tissue[8, 10–12]. Macrophages, in turn, secrete pro-inflammatory cytokines such as TNF-α, IL-6, and IL-1β, which contribute to systemic inflammation and exacerbate IR. This

inflammatory environment disrupts normal insulin signaling pathways in both adipocytes and other insulin-responsive tissues, such as skeletal muscle and liver, impairing glucose uptake and lipid metabolism[13–16].
Nanotechnology has emerged as a promising tool for addressing this issue by providing targeted delivery of therapeutic agents to inflamed WAT, thus modulating inflammation at its source[17–19]. The ability of nanomaterials to deliver drugs with high specificity to adipose tissue and to bypass systemic circulation offers significant advantages over traditional treatments. Nanoparticles (NPs) can be engineered to encapsulate anti-inflammatory agents, cytokine inhibitors, and insulin-sensitizing compounds, ensuring that these agents reach the inflamed tissue at the appropriate concentration and site of action[20–22]. Furthermore, the biocompatibility and surface functionalization of NPs allow for the incorporation of targeting ligands, such as antibodies or peptides, that can specifically bind to receptors expressed on inflamed adipocytes or macrophages, enhancing the specificity and efficacy of the therapy. This review aims to provide a comprehensive overview of the mechanisms by which WAT inflammation contributes to IR and MetS, and how nanotechnology can be used to target and modulate this inflammation. We will discuss various nanotechnology approaches, including the use of nanoparticles, nanostructured lipid carriers (NLCs), and nanomicelles, for the delivery of anti-inflammatory drugs and other therapeutic agents to adipose tissue. We will also explore the challenges associated with the clinical application of nanotechnology, including issues related to targeting efficiency, biocompatibility, and scalability.

2. Pathophysiology of White Adipose Tissue Inflammation

In obesity, the accumulation of excess white adipose tissue (WAT) leads to a range of metabolic disturbances, with inflammation at the core of the pathological process. Under normal conditions, WAT functions as an energy reservoir, storing excess calories as triglycerides and releasing free fatty acids (FFAs) in response to hormonal signals[6, 10, 15, 23]. However, in the obese state, adipocytes undergo hypertrophy, leading to an increase in the size and number of fat cells. This expansion of WAT often exceeds the tissue's capacity to maintain an adequate blood supply, resulting in hypoxia. Hypoxic conditions in adipocytes contribute to cellular stress and the activation of inflammatory pathways[24, 25].
As adipocytes become stressed, they release signals that recruit immune cells to the tissue. Macrophages, which are the primary immune cells in adipose tissue, infiltrate WAT and undergo polarization[24, 25]. In obesity, macrophages predominantly adopt the pro-inflammatory M1 phenotype, characterized by the secretion of cytokines such as TNF-α, IL-6, and IL-1β. These pro-inflammatory mediators exacerbate adipocyte dysfunction and interfere with insulin signaling pathways[13, 14, 26]. The inflammatory milieu also promotes the secretion of other adipokines, such as resistin, which further contribute to insulin resistance. In addition to macrophages, other immune cells, including neutrophils and T-cells, also play roles in WAT inflammation, contributing to the overall inflammatory burden.
The persistence of low-grade inflammation in WAT impairs insulin sensitivity by several mechanisms. One of the primary pathways involves the activation of pro-inflammatory signaling cascades, such as nuclear factor kappa B (NF-κB), which impairs insulin receptor signaling and decreases glucose uptake in adipocytes and muscle cells. Furthermore, the increased release of FFAs from hypertrophic adipocytes further exacerbates insulin resistance by inducing lipotoxicity in peripheral tissues[27, 28]. Over time, this results in a vicious cycle of inflammation, metabolic dysfunction, and worsening insulin resistance[29].
Understanding the cellular mechanisms underlying WAT inflammation is essential for designing targeted therapies to address these processes. Nanotechnology offers a promising solution for modulating these inflammatory pathways by delivering anti-inflammatory agents directly to the site of action, thereby reducing systemic side effects and improving the efficacy of treatment.

