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Review Article

NANOEMULGEL DRUG DELIVERY SYSTEMS FOR WOUND HEALING APPLICATIONS: FOCUS ON CARVACROL AND ANTIMICROBIAL ACTIVITY

Alam Md Noorjamal*, Chasta Pankaj, Sharma Gaurav Kumar, Sharma Tanya
Department of Pharmacy, Mewar University, Gangrar, Chittorgarh -312901 (Rajasthan), India

In this review paper we focused on wound infections remain a major clinical challenge because microbial contamination can delay tissue repair and increase the risk of chronic wounds. Conventional topical formulations such as creams and ointments often suffer from poor drug penetration, low stability, and limited antimicrobial effectiveness. In recent years, nanotechnology-based drug delivery systems have attracted significant attention for improving the therapeutic performance of topical agents. Among these systems, nanoemulgels combine the advantages of nanoemulsions and hydrogels, providing enhanced drug solubility, controlled release, improved stability, and better skin permeation.Carvacrol, a naturally occurring phenolic monoterpene found in essential oils of plants such as Origanum vulgare and Thymus vulgaris, has gained considerable attention due to its strong antimicrobial, anti-inflammatory, and antioxidant properties. These pharmacological activities make carvacrol a promising candidate for the management of infected wounds. However, its clinical application is limited by poor aqueous solubility, volatility, and rapid degradation. Incorporating carvacrol into nanoemulgel systems offers an effective strategy to overcome these limitations by enhancing drug stability, improving bioavailability, and facilitating sustained drug release at the wound site.This review highlights the potential of nanoemulgel-based drug delivery systems for wound healing applications, with particular emphasis on carvacrol-loaded formulations. The article discusses the physiological stages of wound healing, the role of microbial infections in delayed healing, and the advantages of nanoemulgel systems over conventional topical formulations. In addition, formulation strategies, characterization techniques, and in vitro evaluation methods used in the development of carvacrol-loaded nanoemulgels are summarized. Recent advances and future perspectives of nanoemulgel technology in antimicrobial wound therapy are also discussed. Overall, nanoemulgel systems represent a promising approach for improving the therapeutic effectiveness of natural antimicrobial compounds in wound management.

Keywords: Nanoemulgel; Carvacrol; Wound healing; Antimicrobial activity; Topical drug delivery; Nanoemulsion; Controlled drug release.

INTRODUCTION

Wound healing is a complex and dynamic biological process that restores the integrity and function of damaged skin and underlying tissues. It involves a sequence of well-coordinated events, including hemostasis, inflammation, proliferation, and tissue remodelling. These stages work together to repair the injured area and protect the body from infection and further damage. Proper wound healing is clinically important because delayed or impaired healing can lead to chronic wounds, increased healthcare costs, and reduced quality of life for patients.[1] Conditions such as diabetes, microbial infections, and poor blood circulation often interfere with the natural healing process and make wound management more challenging. Wound healing is a complex biological process that restores the integrity and function of damaged tissues after injury.

Every year, millions of patients worldwide suffer from various types of wounds caused by trauma, surgery, burns, and chronic diseases. The global burden of wounds is increasing due to aging populations, lifestyle disorders, and the rising prevalence of chronic diseases such as Diabetes Mellitus, which significantly delays the natural healing process.[2] Worldwide, chronic wounds affect a large number of patients and create a significant healthcare challenge. Conditions such as Diabetic Foot Ulcer, Pressure Ulcers, and Venous Leg Ulcers are among the most common types of non-healing wounds. These wounds often require long-term medical care, increasing the economic burden on healthcare systems globally. [3]According to global health reports, chronic wounds affect millions of people annually and are responsible for prolonged hospital stays, repeated treatments, and reduced quality of life. Conventional wound treatment methods commonly involve the use of creams, ointments, and topical antibiotics.[4] Although these approaches are widely used, they often suffer from several limitations, including poor drug penetration through the skin, low stability of active ingredients, rapid drug degradation, and insufficient antimicrobial activity. In addition, frequent application of conventional formulations may be required to maintain therapeutic effectiveness, which can reduce patient compliance.To overcome these challenges, researchers have increasingly focused on advanced drug delivery systems that can improve the therapeutic efficiency of topical treatments. Nanotechnology-based systems have emerged as promising strategies for enhancing drug solubility, stability, and controlled release.[5] Among these systems, nanoemulgels have attracted significant attention because they combine the advantages of nanoemulsions and hydrogels. Nanoemulgels provide improved drug loading capacity, enhanced skin permeation, better stability, and prolonged drug release, making them suitable for topical drug delivery applications.[6]Natural bioactive compounds have also gained considerable interest in wound healing therapy due to their antimicrobial, anti-inflammatory, and antioxidant properties. One such compound is Carvacrol, a phenolic monoterpene commonly found in the essential oils of aromatic plants such as Origanum vulgare and Thymus vulgaris. Carvacrol exhibits strong antimicrobial activity against various pathogenic microorganisms and has shown potential in promoting wound healing. However, its poor water solubility and volatility limit its direct therapeutic use, which highlights the need for suitable delivery systems.[7]Therefore, incorporating carvacrol into nanoemulgel-based formulations may enhance its stability,

