

## Therapeutic Potential of Deep Eutectic Mixture-Based Nanofluids in Wound Healing and Anti-aging Agents: A Systematic Review

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### Abstract

Deep eutectic mixtures, frequently described as deep eutectic solvents, natural deep eutectic solvents, or therapeutic deep eutectic systems, have emerged as multifunctional platforms in pharmaceutical, cosmetic, and biomedical delivery. Their relevance to wound healing and anti-aging therapy is based on their capacity to improve solubility, enhance skin permeation, stabilize unstable

active compounds, support antimicrobial activity, and integrate with nanocarriers, hydrogels, eutectogels, and topical emulsions. This systematic review evaluates the therapeutic potential of deep eutectic mixture-based nanofluids and related nanoscale systems in wound healing and anti-aging applications. Evidence from preclinical wound

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models, antimicrobial studies, hydrogel dressings, and retinol-based anti-aging systems indicates that these platforms may improve tissue repair, reduce microbial burden, enhance collagen-related activity, suppress oxidative stress, and improve topical tolerability. Menthol–fatty acid therapeutic deep eutectic systems have shown antibacterial and wound-healing effects, while linolenic acid–phosphatidylcholine deep eutectic emulsion systems have improved retinol stability, skin permeation, anti-wrinkle activity, hydration, collagen intensity, and irritation profile. Despite this promise, clinical translation remains limited by inconsistent terminology, insufficient long-term toxicology, variable formulation design, and limited human studies. Overall, deep eutectic mixture-based nanofluids represent a promising but still developing class of therapeutic systems for wound repair and skin anti-aging.

**Keywords:** Deep eutectic solvent, therapeutic deep eutectic system, nanofluid, wound healing, anti-aging, hydrogel, eutectogel, retinol, topical delivery

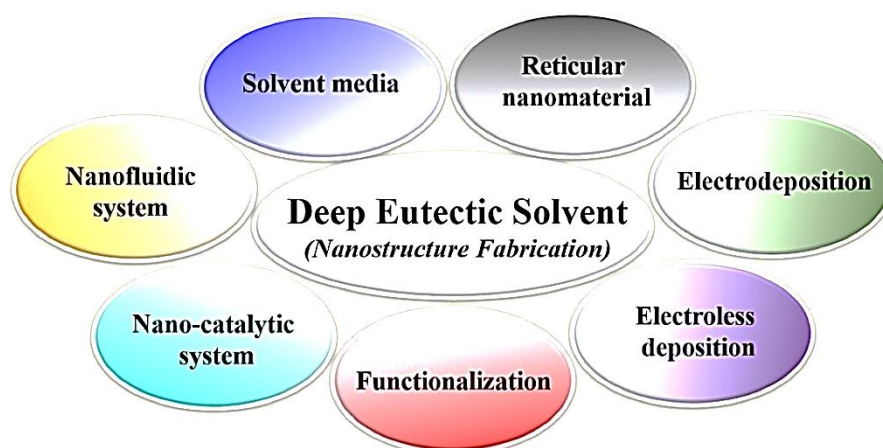
## 1. Introduction

Wound healing is a dynamic biological process involving hemostasis, inflammation, proliferation, re-epithelialization, angiogenesis, extracellular matrix deposition, and tissue remodeling [1-6]. The classical wound-healing process is usually described as four overlapping phases: hemostasis, inflammation, proliferation, and remodeling. Disruption of these phases can lead to delayed healing, chronic wounds, excessive scarring, or infection [7]. Skin aging and impaired wound healing share several biological pathways [8]. Oxidative stress, persistent inflammation, collagen degradation, reduced fibroblast activity, matrix metalloproteinase activation, microbial imbalance, and impaired barrier function are common to both processes [7]. Anti-aging therapy therefore often targets antioxidant protection, collagen stimulation, elastase inhibition, collagenase inhibition, hyaluronidase inhibition, hydration, and restoration of dermal matrix integrity [9].