3. Nanotechnology in Medicine: An Overview

Nanotechnology refers to the manipulation and application of materials at the nanometer scale (1–100 nm), allowing for the development of new materials with unique physical, chemical, and biological properties. In the field of medicine, nanotechnology has revolutionized drug delivery systems by providing enhanced control over the release and targeting of therapeutic agents[19, 30]. Nanoparticles (NPs), nanostructured lipid carriers (NLCs), liposomes, and dendrimers are commonly used nanomaterials that offer several advantages over traditional drug delivery systems. These include improved bioavailability, increased drug stability, enhanced cellular uptake, and the ability to deliver drugs to specific tissues or cells[31, 32].
One of the most promising applications of nanotechnology in medicine is the targeted delivery of drugs to specific tissues, which is particularly important in the treatment of metabolic disorders such as insulin resistance and metabolic syndrome[33]. Traditional therapies for these conditions often suffer from poor targeting and systemic side effects, making nanotechnology a powerful tool to enhance therapeutic efficacy while minimizing adverse effects.
Nanoparticles can be engineered to encapsulate various therapeutic agents, including small molecule drugs, proteins, and nucleic acids. The surface of these nanoparticles can be functionalized with ligands such as antibodies, peptides, or small molecules that enable specific binding to target receptors on cells of interest[34–36]. In the case of metabolic syndrome and insulin resistance, nanoparticles can be designed to target inflamed white adipose tissue, where they can deliver anti-inflammatory drugs, insulin-sensitizing agents, or other therapeutic molecules directly to adipocytes and macrophages.

Additionally, the small size of nanoparticles allows them to easily penetrate biological barriers, such as the blood-brain barrier or the endothelial lining of blood vessels, enabling more efficient drug delivery[35, 37]. Nanoparticles can also be designed to release their payload in a controlled and sustained manner, ensuring that therapeutic agents are delivered over time to maintain their effect without requiring frequent dosing.

Nanotechnology offers a wide range of possibilities for improving the treatment of insulin resistance and metabolic syndrome by providing targeted, efficient, and controlled drug delivery. The ability to design nanoparticles that specifically target inflamed adipose tissue represents a significant step forward in addressing the underlying causes of these metabolic disorders.

4. Nanotechnology Approaches for Targeting Inflamed White Adipose Tissue

Nanotechnology-based drug delivery systems have gained significant attention in recent years as promising approaches to treat insulin resistance (IR) and metabolic syndrome (MetS). The ability of nanoparticles (NPs) to target inflamed white adipose tissue (WAT) with high specificity allows for more effective treatment strategies compared to traditional systemic therapies[38, 39]. Various types of nanomaterials have been developed to address this need, each with distinct properties that make them suitable for targeting WAT and modulating inflammation.

One of the most commonly used nanomaterials for targeting inflamed adipose tissue is lipid-based nanoparticles, such as nanostructured lipid carriers (NLCs). These NLCs are composed of solid and liquid lipid phases, which provide excellent encapsulation efficiency for hydrophobic drugs[40]. NLCs can be functionalized with ligands such as peptides or antibodies that recognize specific receptors on adipocytes or macrophages, enabling targeted delivery of anti-inflammatory agents or insulin-sensitizing drugs[41]. Moreover, the ability to control the release kinetics of NLCs allows for sustained therapeutic effects.

Polymeric nanoparticles are another class of nanomaterials that have shown promise in targeting WAT. These nanoparticles are composed of biocompatible and biodegradable polymers, such as poly(lactic-co-glycolic acid) (PLGA), which can encapsulate a wide range of drugs. The surface of polymeric nanoparticles can be modified with targeting ligands to improve tissue-specific delivery, while the polymers themselves can be designed to degrade over time, releasing the drug in a controlled manner[42, 43].