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Figure 1: overview of wound healing and its clinical importance.

bioavailability, and antimicrobial effectiveness at the wound site. The aim of this review is to provide a comprehensive overview of nanoemulgel drug delivery systems for wound healing applications, with a particular focus on carvacrol and its antimicrobial activity. The review discusses the challenges of conventional wound therapy, the advantages of nanoemulgel formulations, and recent advances in the development and evaluation of carvacrol-loaded nanoemulgels for improved wound management.[8,9]

2. Physiology of Wound Healing

The physiology of wound healing is a complex and well-coordinated biological process that restores the integrity and function of damaged tissues following injury. It involves a series of overlapping cellular and molecular events that occur in a regulated manner to repair the injured skin or tissue. [10]This process is essential for maintaining the protective barrier of the body and preventing infection or further tissue damage. Wound healing generally progresses through four main phases: hemostasis, inflammation, proliferation, and remodelling, each of which plays a critical role in tissue repair.The initial phase, known as hemostasis, begins immediately after tissue injury. During this stage, blood vessels constrict to reduce bleeding, and platelets rapidly

aggregate at the injury site to form a fibrin clot.[11] This clot not only stops blood loss but also acts as a temporary matrix that supports cell migration and tissue repair. Platelets also release several growth factors and cytokines that activate the subsequent inflammatory response. Following haemostasis, the inflammatory phase occurs, typically lasting several days. During this stage, immune cells such as neutrophils and macrophages migrate to the wound site to remove bacteria, debris, and damaged tissue.[12] These cells play an essential role in preventing infection and producing signalling molecules that regulate the healing process. The proliferation phase is characterized by the formation of new tissue. Fibroblasts actively synthesize collagen and other extracellular matrix components, which provide structural support to the regenerating tissue. At the same time, angiogenesis leads to the formation of new blood vessels, ensuring an adequate supply of oxygen and nutrients to the healing tissue. Additionally, epithelial cells migrate and proliferate to cover the wound surface, a process known as re-epithelialization.[13] Remodelling or maturation phase occurs, during which collagen fibres are reorganized and strengthened, leading to increased tensile strength of the repaired tissue. Over time, the scar tissue gradually matures, and the wound regains functional stability. The successful completion of these coordinated phases is essential for effective wound repair, while disturbances in any stage may lead to delayed healing or chronic wound formation.[14]

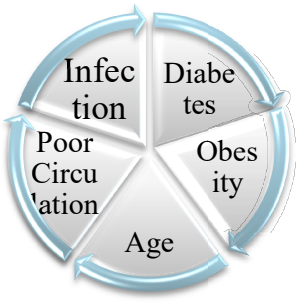

Figure 2: Factors in Wound Healing

3. Microbial Infections in Wounds

Wound healing is a complex physiological process that can be significantly impaired by microbial infections. Open wounds provide a favorable environment for microbial colonization due to the presence of moisture, nutrients, and exposed tissue. When microorganisms invade the wound site, they can multiply rapidly, leading to infection, inflammation, and delayed tissue repair.[15] Microbial contamination is one of the most common complications in wound management and represents a major challenge in both acute and chronic wounds. Several pathogenic microorganisms are commonly associated with wound infections. Among bacterial pathogens, Staphylococcus aureus is one of the most frequently isolated organisms from infected wounds. It can cause severe skin and soft tissue infections due to its ability to produce toxins and form biofilms.[16] Another common

pathogen is Pseudomonas aeruginosa, which is particularly prevalent in burn wounds and chronic ulcers. This bacterium is known for its high resistance to antibiotics and its ability to thrive in moist environments. Other significant wound pathogens include Escherichia coli, Klebsiella pneumoniae, and Streptococcus pyogenes, which can contribute to severe infection and tissue damage. Microbial infection can greatly delay the wound healing process.[17] The presence of pathogenic microorganisms stimulates prolonged inflammation, which disrupts the normal stages of wound healing. Bacteria release toxins, enzymes, and other virulence factors that damage surrounding tissues and inhibit the activity of fibroblasts and keratinocytes, which are essential for tissue regeneration. Additionally, many bacteria form biofilms, structured communities of microorganisms that adhere to the wound surface and are highly resistant to antibiotics and immune responses.[18] These biofilms act as protective barriers, making infections persistent and difficult to treat.The impact of microbial infection on wound healing includes increased tissue necrosis, excessive exudate formation, and delayed re-epithelialization. Chronic wounds such as diabetic ulcers, pressure ulcers, and burn wounds are particularly susceptible to microbial colonization, which can lead to prolonged healing times and increased risk of systemic infection.Effective antimicrobial therapy plays a crucial role in wound management.[19] The use of topical and systemic antimicrobial agents helps reduce the microbial load at the wound site and prevents the spread of infection. Antimicrobial dressings, antiseptic solutions, and advanced drug delivery systems are commonly employed to control microbial growth. Recently, novel drug delivery systems such as nanoemulsions and nanoemulgels have gained attention for their ability to enhance the delivery of antimicrobial agents directly to the wound site.[20] Natural bioactive compounds with antimicrobial properties, such as plant-derived essential oils, are also being explored as promising alternatives for infection control. Proper antimicrobial therapy not only eliminates pathogenic microorganisms but also promotes faster wound healing by restoring the natural healing environment.[21]