Deep eutectic mixtures are formed by combining two or more components, usually hydrogen-bond donors and hydrogen-bond acceptors, in ratios that produce a eutectic system with a melting point lower than that of the individual components [10]. In biomedical research, these systems are commonly described as deep eutectic solvents, natural deep eutectic solvents, or therapeutic deep eutectic systems [11]. Pharmaceutical reviews describe therapeutic deep eutectic systems as platforms capable of improving

drug solubility, permeability, and bioavailability [12]. The term “nanofluid” in this review refers to deep eutectic mixture-containing nanoscale or colloidal fluidic systems, including nanoemulsions, nanoparticle dispersions, eutectogels, nanostructured hydrogels, and topical emulsions [13]. This definition is necessary because biomedical literature often uses “nanoformulation,” “eutectogel,” “hydrogel,” or “emulsion” rather than the engineering term “nanofluid.”

Deep eutectic mixture-based nanofluids are attractive for wound healing and anti-aging because they can function as more than passive carriers [14]. Depending on composition, they may act as solubilizers, penetration enhancers, stabilizers, antimicrobial agents, antioxidants, moisturizers, and polymer-network modifiers [15-20]. In skin therapy, this is valuable because many biologically active compounds, including retinoids, phenolics, fatty acids, essential oils, and antimicrobial agents, suffer from poor solubility, poor stability, irritation, or inadequate skin penetration. This review evaluates current evidence on deep eutectic mixture-based nanofluids and related formulations for wound healing and anti-aging therapy.



*Figure 2: Deep eutectic solvents: Recent advances in fabrication approaches and pharmaceutical applications [21]*

## 2. Methods

This review was structured according to PRISMA 2020 principles. PRISMA 2020 provides a 27-item checklist and flow-diagram framework for transparent systematic-review reporting [22].

## 2.1 Search Strategy

The literature search focused on studies involving deep eutectic solvents, natural deep eutectic solvents, therapeutic deep eutectic systems, eutectogels, hydrogels, nanoemulsions, nanocarriers, and topical delivery systems applied to wound healing, antimicrobial therapy, skin repair, collagen regulation, oxidative stress, and anti-aging outcomes.

**Table 1:** *Search strategy and eligibility framework for the systematic review*

Component	Description
Review title	Therapeutic Potential of Deep Eutectic Mixture-Based Nanofluids in Wound Healing and Anti-aging Agents: A Systematic Review
Review type	Qualitative systematic review
Reporting framework	PRISMA-based systematic review structure
Main concept	Deep eutectic mixture-based nanofluids and related topical delivery systems
Databases considered	PubMed, Scopus, Web of Science, ScienceDirect, Google Scholar, ACS Publications, SpringerLink, Wiley Online Library
Core search terms	"deep eutectic solvent," "deep eutectic mixture," DES, NADES, THEDES, "therapeutic deep eutectic system," eutectogel
Formulation terms	nanofluid, nanoemulsion, nanoparticle, nanocarrier, hydrogel, eutectogel, topical delivery, transdermal delivery, dermal formulation
Therapeutic terms	wound healing, wound repair, burn healing, antibacterial, antibiofilm, anti-inflammatory, antioxidant, anti-aging, antiwrinkle, collagen, elastase, collagenase, hyaluronidase, retinol
Population / model	In vitro skin cells, fibroblasts, keratinocytes, microbial strains, ex vivo skin, animal wound models, human skin or clinical cosmetic studies
Intervention	DES-, NADES-, THEDES-, eutectogel-, hydrogel-, nanoemulsion-, or nanocarrier-based therapeutic system
Comparator	Free drug, conventional solvent, blank formulation, untreated control, commercial dressing, or standard topical formulation
Main	Wound closure, antibacterial activity, antibiofilm effect, collagen

outcomes	deposition, angiogenesis, inflammation reduction, oxidative stress reduction, wrinkle reduction, hydration, skin permeation, irritation profile
Inclusion criteria	Studies involving deep eutectic mixtures or DES-related systems with wound-healing, skin-repair, topical, transdermal, antimicrobial, antioxidant, or anti-aging relevance
Exclusion criteria	Heat-transfer nanofluids, non-biomedical DES studies, extraction-only studies without biological relevance, theoretical studies without experimental data
Data synthesis	Qualitative synthesis
Meta-analysis status	Not performed because of heterogeneity in DES composition, formulation type, biological model, and outcome measurement