Nanomicelles, which are amphiphilic nanoparticles composed of surfactant molecules, are also being investigated for the delivery of hydrophobic drugs to WAT. These nanocarriers can solubilize hydrophobic drugs and improve their bioavailability. Furthermore, nanomicelles can be modified to target specific receptors on inflamed adipocytes or macrophages, enhancing their specificity for WAT[44].

Nanoparticles can also be used to deliver non-drug therapeutic agents, such as nucleic acids, including siRNA or miRNA, which can regulate the expression of genes involved in inflammation or insulin signaling[45]. By targeting the inflammatory pathways in WAT, these nanomaterials can reduce the activation of macrophages and decrease the production of pro-inflammatory cytokines[45].

Despite the promising potential of these nanotechnology approaches, several challenges remain in their clinical application. These include issues related to biocompatibility, toxicity, and scalability. Nonetheless, ongoing research into the optimization of nanomaterials and targeting strategies continues to advance the development of nanotechnology-based therapies for metabolic diseases.

5. Role of Nanoparticles in Modulating Adipose Tissue Macrophage Activation

Macrophages play a critical role in the inflammatory response of white adipose tissue (WAT), particularly in the context of obesity and insulin resistance. Macrophages in WAT undergo polarization into two distinct phenotypes: the pro-inflammatory M1 phenotype and the anti-inflammatory M2 phenotype[46]. M1 macrophages secrete a variety of pro-inflammatory cytokines, including TNF-α, IL-6, and IL-1β, which exacerbate inflammation and contribute to the development of insulin resistance. In contrast, M2 macrophages promote tissue repair and the resolution of inflammation. The polarization of macrophages in WAT plays a key role in the progression of insulin resistance and metabolic syndrome[46].

Nanotechnology offers a promising approach to modulate macrophage activation in WAT. Nanoparticles can be engineered to deliver therapeutic agents that promote the M2 phenotype or suppress the M1 phenotype, thus reducing inflammation and improving insulin sensitivity[5, 8, 27]. For example, nanoparticles loaded with anti-inflammatory drugs or cytokine inhibitors can selectively target macrophages in inflamed adipose tissue, where they can inhibit the secretion of pro-inflammatory cytokines and promote the polarization of macrophages towards the M2 phenotype.

In addition to delivering anti-inflammatory agents, nanoparticles can also be designed to influence macrophage polarization directly by targeting specific signaling pathways. For example, nanoparticles can be functionalized with ligands that bind to receptors on macrophages involved in the regulation of polarization, such as the Toll-like receptors (TLRs) or the peroxisome proliferator-activated receptor (PPAR)γ[47]. By modulating these pathways, nanoparticles can shift the balance of macrophage polarization in favor of the M2 phenotype, thereby reducing inflammation and improving metabolic outcomes.

6. Challenges and Limitations in Nanotechnology for Metabolic Syndrome

While the potential of nanotechnology in treating insulin resistance and metabolic syndrome is immense, there are several challenges that need to be addressed before these therapies can be widely implemented. One of the primary concerns is the biocompatibility and toxicity of nanoparticles. Although many nanomaterials are

biocompatible, the long-term safety of these materials remains uncertain, particularly when used for chronic conditions such as metabolic syndrome[48]. The potential for nanoparticles to accumulate in various organs, including the liver, kidneys, and spleen, raises concerns about their toxicity and potential adverse effects.

Another major challenge is achieving targeted delivery of nanoparticles to specific regions of adipose tissue. Despite the ability of nanoparticles to be functionalized with targeting ligands, the efficiency of targeting remains a critical issue[49]. Inflammation in WAT is often heterogeneous, with different regions of the adipose tissue displaying varying levels of inflammation. Developing nanoparticles that can specifically target areas of the tissue with the highest degree of inflammation will be essential for maximizing therapeutic efficacy[49].

Furthermore, the scale-up production of nanoparticles for clinical use presents logistical challenges. Producing nanoparticles in large quantities with consistent quality and functionality is a complex and expensive process. Additionally, regulatory hurdles related to the approval of nanomaterial-based therapies remain a significant barrier to the clinical translation of these treatments.