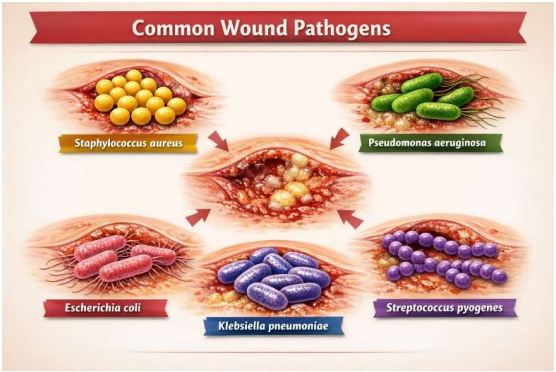

Figure 3: Common Wound Pathogens

4. Carvacrol as a Bioactive Compound for Wound Healing

Carvacrol is a naturally occurring monoterpen-

-oid phenolic compound widely recognized for its significant antimicrobial, anti-inflammatory, and antioxidant properties. It is primarily found in essential oils of aromatic medicinal plants such as Origanum vulgare (oregano) and Thymus vulgaris (thyme). [22]Due to its potent biological activities, carvacrol has gained considerable attention as a promising natural bioactive compound for wound healing applications. Natural plant-derived compounds are increasingly being explored in modern pharmaceutical formulations because of their therapeutic efficacy and relatively lower toxicity compared to synthetic drugs.[23]

Natural Sources of Carvacrol

Carvacrol is mainly obtained from essential oils of plants belonging to the Lamiaceae family. The highest concentrations are found in Origanum vulgare, Thymus vulgaris, and Satureja hortensis (summer savory). These plants have been traditionally used in herbal medicine for the treatment of infections, inflammation, and skin disorders. The essential oils extracted from these plants contain carvacrol as a major active constituent responsible for their antimicrobial and therapeutic activities.[24,25]

Chemical Structure and Physicochemical Properties

Carvacrol is chemically classified as a monoterpenoid phenol with the molecular formula $C_{10}H_{14}O$. Structurally, it consists of a phenolic ring substituted with a methyl group and an isopropyl group, which contribute to its lipophilic nature. The compound is slightly soluble in water but highly soluble in organic solvents and lipids. These physicochemical properties enable carvacrol to interact with biological membranes and penetrate microbial cell walls effectively. However, its hydrophobic nature also limits its direct application in aqueous pharmaceutical formulations.[26,27]

Antimicrobial Mechanism of Action

Carvacrol exhibits broad-spectrum antimicrobial activity against a wide range of pathogenic microorganisms. Studies have demonstrated its effectiveness against common wound pathogens such as Staphylococcus aureus, Pseudomonas aeruginosa, and Escherichia coli. The antimicrobial mechanism of carvacrol primarily involves disruption of microbial cell membranes. Due to its lipophilic nature, carvacrol can integrate into the phospholipid bilayer of bacterial membranes, leading to increased membrane permeability. This results in leakage of intracellular components, disruption of ion gradients, and eventual cell death. Additionally, carvacrol may interfere with enzyme activity and energy metabolism in microbial cells, further enhancing its antibacterial effects.[28,29]