**2.2 Inclusion Criteria**

Studies were included when they met the following criteria:

- i. Investigated a deep eutectic mixture, DES, NADES, THEDES, eutectogel, DES-based hydrogel, or DES-based topical nanocarrier.
- ii. Reported relevance to wound healing, antibacterial wound care, burn healing, topical delivery, transdermal delivery, anti-aging, wrinkle reduction, collagen regulation, antioxidant activity, or cosmetic dermatology.
- iii. Included experimental, preclinical, ex vivo, in vivo, formulation, or clinical evidence.
- iv. Provided biological, physicochemical, antimicrobial, wound-healing, permeability, irritation, or anti-aging outcomes.

**Table 2: Classification of deep eutectic mixture-based systems relevant to wound healing and anti-aging**

DES-based system	Typical components	Formulation form	Main function	Relevance to wound healing	Relevance to anti-aging	Reference
DES	Hydrogen-bond donor + hydrogen-bond acceptor	Liquid eutectic mixture	Solvent, stabilizer, permeability	Improves delivery of wound-healing	Improves delivery of poorly soluble	[23]

			enhancer	agents	cosmetic actives	
NADES	Natural components such as sugars, amino acids, organic acids, polyols, choline derivatives	Natural eutectic solvent, extract carrier, topical vehicle	Green solvent and bioactive extraction medium	Can deliver antioxidant and anti-inflammatory compounds	Useful botanical anti-aging formulations	for [24]
THEDES	Therapeutic compounds forming eutectic systems	Therapeutic eutectic liquid or semi-solid	Active carrier with intrinsic therapeutic effect	May provide antibacterial, anti-inflammatory, or wound-healing effects	May improve delivery and tolerability of active dermatological agents	[23]
Hydrophobic DES	Menthol, fatty acids, terpenes, hydrophobic organic acids	Lipophilic eutectic phase	Delivery of hydrophobic actives and antimicrobial components	Useful for infected wounds and lipophilic antimicrobial delivery	Useful for retinoids, fatty acids, and lipid-compatible anti-aging agents	[25]
DES nanoemulsion	DES phase + oil/surfactant/water system	Nanoemulsion or nanofluid	Improved dispersion, permeation, and stability	Supports topical delivery of antibacterial or healing	Enhances stability and delivery of retinol and antioxidants	[26]

					agents		
DES nanoparticle system	DES combined with or lipid nanoparticles	Nanocarrier dispersion	Controlled delivery and improved skin penetration	Can localize drugs at wound site	May improve dermal delivery of anti-aging actives	[27]	
DES hydrogel	DES incorporated into hydrogel polymers such as chitosan, PVA, hyaluronic acid, sodium alginate	Hydrogel dressing	Moisture retention, controlled release, tissue support	Promotes wound closure, hydration, and protection	Provides hydration and prolonged skin contact	[28]	
Eutectogel	Polymer network swollen with DES	Flexible gel or adhesive dressing	Conductivity, adhesiveness, self-healing, controlled release	Useful for wound dressings, burn healing, and monitoring	Useful for anti-aging patches and long-contact topical systems	[29]	
DES-assisted botanical extract	Plant bioactives extracted using NADES	Extract-loaded topical formulation	Antioxidant and enzyme-inhibitory delivery	Reduces oxidative stress and inflammation	Supports anti-collagenase, anti-elastase, and anti-hyaluronidase effects	[30]	
DES-retinol	Retinol with DES emulsion	Retinol	Retinol	May	Improves	[31]	

system	fatty acid/phospholipid DES	or nanofluid	stabilization and irritation reduction	support and repair through collagen modulation	wrinkle, hydration, collagen, and irritation outcomes
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### 2.3 Exclusion Criteria

Studies were excluded when they focused only on industrial heat-transfer nanofluids, DES extraction without skin or wound relevance, non-biomedical solvent chemistry, or theoretical eutectic systems without biological evaluation.