CONCLUSION

Nanotechnology represents a promising approach to targeting inflamed white adipose tissue in insulin resistance and metabolic syndrome. By delivering therapeutic agents specifically to adipocytes and macrophages in the inflamed tissue, nanomaterials offer the potential for more effective treatments with reduced side effects compared to traditional therapies. Nanotechnology-based approaches, such as nanoparticles and nanostructured lipid carriers, have shown promise in modulating inflammation, improving insulin sensitivity, and restoring metabolic function. However, several challenges remain, including issues related to biocompatibility, targeted delivery efficiency, and the scalability of production. Overcoming these challenges will be essential for the successful clinical application of nanotechnology in metabolic disorders. With continued advancements in nanomaterials and targeting strategies, nanotechnology holds great promise for revolutionizing the treatment of insulin resistance and metabolic syndrome, offering personalized therapies that address the underlying causes of these complex conditions.

REFERENCES

1. Alanazi, A., Craven, A., Spirou, S.V., Santos-Martinez, M.J., Medina, C., Gobbo, O.L.: Nanomedicine as a Promising Treatment Approach for Obesity. J. Nanotheranostics. 6, (2025). https://doi.org/10.3390/jnt6030021
2. 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 Chem. X. 21, 101233 (2024). https://doi.org/10.1016/j.fochx.2024.101233
3. Alum, E.U.: Metabolic memory in obesity: Can early-life interventions reverse lifelong risks? Obes. Med. 55, 100610 (2025). https://doi.org/10.1016/j.obmed.2025.100610
4. Ugwu, O.P.-C., Wokoma, M.A., Oplekwu, R.I., Atangwho, I.J., Egbung, G.E.: Targeting CD44-Hyaluronic Acid Signalling in Obesity Treatment: Insights from Small Molecules and Nanobioconjugates. Nutr. Metab. Insights. 19, 11786388251408961 (2026). https://doi.org/10.1177/11786388251408961
5. Gkrinia, E.M.M., Belančić, A.: The Mechanisms of Chronic Inflammation in Obesity and Potential Therapeutic Strategies: A Narrative Review. Curr. Issues Mol. Biol. 47, (2025). https://doi.org/10.3390/cimb47050357
6. Jayarathne, S., Koboziev, I., Park, O.-H., Oldewage-Theron, W., Shen, C.-L., Moustaid-Moussa, N.: Anti-Inflammatory and Anti-Obesity Properties of Food Bioactive Components: Effects on Adipose Tissue. Prev. Nutr. Food Sci. 22, 251–262 (2017). https://doi.org/10.3746/pnf.2017.22.4.251
7. Li, R., Andreu-Sánchez, S., Kuipers, F., Fu, J.: Gut microbiome and bile acids in obesity-related diseases. Best Pract. Res. Clin. Endocrinol. Metab. 35, 101493 (2021). https://doi.org/10.1016/j.beem.2021.101493
8. Divella, R., De Luca, R., Abbate, I., Naglieri, E., Daniele, A.: Obesity and cancer: the role of adipose tissue and adipo-cytokines-induced chronic inflammation. J. Cancer. 7, 2346–2359 (2016). https://doi.org/10.7150/jca.16884
9. 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
10. Alexaki, V.I.: Adipose tissue-derived mediators of systemic inflammation and metabolic control. Curr. Opin. Endocr. Metab. Res. 37, 100560 (2024). https://doi.org/10.1016/j.coemr.2024.100560
11. Ariyanto, E.F., Wirajati, F., Rahman, P.H., Berbudi, A., Rohmawaty, E.: Mechanism of action of Indonesian medicinal plants in inhibiting 3T3-L1 adipocyte differentiation: A review. J. Appl. Pharm. Sci. 13, 050–057 (2023). https://doi.org/10.7324/JAPS.2023.6711
12. Auger, C., Kajimura, S.: Adipose Tissue Remodeling in Pathophysiology. Annu. Rev. Pathol. Mech. Dis. 18, 71–93 (2023). https://doi.org/10.1146/annurev-pathol-042220-023633
13. Brancewicz, J., Wójcik, N., Sarnowska, Z., Robak, J., Król, M.: The Multifaceted Role of Macrophages in Biology and Diseases. Int. J. Mol. Sci. 26, 2107 (2025). https://doi.org/10.3390/ijms26052107