Stages in Wounds Healing

Anti-inflammatory and Antioxidant Properties

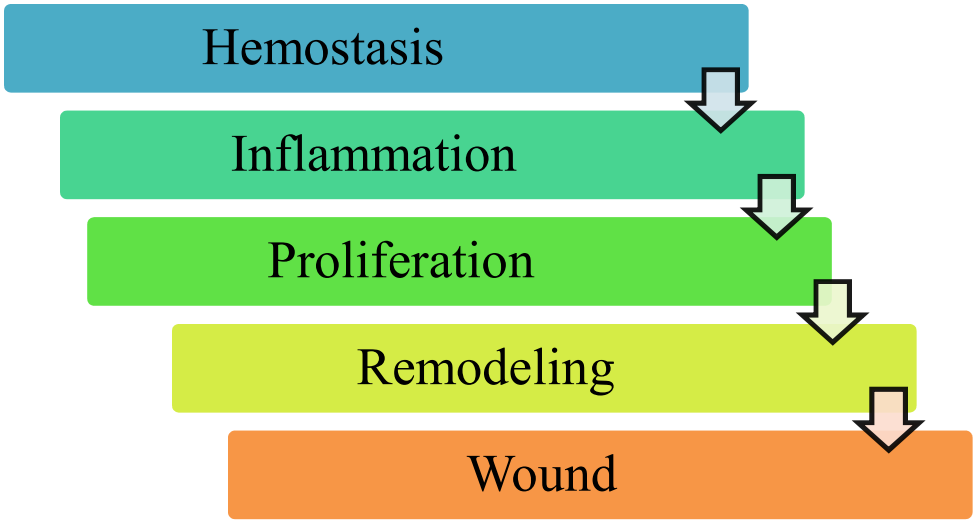

Figure 4: Stages of wound Healing

In addition to its antimicrobial activity, carvacrol possesses significant anti-inflammatory and antioxidant properties that contribute to wound healing. It can modulate inflammatory responses by reducing the production of pro-inflammatory mediators and cytokines.[30] This helps control excessive inflammation at the wound site, which is essential for proper tissue repair. Furthermore, carvacrol acts as a free radical scavenger, neutralizing reactive oxygen species (ROS) that can damage cells and delay healing. By reducing oxidative stress and inflammation, carvacrol promotes faster tissue regeneration and improved wound healing outcomes.[31]

Limitations of Conventional Delivery of Carvacrol

Despite its promising therapeutic potential, the conventional delivery of carvacrol presents several challenges. The compound has poor water solubility, high volatility, and limited stability when exposed to light and air. These factors can reduce its bioavailability and therapeutic effectiveness when applied directly to the skin or wound surface. Moreover, rapid evaporation and degradation may limit its sustained antimicrobial activity. To overcome these limitations, advanced drug delivery systems such as nanoemulsions, liposomes, and nanoemulgels have been developed to enhance the stability, controlled release, and bioavailability of carvacrol in topical formulations.[32,33]

6. Recent Advances in Nanoemulgel for Wound Healing

Recent developments in nanotechnology have significantly improved the design and performance of nanoemulgel systems for wound healing applications. Nanoemulgels combine the advantages of nanoemulsions

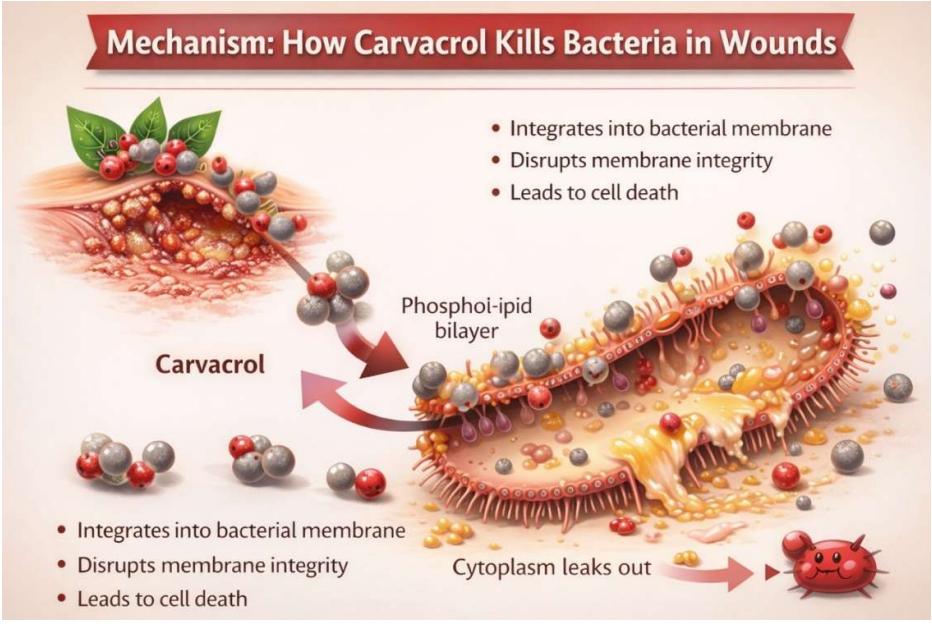

Figure 4: Mechanism of action of carvacrol on bacteria

and hydrogels, offering enhanced drug solubility, improved skin penetration, controlled drug release, and better patient compliance. In recent years, several innovative approaches have been explored to enhance the therapeutic efficiency of nanoemulgel formulations in wound management.[34]