### 2.4 Data Extraction and Synthesis

Extracted data included eutectic composition, formulation type, active ingredient, biological model, wound or skin-aging endpoint, antimicrobial activity, permeation behavior, cytotoxicity, irritation testing, and therapeutic outcome. Because included studies used different formulations, biological models, and endpoints, a qualitative synthesis was performed instead of meta-analysis.

## 3. Results

### 3.1 Deep Eutectic Mixtures as Therapeutic Delivery Systems

Deep eutectic mixtures have become relevant to drug delivery because they can increase the apparent solubility and permeability of active pharmaceutical ingredients. Reviews on therapeutic deep eutectic systems emphasize their potential to improve poorly soluble drug delivery and increase bioavailability. For dermatological use, their importance lies in three connected properties: solubilization of poorly soluble actives, interaction with the skin barrier, and compatibility with polymeric or nanostructured delivery systems. Skin delivery is especially difficult because the stratum corneum blocks both hydrophilic and high-molecular-weight compounds. Deep eutectic systems have therefore been explored as vehicles for improving skin permeability, particularly in choline-derivative and therapeutic DES platforms.

### 3.2 Wound-Healing Potential

The most direct wound-healing evidence comes from therapeutic deep eutectic systems based on menthol and saturated fatty acids. Silva et al. investigated menthol-based hydrophobic therapeutic deep eutectic solvents containing fatty acids such as stearic,

myristic, and lauric acid. The menthol–stearic acid system was especially notable because it showed wound-healing potential and antibacterial activity against *Staphylococcus aureus* and *Staphylococcus epidermidis*, including methicillin-resistant strains [28]. This result is important because wound repair requires both tissue regeneration and microbial control. A system that supports healing while suppressing common wound pathogens has a stronger therapeutic profile than a carrier that only improves drug solubility [32]. The biological rationale is clear. Fatty acids may support barrier repair and antimicrobial activity, while menthol-based eutectic systems may improve local delivery and tissue interaction. In eutectic form, these components may behave differently from the individual substances because hydrogen-bond networks alter physicochemical properties such as viscosity, melting point, diffusion, and membrane interaction.

**Table 3:** *Therapeutic effects of deep eutectic mixture-based nanofluids and related systems in wound healing*

DES / system	eutectic type	Formulation	Therapeutic role	Biological target model	Main wound- healing effects	Key limitation	References
Menthol–stearic acid THEDES	Hydrophobic therapeutic deep eutectic system	Active carrier and antimicrobial wound- healing agent	In vitro skin/wound models; <i>S. aureus</i> , MRSA, <i>S. epidermidis</i>	Improved wound-healing activity; antibacterial effect against common wound pathogens; acceptable cytocompatibility	Mostly preclinical evidence	[33]	

Menthol–myristic acid / menthol–lauric acid THEDES	Hydrophobic DES systems	Antibacterial and dermal delivery platform	Bacterial wound-associated strains	Potential antimicrobial activity and enhanced local delivery	Biological performance varies with fatty acid chain length	[34]
NADES-based wound dressing	Hydrogel wound dressing	/ Moist healing, bioactive delivery, tissue protection	Experimental wound models	Improved dressing functionality, moisture retention, and wound protection	Limited clinical validation	[35]
DES–chitosan hydrogel	Polymeric hydrogel	Antibacterial dressing and healing scaffold	Infected wound models	Supports wound closure, microbial inhibition, and tissue regeneration	Requires optimization of mechanical strength and degradation	[36]
PVA/chitosan DES hydrogel	Injectable or film-forming hydrogel	MRSA-infected wound healing	MRSA-infected wounds	Antibacterial action, wound closure support, and biocompatibility	Needs comparison with commercial dressings	[37]
Hyaluronic acid/DES hydrogel	Conductive hydrogel dressing	Burn healing and tissue remodeling	Burn wound models	Promotes cell migration, collagen deposition, angiogenesis, and remodeling	Electrical stimulation conditions may affect outcomes	[38]