14. Guria, S., Hoory, A., Das, S., Chattopadhyay, D., Mukherjee, S.: Adipose tissue macrophages and their role in obesity-associated insulin resistance: an overview of the complex dynamics at play. Biosci. Rep. 43, BSR20220200 (2023). https://doi.org/10.1042/BSR20220200
15. Nawaz, A., Fujisaka, S., Kado, T., Jeelani, I., Tobe, K.: Heterogeneity of adipose tissue-resident macrophages-beyond M1/M2 paradigm. Diabetol. Int. 14, 125–133 (2023). https://doi.org/10.1007/s13340-023-00624-2
16. Obasi, D.C., Abba, J.N., Aniokete, U.C., Okoroh, P.N., Akwari, A.Ak.: Evolving Paradigms in Nutrition Therapy for Diabetes: From Carbohydrate Counting to Precision Diets. Obes. Med. 100622 (2025). https://doi.org/10.1016/j.obmed.2025.100622
17. Wokoma, M.A., Oplekwu, R.I., Atangwho, I.J., Egbung, G.E.: Combined Hyaluronic Acid Nanobioconjugates Impair CD44-Signaling for Effective Treatment Against Obesity: A Review of Comparison with Other Actors. Int. J. Nanomedicine. 20, 10101–10126 (2025). https://doi.org/10.2147/IJN.S529250
18. 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
19. Sukubo, N.G., Bigini, P., Morelli, A.: Nanocarriers and macrophage interaction: from a potential hurdle to an alternative therapeutic strategy. Beilstein J. Nanotechnol. 16, 97–118 (2025). https://doi.org/10.3762/bjnano.16.10
20. Anselmo, A.C., Mitragotri, S.: A Review of Clinical Translation of Inorganic Nanoparticles. AAPS J. 17, 1041–1054 (2015). https://doi.org/10.1208/s12248-015-9780-2
21. Fatima, I., Khan, A., Rahdar, A., Fathi-karkan, S., Kharaba, Z., Baino, F.: Optimized mesalamine-loaded polyelectrolyte complex nanoparticles for targeted colon delivery in inflammatory bowel disease treatment: A central composite design approach. Mater. 8, 100530 (2025). https://doi.org/10.1016/j.nxmate.2025.100530
22. Ghandforoushan, P., Hanaee, J., Aghazadeh, Z., Samiei, M., Navali, A.M., Khatibi, A., Davaran, S.: Enhancing the function of PLGA-collagen scaffold by incorporating TGF-β1-loaded PLGA-PEG-PLGA nanoparticles for cartilage tissue engineering using human dental pulp stem cells. Drug Deliv. Transl. Res. 12, 2960–2978 (2022). https://doi.org/10.1007/s13346-022-01161-2
23. Trayhurn, P.: Brown Adipose Tissue—A Therapeutic Target in Obesity? Front. Physiol. 9, 1672 (2018). https://doi.org/10.3389/fphys.2018.01672