One important advancement is the development of natural compound-loaded nanoemulgels. Many plant-derived bioactive compounds such as carvacrol, curcumin, thymol, eugenol, and aloe vera extract have demonstrated strong antimicrobial, antioxidant, and anti-inflammatory properties that are beneficial for wound healing. However, these compounds often suffer from poor water solubility and low bioavailability. Incorporating them into nanoemulgel systems improves their stability, enhances skin permeation, and allows sustained release at the wound site. Recent studies have shown that nanoemulgels containing natural compounds can effectively reduce microbial infections, promote collagen synthesis, and accelerate tissue regeneration, making them promising alternatives to conventional topical formulations.[35,36]

Another emerging area is the development of smart and responsive nanoemulgel systems. These advanced formulations are designed to respond to specific physiological stimuli present in the wound environment, such as pH, temperature, or enzymatic activity. For example, pH-responsive nanoemulgels can release therapeutic agents selectively in infected or inflamed wound tissues where the pH is slightly acidic. Similarly,

Sustainable Approach	Description	Benefits	Reference
Natural compound-loaded nanoemulgels	Nanoemulgels containing plant-derived bioactive compounds such as **Carvacrol**, curcumin, and essential oils. These natural compounds are incorporated into nanoemulsion droplets and further formulated into gels for topical wound treatment.	Enhanced antimicrobial activity, reduced toxicity, improved wound healing, and better drug penetration into skin tissues.	**[39]**
Smart and responsive nanoemulgel systems	Advanced nanoemulgel formulations designed to respond to environmental stimuli such as pH, temperature, or enzymatic activity at the wound site. These systems release drugs in a controlled and targeted manner.	Controlled drug release, improved therapeutic efficiency, reduced dosing frequency, and targeted treatment at infected wound sites.	**[40]**
Nanotechnology trends in topical therapy	Integration of nanotechnology with topical drug delivery systems including nanoemulsions, nanogels, and nanoemulgels for improved skin permeation and therapeutic effectiveness.	Improved drug stability, enhanced skin penetration, sustained release, and faster wound healing outcomes.	**[41]**

thermoresponsive gels can undergo sol-gel transitions at body temperature, improving drug retention at the application site. Such intelligent systems allow more precise and controlled drug delivery, which enhances therapeutic outcomes while minimizing side effects.[37,38]

12. Challenges and Limitations of nanoemulgels Containing Plant-Derived Bioactive Compounds such as Carvacrol

Nanoemulgel systems have gained significant attention as advanced topical drug delivery platforms for wound healing and antimicrobial therapy. Despite their promising therapeutic potential, several challenges and limitations remain when formulating nanoemulgels containing plant-derived bioactive compounds such as carvacrol.One of the major challenges is formulation stability. Nanoemulsions are thermodynamically unstable systems and may

undergo physical instability over time, including phase separation, droplet aggregation, coalescence, or Ostwald ripening. These issues can lead to changes in droplet size distribution and viscosity of the nanoemulgel, ultimately affecting drug release and therapeutic efficacy.[42] In addition, plant-derived compounds like carvacrol are often sensitive to environmental conditions such as light, temperature, and oxygen, which can cause degradation or loss of bioactivity during storage. Maintaining long-term stability, therefore, requires careful selection of surfactants, co-surfactants, and gelling agents, as well as optimisation of formulation parameters.Another important limitation is related to scale-up and manufacturing challenges. While nanoemulgels can be successfully developed at the laboratory scale, translating these formulations to large-scale industrial production can be complex.[43] The preparation of stable nanoemulsions often requires high-energy techniques such as high-pressure homogenization or ultrasonication, which may be costly and difficult to maintain consistently during large-scale production. Variations in processing conditions, equipment performance, and raw material quality can also affect the reproducibility of the final formulation. These factors may increase manufacturing costs and limit the commercial feasibility of nanoemulgel-based products.[44]Furthermore, regulatory considerations represent a significant barrier to the clinical translation of nanoemulgel formulations containing natural bioactive compounds. Regulatory authorities require extensive evaluation of safety, toxicity, quality, and efficacy before approval. Plant-derived compounds may show variability in composition depending on their natural source, extraction method, and purity, which complicates standardisation and quality control. In addition, there are still limited regulatory guidelines specifically addressing nanotechnology-based topical formulations, which may slow down the approval process. Although nanoemulgels containing plant-derived bioactive compounds such as carvacrol show great potential for topical therapeutic applications, overcoming issues related to formulation stability, large-scale manufacturing, and regulatory approval remains essential for their successful clinical and commercial development.[45]