Sodium hyaluronate hydrogel	Multifunctional DES hydrogel	Wound healing and health monitoring	Wound model and sensing platform	Provides moist environment, tissue support and monitoring function	More device-level validation needed	[28]
Polymerizable DES eutectogel	Self-healing adhesive eutectogel	Wound protection and motion-compatible dressing	Skin wound model / motion sensing	Adhesive, antibacterial, conductive, mechanically resilient wound support	Long-term dermal safety unclear	[39]
DES-loaded essential oil system	DES-based antimicrobial delivery platform	Treatment of infected wounds	Bacterial wound infection models	Improves delivery of lipophilic antimicrobial agents and supports infected-wound repair	Essential oil of irritation risk requires dose control	[40]
Saponin-based THEDES	Therapeutic DES	Antibiofilm and antibacterial activity	<i>Pseudomonas aeruginosa</i> models	Biofilm inhibition, membrane disruption, antimicrobial effect	Translation to skin wounds still early	[41]

### 3.3 Antibacterial and Antibiofilm Activity

Bacterial contamination is a major cause of delayed wound healing. *S. aureus*, MRSA, *S. epidermidis*, and *Pseudomonas aeruginosa* are particularly relevant in infected and chronic wounds. Deep eutectic mixture-based formulations may contribute to antimicrobial control through direct membrane disruption, improved antimicrobial

delivery, biofilm weakening, and pH-related stress. Menthol-based deep eutectic systems have shown antimicrobial activity against clinically relevant microorganisms. A later study on menthol-based natural deep eutectic systems with saturated free fatty acids further supported the antimicrobial relevance of these systems. Saponin-based therapeutic deep eutectic systems have also been investigated for antimicrobial and antibiofilm effects against *Pseudomonas aeruginosa*. Reported assays included minimum inhibitory concentration, minimum bactericidal concentration, biofilm inhibition, membrane permeability, reactive oxygen species evaluation, and zebrafish infection modeling. These findings indicate that deep eutectic mixtures may have value in infected-wound therapy, particularly when combined with hydrogel dressings or nanocarriers that retain the formulation at the wound surface.

### 3.4 DES-Based Hydrogels and Eutectogels for Wound Dressing

Hydrogels and eutectogels are among the most promising wound-healing formats for deep eutectic mixtures. A wound dressing must maintain moisture, protect against microbial invasion, absorb exudate, adhere adequately, and support cell migration. DES-based hydrogels can add tunable viscosity, ionic conductivity, mechanical flexibility, and bioactive delivery. A natural deep eutectic solvent-based multifunctional wound dressing was reported as an environmentally friendly hydrogel platform. Conductive hyaluronic acid/deep eutectic solvent composite hydrogels have also been studied for burn healing under electrical stimulation; the reported system was designed to reduce inflammation, stimulate cell proliferation and migration, promote collagen deposition, enhance angiogenesis, and support skin remodeling. Polyvinyl alcohol/chitosan hydrogels based on deep eutectic solvent have been reported for MRSA-infected wound healing. This is relevant because chitosan contributes biocompatibility, film formation, and antimicrobial properties, while PVA contributes mechanical strength and hydrogel structure. These hydrogel and eutectogel studies show that deep eutectic mixtures can be embedded into wound dressings rather than used only as liquid solvents. That matters because wound treatment needs residence time. A free liquid can spread, dilute, or leak; a DES-containing hydrogel can stay where the biology needs it.