24. Elieh Ali Komi, D., Shafaghat, F., Christian, M.: Crosstalk Between Mast Cells and Adipocytes in Physiologic and Pathologic Conditions. Clin. Rev. Allergy Immunol. 58, 388–400 (2020). https://doi.org/10.1007/s12016-020-08785-7
25. Zhang, Q., Lu, C., Lu, F., Liao, Y., Cai, J., Gao, J.: Challenges and opportunities in obesity: the role of adipocytes during tissue fibrosis. Front. Endocrinol. 15, (2024). https://doi.org/10.3389/fendo.2024.1365156
26. Alum, E.U., Izah, S.C., Betiang, P.A., Paul-Chima Ugwu, O., Ainebyoona, C., Uti, D.E., Echegu, D.A., Alum, B.N.: The Ketogenic Diet in Obesity Management: Friend or Foe? Cell Biochem. Biophys. (2025). https://doi.org/10.1007/s12013-025-01878-0
27. Minihane, A.M., Vinoy, S., Russell, W.R., Baka, A., Roche, H.M., Tuohy, K.M., Teeling, J.L., Blaak, E.E., Fenech, M., Vauzour, D., McArdle, H.J., Kremer, B.H.A., Sterkman, L., Vafeiadou, K., Benedetti, M.M., Williams, C.M., Calder, P.C.: Low-grade inflammation, diet composition and health: current research evidence and its translation. Br. J. Nutr. 114, 999–1012 (2015). https://doi.org/10.1017/S0007114515002093
28. Wang, Z., Yuan, C., Huang, T., Lu, B.: Early nutritional interventions for chronic low-grade inflammation. Trends Endocrinol. Metab. (2025). https://doi.org/10.1016/j.tem.2025.06.001
29. Aloh, H., Obasi, D., Okoroh, P., Aniokete, U., & Emeruwa, A. (2025). Maternal Nutrition, Toxicants, and Epigenetic Programming of Obesity Across Generations. Diabetes Metabolic Syndrome and Obesity, Volume 18, 4873-4911. https://doi.org/10.2147/dmso.s579409
30. Mansoori, G.-A.: The Role of Nanotechnology to Combat Major Recent Worldwide Challenges. Curr. Appl. Sci. 1, 1–8 (2023). https://doi.org/10.22034/cas.2021.144244
31. Mall, J., Naseem, N., Haider, M.F., Rahman, M.A., Khan, S., Siddiqui, S.N.: Nanostructured lipid carriers as a drug delivery system: A comprehensive review with therapeutic applications. Intell. Pharm. 3, 243–255 (2025). https://doi.org/10.1016/j.ipha.2024.09.005
32. Khan, S., Sharma, A., Jain, V.: An Overview of Nanostructured Lipid Carriers and its Application in Drug Delivery through Different Routes. Adv. Pharm. Bull. 13, 446–460 (2023). https://doi.org/10.34172/apb.2023.056
33. Hu, F., Sun, D.-S., Wang, K.-L., Shang, D.-Y.: Nanomedicine of Plant Origin for the Treatment of Metabolic Disorders. Front. Bioeng. Biotechnol. 9, 811917 (2022). https://doi.org/10.3389/fbioe.2021.811917