13. Future Perspectives

Nanoemulgel-based drug delivery systems have demonstrated significant potential to improve wound-healing outcomes; however, further advancements are expected to enhance their clinical applicability and therapeutic efficacy. Future research is likely to focus on integrating nanoemulgels with advanced biomaterials, improving their clinical translation, and developing personalised wound therapy

strategies.One promising direction is the integration of nanoemulgels with advanced biomaterials. The combination of nanoemulgel systems with biomaterials such as biopolymers, hydrogels, nanofibers, and biodegradable scaffolds can enhance the therapeutic performance of wound dressings. Biomaterials such as chitosan, alginate, collagen, and hyaluronic acid possess intrinsic properties, including biocompatibility, biodegradability, and antimicrobial activity, which are beneficial for wound healing. Incorporating nanoemulgels into these biomaterial-based matrices may provide sustained drug release, improved moisture retention, and enhanced protection of the wound site. Such hybrid systems could serve as multifunctional wound dressings capable of promoting tissue regeneration while delivering therapeutic agents in a controlled manner. Another important future direction is the clinical translation potential of nanoemulgel formulations. Although numerous laboratory and preclinical studies have reported promising results, the transition from experimental research to clinical application remains limited. Future studies should emphasize large-scale clinical trials to evaluate the safety, efficacy, and long-term stability of nanoemulgel formulations in human patients. Additionally, standardization of formulation processes, quality control parameters, and regulatory guidelines will be essential to facilitate the commercialization of nanoemulgel-based therapeutic products.The development of personalized wound therapy approaches represents an emerging trend in modern healthcare. Different patients exhibit variations in wound type, severity, infection status, and healing capacity. Personalized nanoemulgel formulations could be designed by tailoring drug combinations, concentrations, and release profiles according to individual patient needs. Advances in precision medicine, biomarker analysis, and digital health technologies may support the development of customized wound care strategies. Such personalized approaches have the potential to optimize therapeutic outcomes, reduce treatment duration, and improve patient quality of life. [46]

CONCLUSION

Nanoemulgel-based drug delivery systems have emerged as promising platforms for improving the effectiveness of topical therapies, particularly in the management of wound infections and delayed wound healing. This review highlights the significant role of nanoemulgels in enhancing the solubility, stability, and skin penetration of therapeutic agents, thereby improving their overall bioavailability and therapeutic outcomes. The integration of nanoemulsion technology with gel-based systems provides a suitable formulation strategy that ensures controlled drug release, prolonged retention at the wound

site, and improved patient compliance. These characteristics make nanoemulgels an attractive alternative to conventional topical formulations. A key focus of this review is the potential of carvacrol-based nanoemulgels for antimicrobial wound healing applications. Carvacrol, a naturally occurring phenolic compound found in essential oils of plants such as oregano and thyme, exhibits strong antimicrobial, antioxidant, and anti-inflammatory properties. However, its clinical application is often limited by poor aqueous solubility and volatility. Incorporation of carvacrol into nanoemulgel formulations can overcome these limitations by enhancing its stability, improving dermal penetration, and enabling sustained release at the wound site. Several studies have demonstrated that carvacrol-loaded nanoemulgels exhibit significant antimicrobial activity against common wound pathogens and may promote faster tissue repair and regeneration. Despite these promising findings, further research is required to fully realize the therapeutic potential of nanoemulgel systems. Future studies should focus on optimizing formulation strategies to improve long-term stability, scalability, and reproducibility of nanoemulgel preparations. In addition, more in vivo and clinical investigations are necessary to confirm their safety, efficacy, and therapeutic advantages in real-world wound management. Advances in nanotechnology, biomaterials, and smart drug delivery systems may further enhance the performance of nanoemulgel formulations. Carvacrol-loaded nanoemulgels represent a promising and innovative approach for antimicrobial wound healing therapy. With continued research and technological development, these advanced formulations have the potential to contribute significantly to the next generation of effective and targeted wound care treatments.

REFERENCE

1. Soliman, W. E., Younis, N. S., Mostafa, S. K., Mohamed, M. E., et al (2025). A novel antibacterial approach: targeting methicillin-resistant Staphylococcus aureus with carvone nanoemulgel. Applied Microbiology and Biotechnology, 109(1), 1-18.
2. Elsayed, T. M. A., Zan, M. A. H. C. M., & Suhaili, Z. (2025). Carvacrol-Loaded Nanoemulgel for Improved Antifungal Effect. Asian Journal of Medicine and Biomedicine, 9(1), 37-47.
3. Alhasso, B. (2023). Development and Characterisation of Nanoemulsion and Nanoemulgel Formulations for Topical Application of mupirocin.
4. Bujubarah, M. M., Elsewedy, H. S., Shehata, T. M., & Soliman, W. E. (2023). Formulation by design of an innovative tea tree oil nanoemulgel incorporating mupirocin for enhanced wound healing activity. Applied

Sciences, 13(24), 13244.

5. Osanloo, M., Noori, F., Varaa, N., Tavassoli, A., et al (2024). The wound healing effect of polycaprolactone-chitosan scaffold coated with a gel containing Zataria multiflora Boiss. volatile oil nanoemulsions. BMC Complementary Medicine and Therapies, 24(1), 56.

6. Elsayed, T. M. A., Zan, M. A. H. C. M., & Suhaili, Z. (2025). Carvacrol-Loaded Nanoemulgel for Improved Antifungal Effect. Asian Journal of Medicine and Biomedicine, 9(1), 37-47.