### 3.5 Anti-Aging Potential

Anti-aging evidence is smaller than wound-healing evidence but clinically interesting. Retinol is one of the best-established cosmetic anti-aging ingredients, but it is unstable, oxidation-prone, irritating, and difficult to formulate. A 2024 study developed a retinol-loaded deep eutectic solvent emulsion based on linolenic acid and phosphatidylcholine. The DES-retinol emulsion improved retinol stability and therapeutic efficiency. The formulation showed lower cytotoxicity than free retinol and reduced irritation in chicken embryo, pig-skin, and human patch testing. It also improved permeation, reduced inflammatory markers, promoted type I collagen production, suppressed matrix metalloproteinase-1 activity, reduced reactive oxygen species, improved wrinkle-related parameters, increased hydration, improved collagen intensity, and reduced retinol-induced irritation. This is one of the strongest examples of deep eutectic mixture-based anti-aging delivery because it addresses three major retinol problems simultaneously: instability, irritation, and poor delivery. In simple terms, the eutectic emulsion works like a smarter "skin carrier" for retinol — it protects the passenger, improves entry, and causes less irritation at the destination. Natural deep eutectic solvents are also relevant to anti-aging through botanical extraction and delivery. A review of NaDES applications in cosmetic and pharmaceutical fields highlighted their use as green solvents and functional ingredients in cosmetic systems. NADES-based extraction has also been associated with antioxidant and enzyme-inhibitory activity relevant to cosmeceuticals, including collagenase, hyaluronidase, elastase, and lipoxygenase inhibition in plant-extract studies.

**Table 4:** *Anti-aging mechanisms and outcomes of deep eutectic mixture-based nanofluids*

DES / system	eutectic	Active ingredient / component	Formulation type	Anti-aging mechanism	Reported outcome	Relevance to cosmetic dermatology	Reference
Linolenic acid–phosphatidylcholine DES	acid–	Retinol	DES emulsion / nanofluid	Stabilization of retinol,	Increased retinol stability,	Strong candidate for	[42]

				improved skin permeation, reduced irritation	enhanced collagen-related activity, reduced wrinkle parameter s, improved hydration	retinoid-based anti-aging formulations	
NADES extract	plant-based systems	Polyphenols, flavonoids, antioxidants	NADES extract topical delivery system	Antioxidant activity and enzyme inhibition	Improved antioxidant capacity; inhibition of collagenase, elastase, and hyaluronidase	Useful for botanical anti-aging products	[43]
Fatty DES	acid-based	Fatty acids and hydrogen-bond acceptors	Hydrophobic DES / topical carrier	Barrier support, emollient effect, permeation enhancement	Improved compatibility with lipophilic actives and possible skin-softening effect	Relevant for dry, aged, barrier-impaired skin	[44]
Choline based NADES	chloride-	Organic acids, sugars, amino acids, polyols	Natural eutectic solvent system	Solubilization and stabilization of hydrophilic	Enhanced extraction and delivery of cosmetic	Green alternative to conventional	[45]

				c or amphiphilic actives	bioactives	cosmetic solvents	
DES nanoemulsion systems	Lipophilic antioxidants or retinoids	Nanoemulsion / nanofluid	Increased surface area, improved dispersion, enhanced dermal delivery	Better topical distribution and active stability	Useful for unstable or poorly soluble anti-aging agents	[46]	
DES hydrogel systems	Hyaluronic acid, polysaccharides, antioxidants	Hydrogel / eutectogel	Hydration, occlusion, controlled release, matrix support	Improved moisture retention and prolonged skin contact	Relevant for anti-aging masks, patches, and dermal gels	[47]	
DES-assisted botanical formulations	Plant extracts	NADES-based extract delivery	Antioxidant, anti-inflammatory, anti-collagenase effects	Potential protection against oxidative skin aging	Useful in cosmetic formulations	[48]	
THEDES-based topical systems	Therapeutic molecules or bioactive eutectic components	Topical eutectic carrier	Improved permeability and reduced crystallization of active ingredients	Enhanced delivery of poorly soluble anti-aging agents	May reduce need for harsh penetration enhancers	[49]	
DES-polymer hybrid systems	Polymers with	Eutectogel / polymeric	Mechanical support,	Prolonged residence	Useful for overnight	[50]	

	humectants or bioactives	nanofluid	hydration, controlled release	time and improved skin contact	or patch-based anti-aging delivery	
DES-based multifunctional nanofluids	Retinoids, phenolics, fatty acids, peptides	Nanofluid / nanoformula tion	Combined antioxidant, collagen-supportive, hydrating, and delivery-enhancing effects	Potential improvement in elasticity, hydration, wrinkle appearance, and barrier recovery	Promising but needs more human trials	[51]