34. Sun, X., Zhao, R., Zhao, E., Wang, Q., Lian, W., Xiong, J.: Targeting CD44-positive ovarian cancers *via* engineered paclitaxel prodrug nanoparticles for enhanced chemotherapeutic efficacy. Biomed. Pharmacother. 154, 113655 (2022). https://doi.org/10.1016/j.biopha.2022.113655
35. Zhang, Y., Tian, J.: Strategies, Challenges, and Prospects of Nanoparticles in Gynecological Malignancies. ACS Omega. 9, 37459–37504 (2024). https://doi.org/10.1021/acsomega.4c04573
36. Zheng, J., Sun, Y., Shen, Y., Zhou, Z.: Surface engineering of nanoparticles for precision medicine. Precis. Med. Eng. 2, 100037 (2025). https://doi.org/10.1016/j.preme.2025.100037
37. Ying, S., Guan, Z., Ofoegbu, P.C., Clubb, P., Rico, C., He, F., Hong, J.: Green synthesis of nanoparticles: Current developments and limitations. Environ. Technol. Innov. 26, 102336 (2022). https://doi.org/10.1016/j.eti.2022.102336
38. 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
39. Liu, M., Wang, R., Hoi, M.P.M., Wang, Y., Wang, S., Li, G., Vong, C.T., Chong, C.-M.: Nano-Based Drug Delivery Systems for Managing Diabetes: Recent Advances and Future Prospects. Int. J. Nanomedicine. 20, 6221–6252 (2025). https://doi.org/10.2147/IJN.S508875
40. Alum, E.U., Nwuruku, O.A., Ugwu, O.P.-C., Uti, D.E., Alum, B.N., Edwin, N.: Harnessing nature: plant-derived nanocarriers for targeted drug delivery in cancer therapy. Phytomedicine Plus. 5, 100828 (2025). https://doi.org/10.1016/j.phyplu.2025.100828
41. Priya, Chaudhary, A., Rejeeth, C., Kumar, S., Ding, X., Sharma, A.: Exploring plant-based metallic nanoparticles for advanced medicinal application in diabetes. Nanotechnol. 8, 100243 (2025). https://doi.org/10.1016/j.nxnano.2025.100243
42. Zielińska, A., Carreiró, F., Oliveira, A.M., Neves, A., Pires, B., Venkatesh, D.N., Durazzo, A., Lucarini, M., Eder, P., Silva, A.M., Santini, A., Souto, E.B.: Polymeric Nanoparticles: Production, Characterization, Toxicology and Ecotoxicology. Molecules. 25, 3731 (2020). https://doi.org/10.3390/molecules25163731
43. Eltaib, L.: Polymeric Nanoparticles in Targeted Drug Delivery: Unveiling the Impact of Polymer Characterization and Fabrication. Polymers. 17, (2025). https://doi.org/10.3390/polym17070833
44. Bose, A., Roy Burman, D., Sikdar, B., Patra, P.: Nanomicelles: Types, properties and applications in drug delivery. IET Nanobiotechnol. 15, 19–27 (2021). https://doi.org/10.1049/nbt2.12018
45. Huang, J., Xiao, K.: Nanoparticles-Based Strategies to Improve the Delivery of Therapeutic Small Interfering RNA in Precision Oncology. Pharmaceutics. 14, 1586 (2022). https://doi.org/10.3390/pharmaceutics14081586
46. Dahdah, N., Tercero-Alcázar, C., Malagón, M.M., Garcia-Roves, P.M., Guzmán-Ruiz, R.: Interrelation of adipose tissue macrophages and fibrosis in obesity. Biochem. Pharmacol. 225, 116324 (2024). https://doi.org/10.1016/j.bcp.2024.116324
47. Medrano-Bosch, M., Moreno-Lanceta, A., Melgar-Lesmes, P.: Nanoparticles to Target and Treat Macrophages: The Ockham's Concept? Pharmaceutics. 13, 1340 (2021). https://doi.org/10.3390/pharmaceutics13091340
48. Cheng, T.-M., Chu, H.-Y., Huang, H.-M., Li, Z.-L., Chen, C.-Y., Shih, Y.-J., Whang-Peng, J., Cheng, R.H., Mo, J.-K., Lin, H.-Y., Wang, K.: Toxicologic Concerns with Current Medical Nanoparticles. Int. J. Mol. Sci. 23, (2022). https://doi.org/10.3390/ijms23147597
49. Barua, S., Mitragotri, S.: Challenges associated with Penetration of Nanoparticles across Cell and Tissue Barriers: A Review of Current Status and Future Prospects. Nano Today. 9, 223–243 (2014). https://doi.org/10.1016/j.nantod.2014.04.008

CITE AS: Serunjogi Ruth (2026). Nanotechnology Approaches for Targeting Inflamed White Adipose Tissue: Implications for Insulin Resistance and Metabolic Syndrome. NEWPORT INTERNATIONAL JOURNAL OF SCIENTIFIC AND EXPERIMENTAL SCIENCES, 7(2):72-77. https://doi.org/10.59298/NIJSES/2026/72.7277