7. Ali, T., Majeed, S. T., Majeed, R., Bashir, R., Mir, S. A., Jan, I., ... & Andrabi, K. I. (2024). Recent advances in the pharmacological properties and molecular mechanisms of carvacrol. Revista Brasileira de Farmacognosia, 34(1), 35-47.

8. Silva, E. R., de Carvalho, F. O., Teixeira, L. G., et al (2018). Pharmacological effects of carvacrol in in vitro studies: A review. Current pharmaceutical design, 24(29), 3454-65.

9. Suntres, Z. E., Coccimiglio, J., & Alipour, M. (2015). The bioactivity and toxicological actions of carvacrol. Critical reviews in food science and nutrition, 55(3), 304-18.

10. Suganthi, R. U., & Manpal, S. (2013). Biological and pharmacological of actions carvacrol and its effects on poultry: an updated review. World J Pharm Pharm Sci, 2(2013), 3581-95.

11. Imran, M., Aslam, M., Alsagaby, S. A., et al (2022). Therapeutic application of carvacrol: A comprehensive review. Food science & nutrition, 10(11), 3544-61.

12. Suganthi, R. U., & Manpal, S. (2013). Biological and pharmacological of actions carvacrol and its effects on poultry: an updated review. World J Pharm Pharm Sci, 2(2013), 3581-95.

13. Nostro, A. and Papalia, T. (2012). Antimicrobial activity of carvacrol: current progress and future prospectives. Recent patents on anti-infective drug discovery, 7(1), 28-35.

14. Ben Arfa, A., Combes, S., Preziosi-Belloy, L., Gontard, N., & Chalier, P. (2006). Antimicrobial activity of carvacrol related to its chemical structure. Letters in applied microbiology, 43(2), 149-54.

15. Silva, F. V., Guimarães, A. G., Silva, E. R., et al (2012). Anti-inflammatory and anti-ulcer activities of carvacrol, a monoterpene present in the essential oil of oregano. Journal of medicinal food, 15(11), 984-91.

16. Sharifi-Rad, M., Varoni, E. M., Iriti, M., Martorell, M., Setzer, et al, J. (2018). Carvacrol and human health: A comprehensive review. Phytotherapy research, 32(9), 1675-87.

17. Guimarães, A. G., Xavier, M. A., et al (2012). Carvacrol attenuates mechanical hypernociception and inflammatory response. Naunyn-Schmiedeberg's archives of

pharmacology, 385(3), 253-63.

18. Azizi, Z., Ebrahimi, S., Saadatfar, E., Kamalinejad, M., & Majlessi, N. (2012). Cognitive-enhancing activity of thymol and carvacrol in two rat models of dementia. Behavioural pharmacology, 23(3), 241-249.

19. Mohammedi, Z. (2017). Carvacrol: An update of biological activities and mechanism of action. Open Access Journal of Chemistry, 1(1), 53-62.

20. Zotti, M., Colaianna, M., Morgese, M. G., et al (2013). Carvacrol: from ancient flavoring to neuromodulatory agent. Molecules, 18(6), 6161-72.

21. Hoca, M., Becer, E., & Vatansever, H. S. (2024). Carvacrol is potential molecule for diabetes treatment. Archives of Physiology and Biochemistry, 130(6), 823-30.

22. Cavalcante Melo, F. H., Rios, E. R. V., Rocha, et al (2012). Antinociceptive activity of carvacrol (5-isopropyl-2-methylphenol) in mice. Journal of Pharmacy and Pharmacology, 64(12), 1722-29.

23. Bonfim, R. R., Paiva-Souza, et al (2014). Isopropoxy-carvacrol, a derivative obtained from carvacrol, reduces acute inflammation and nociception in rodents. Basic & clinical pharmacology & toxicology, 115(3), 237-43.

24. Scaffaro, R., Maio, A., and Nostro, A. (2020). Poly (lactic acid)/carvacrol-based materials: preparation, physicochemical properties, and antimicrobial activity. Applied microbiology and biotechnology, 104(5), 1823-35.

25. da Silva Lima, M., Quintans-Junior, L. J., de Santana, W. A., Kaneto, C. M., Soares, M. B. P., & Villarreal, C. F. (2013). Anti-inflammatory effects of carvacrol: evidence for a key role of interleukin-10. European journal of pharmacology, 699(1-3), 112-17.

26. Can Baser, K. H., Haskologlu, I. C., & Erdag, E. (2025). An Updated Review of Research into Carvacrol and Its Biological Activities. Records of Natural Products, 19.

27. de Oliveira, A. S., Llanes, L. C., Nunes, R. J., Nucci-Martins, C., de Souza, A. S., et al (2021). Antioxidant activity, molecular docking, quantum studies and in vivo antinociceptive activity of sulfonamides derived from carvacrol. Frontiers in Pharmacology, 12, 788850.