3.6 Mechanisms of Action

Table 5: *Therapeutic effects of deep eutectic mixture-based nanofluids appear to involve multiple mechanisms*

Mechanism	Wound-healing relevance	Anti-aging relevance
Solubility enhancement	Improves delivery of hydrophobic antimicrobials and healing agents	Improves delivery of retinoids, fatty acids, phenolics
Permeation enhancement	Supports penetration into wound margins and skin layers	Improves dermal delivery of anti-aging actives
Antimicrobial activity	Reduces wound bioburden and infection risk	Helps protect compromised or acne-prone aging skin
Antioxidant activity	Reduces oxidative stress in damaged tissue	Limits ROS-mediated collagen degradation
Hydrogel/eutectogel formation	Supports moist healing and dressing retention	Supports hydration and topical residence
Collagen modulation	Promotes matrix repair and remodeling	Improves firmness and wrinkle appearance

Irritation reduction

Improves tolerability of wound treatments

Reduces associated irritation

retinoid-

The key point is that DES-based nanofluids are not merely “green solvents.” In dermatological systems, they may behave as active formulation environments that reshape solubility, diffusion, hydration, skin interaction, and biological response.

### 3.7. L-Carnitine Stearic Acid Eutectic as a Potential Wound Healing and Anti-aging Agent

L-Carnitine Stearic Acid Eutectic represents an emerging bioactive system that combines the metabolic benefits of L-carnitine with the structural and barrier-enhancing properties of stearic acid in a single low-melting eutectic formulation. L-Carnitine plays a critical role in mitochondrial  $\beta$ -oxidation, facilitating the transport of long-chain fatty acids into mitochondria for ATP production, which is essential for fueling keratinocyte proliferation, fibroblast migration, and collagen synthesis during wound repair. Its antioxidant activity also helps neutralize reactive oxygen species at the wound site, reducing oxidative stress and chronic inflammation that can delay healing. Stearic acid, a saturated C18 fatty acid, contributes to skin barrier restoration by integrating into the stratum corneum lipid matrix, reducing transepidermal water loss and protecting nascent tissue from microbial invasion. When formulated as a eutectic, the two components exhibit enhanced solubility, skin permeation, and bioavailability compared to physical mixtures, allowing deeper delivery of L-carnitine to dermal fibroblasts. This synergy may accelerate re-epithelialization, promote angiogenesis, and stimulate extracellular matrix remodeling, all key phases of wound closure. For anti-aging, the eutectic targets two hallmarks: energy decline in aging skin cells and barrier dysfunction. By boosting cellular ATP and fatty acid metabolism, it can improve skin cell turnover and dermal collagen density, while stearic acid reinforces lipid lamellae to improve hydration, elasticity, and smoothness. Early *in vitro* and preclinical studies suggest improved fibroblast viability and collagen I expression with reduced MMP-1 activity, indicating potential to mitigate fine lines, sagging, and photoaging. Its biocompatible, non-toxic profile and ability to act as both a bioactive and a penetration-enhancing carrier make L-Carnitine Stearic Acid Eutectic a promising candidate for topical wound dressings and cosmeceutical anti-aging formulations.

#### 4. Discussion

The reviewed evidence supports the therapeutic potential of deep eutectic mixture-based nanofluids in wound healing and anti-aging therapy. The strongest wound-healing evidence currently comes from menthol–fatty acid therapeutic deep eutectic systems and DES-based hydrogel or eutectogel wound dressings. The strongest anti-aging evidence comes from retinol-loaded DES emulsion systems [52]. For wound healing, deep eutectic mixtures offer three major advantages. First, they can improve the delivery of poorly soluble therapeutic molecules. Second, they can contribute intrinsic biological effects through their components, such as fatty acids, menthol, organic acids, polyphenols, or saponins. Third, they can be incorporated into hydrogels and wound dressings that provide moisture retention, mechanical protection, and controlled local exposure [36].