28. Kachur, K., and Suntres, Z. (2020). The antibacterial properties of phenolic isomers, carvacrol and thymol. Critical reviews in food science and nutrition, 60(18), 3042-53.

29. Khazdair, M. R., Moshtagh, M., Anaeigoudari, A., Jafari, S., & Kazemi, T. (2024). Protective effects of carvacrol on lipid profiles, oxidative stress, hypertension, and cardiac dysfunction–A comprehensive review. Food Science & Nutrition, 12(5), 3137-49.

30. Mondal, A., Bose, S., Mazumder, K., and

Khanra, R. (2020). Carvacrol (Origanum vulgare): Therapeutic properties and molecular mechanisms. In Bioactive Natural Products for Pharmaceutical Applications (pp. 437-462). Cham: Springer International Publishing.

31. de Santana, M. T., Silva, V. B., de Brito, R. G., Dos Santos, P. L., et al (2014). Synthesis and pharmacological evaluation of carvacrol propionate. Inflammation, 37(5), 1575-87.

32. Sampaio, L. A., Pina, L. T. S., Serafini, M. R., Tavares, D. D. S., & Guimaraes, A. G. (2021). Antitumor effects of carvacrol and thymol: a systematic review. Frontiers in Pharmacology, 12, 702487.

33. Gandova, V., Lazarov, A., et al. (2023). Physicochemical and biological properties of carvacrol. Open chemistry, 21(1), 20220319.

34. Guimarães, A. G., Oliveira, G. F., Melo, M. S., Cavalcanti, S. C., et al (2010). Bioassay-guided evaluation of antioxidant and antinociceptive activities of carvacrol. Basic & clinical pharmacology & toxicology, 107(6), 949-57.

35. Monzote, L., Scherbakov, A. M. et al (2020). Pharmacological assessment of the carvacrol chemotype essential oil from Plectranthus amboinicus growing in Cuba. Natural Product Communications, 15(10), 1934578X20962233.

36. Alamri, M. A., Abdel-Kader, M. S., Salkini, M. A., & Alamri, M. A. (2024). Thymol and carvacrol derivatives as anticancer agents; synthesis, in vitro activity, and computational analysis of biological targets. RSC advances, 14(42), 30662-672.

37. de Santana Souza, M. T., Teixeira, D. F., de Oliveira, J. P., et al (2017). Protective effect of carvacrol on acetic acid-induced colitis. Biomedicine & Pharmacotherapy, 96, 313-19.

38. Muñoz-Pérez, V. M., Ortiz, M. I., Salas-Casas, A., & Pérez-Sánchez, A. (2024). Thymol and carvacrol as potential tocolytic and anti-inflammatory agents in pregnant rat uterus. Current Molecular Pharmacology, 17(1), E18761429342128.

39. Pinki, K. C., and Duggal, S. (2025). A Review of Nano-Herbal Formulations: A Futuristic Approach in Herbal Drug Delivery. Research Journal of Pharmacy and Medical Sciences (IRJPMS), 8(3), 89-97.

40. Bellarmin, M., Nandhini, J., Karthikeyan, E., Mahalakshmi, D., & Karthik, K. K. (2025). A comprehensive review on stimuli-responsive nanomaterials: advancements in wound healing and tissue regeneration. Biomedical Materials & Devices, 1-25.

41. Alencar, M. S. F., Silva, G. H. C., da Silva, A. A., et al (2024). Evidence-based practices on nanotechnology in wound treatment. Caderno Pedagógico, 21(12), e10234-e10234.

42. Sahoo, u. K., vidyacharan, s., kayal, p., &

jawahar, n. (2025). Nanotechnology-driven innovations in hypertension management: formulation strategies, challenges, and future directions. Nanotechnology, 18(4).

43. Mohamed, D., Skran, W., & Abo-zeid, Y. (2023). Application of several nano carriers to improve the solubility and the bioavailability of Carvedilol. Journal of Advanced Pharmacy Research, 7(1), 50-65.

44. Baveloni, F. G., Riccio, B. V., Di Filippo, L. D., Fernandes, M. A., Meneguin, A. B., and Chorilli, M. (2021). Nanotechnology-based drug delivery systems as potential for skin application: a review. Current Medicinal Chemistry, 28(16), 3216-48.

45. Shinde, P., and Page, A. (2025). Advancements in skin cancer treatment: 5-fluorouracil and carvedilol-loaded transethosomes using Lipoid S100. Drug Development and Industrial Pharmacy, 51(5), 492-505.

46. Rani, J., Beniwal, D., Dhull, S., Gulia, V., Barwant, M. M., & Singh, B. (2025). Applications of nanotechnology in herbal pharmacology. CRC Press.In Herbal Pharmacopeia (pp. 213-237).

Conflict of Interest

The authors declare that they have no conflict of interest