For anti-aging, deep eutectic systems are most valuable when they stabilize unstable actives and reduce irritation. Retinol is the clearest case. Free retinol is effective but difficult to use because it is sensitive to oxidation and commonly causes irritation. The linolenic acid–phosphatidylcholine DES emulsion shows how a eutectic platform can improve both performance and tolerability [41]. The overlap between wound healing and anti-aging is biologically meaningful. Both depend on fibroblast function, collagen metabolism, inflammation control, oxidative stress reduction, and epidermal barrier recovery. A formulation that improves collagen deposition, lowers ROS, improves hydration, and reduces inflammation can reasonably affect both wound repair and skin aging [42].

However, the field has limitations. The term “nanofluid” is not consistently used in biomedical DES literature. Many relevant systems are instead described as nanoemulsions, hydrogels, eutectogels, or nanocarriers. This creates indexing problems and makes systematic retrieval difficult. Another limitation is that most evidence remains preclinical. Few studies include robust human data, and long-term dermal toxicity is still underdeveloped. Safety is the biggest translational barrier. A DES made from natural or biocompatible components is not automatically safe. Eutectic formation can alter skin penetration, cellular exposure, irritation potential, and systemic absorption. For wound applications, this matters even more because damaged skin has a weaker barrier than

intact skin. Therefore, wound-healing DES systems require cytotoxicity testing, hemocompatibility testing, irritation studies, sensitization assessment, microbial selectivity studies, and in vivo wound-model validation [43].

The second barrier is formulation stability. DES systems can be viscous, hygroscopic, or structurally altered by water dilution. When incorporated into hydrogels, emulsions, or dressings, their eutectic structure may change. Therefore, physicochemical characterization is essential. A formulation cannot simply claim to be DES-based; it must show that the eutectic mixture remains functionally relevant after processing [48]. The third barrier is clinical evidence. Current studies suggest strong potential, but clinical translation requires controlled human trials comparing DES-based systems with standard dressings, conventional emulsions, and established topical anti-aging formulations.

### 5. Limitations of the Review

This review is limited by heterogeneity in terminology, formulation type, model systems, and biological endpoints. Included studies differ in DES composition, active ingredients, wound models, microbial strains, anti-aging assays, and safety methods. Because of this heterogeneity, meta-analysis was not appropriate. Another limitation is that many DES-based dermatological systems are reported as formulation studies rather than clinical studies, so therapeutic conclusions remain preliminary.

### 6. Conclusion

Deep eutectic mixture-based nanofluids represent a promising therapeutic platform for wound healing and anti-aging applications. Their value lies in multifunctionality: they can solubilize poorly soluble actives, enhance skin permeation, stabilize unstable compounds, reduce irritation, provide antimicrobial effects, support hydrogel wound-dressing design, and modulate biological pathways linked to collagen repair, oxidative stress, inflammation, and tissue remodeling. In wound healing, menthol–fatty acid therapeutic deep eutectic systems, DES-based hydrogels, conductive eutectogels, and antibacterial DES formulations show strong preclinical promise. In anti-aging therapy, retinol-loaded DES emulsions provide one of the clearest examples of improved stability, permeation, collagen-related activity, wrinkle reduction, hydration, and irritation control. The field is promising, but not mature. The next scientific challenge is proving safety,

reproducibility, and clinical superiority over conventional topical systems. Based on current evidence, deep eutectic mixture-based nanofluids should be considered a serious emerging platform at the intersection of green chemistry, nanomedicine, wound care, and cosmetic dermatology.

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#### Declaration of Interest

The authors declare no competing financial interests.

#### Author Contribution declaration

Farhan Khan: Methodology, writing–original draft, software, Formal analysis, Masab Saeed: Data curation. Rida Zameer\*: Validation. Irum Aziz: Conceptualization. Muhammad Tariq Asif: Visualization, Sardar Muhammad Mubashir: Formal Analysis.

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