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Review Article

Herbal Extract and Phytoconstituents Delivered by Microneedle

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ABSTRACT

Microneedle (MN) technology represents a promising, minimally invasive approach for transdermal drug delivery, combining the benefits of injections and patches while minimizing pain and tissue damage. Herbal extracts and phytoconstituents, known for their antioxidant, anti-inflammatory, antimicrobial, and anticancer properties, often face challenges such as poor solubility, instability, and limited bioavailability. Conventional oral and topical formulations are inadequate due to the skin's barrier function and hepatic first-pass metabolism. Integrating MN technology with herbal drug delivery provides an innovative solution by creating transient microchannels in the skin, enhancing permeability, and allowing controlled, sustained release of phytochemicals. Recent studies have successfully incorporated compounds such as curcumin, resveratrol, mangiferin, and quercetin into dissolving, hydrogel, and stimuli-responsive MN systems. These formulations improved dermal absorption, therapeutic efficacy, and multifunctional outcomes, including wound healing and targeted anticancer activity. Furthermore, nanocarrier-based MN systems—utilizing nanoparticles, nanocrystals, or lipid carriers—have shown potential to increase stability and bioavailability of plant-derived molecules. Despite these advances, the field remains in early development, with challenges in large-scale production, standardization, and regulatory approval. Addressing safety, stability, and patient compliance is essential for translating microneedle-assisted herbal drug delivery into practical and clinically accepted therapies.

INTRODUCTION

Microneedle (MN) technology is a minimally invasive transdermal drug delivery approach that combines the benefits of hypodermic injections and transdermal patches while reducing pain and tissue damage [1]. By forming microscopic pores in the skin, MNs effectively bypass the stratum corneum barrier, enhancing the permeation of both

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small and large drug molecules [2]. This technology is particularly advantageous for herbal extracts and phytoconstituents, which often exhibit poor solubility, chemical instability, and limited oral bioavailability due to gastrointestinal degradation and first-pass metabolism [3]. Conventional herbal formulations such as creams, gels, and oral dosage forms generally produce low therapeutic efficacy, restricting their clinical applicability [4]. Incorporating phytoconstituents into MN systems enhances drug absorption, prolongs therapeutic activity, and improves patient compliance by integrating traditional herbal medicine with modern delivery technologies [5].

Several studies have reported successful incorporation of phytochemicals such as curcumin, resveratrol, and mangiferin into MN platforms [6]. Curcumin-loaded dissolving MNs demonstrated improved skin deposition, controlled release, and superior wound healing and anticancer effects [4]. Likewise, resveratrol-loaded MNs achieved enhanced local delivery, anti-inflammatory action, and metabolic regulation [7]. Mangiferin-loaded ROS/pH-responsive MNs allowed controlled release for infected wound therapy [5]. These systems overcome solubility and permeability barriers associated with phytoconstituents and provide multifunctional drug delivery potential [6]. However, most investigations remain at the preclinical level, with further studies needed on large-scale production, stability, and regulatory considerations [1]. Overall, MN-assisted delivery of herbal extracts represents a promising frontier in transdermal phytomedicine [7].

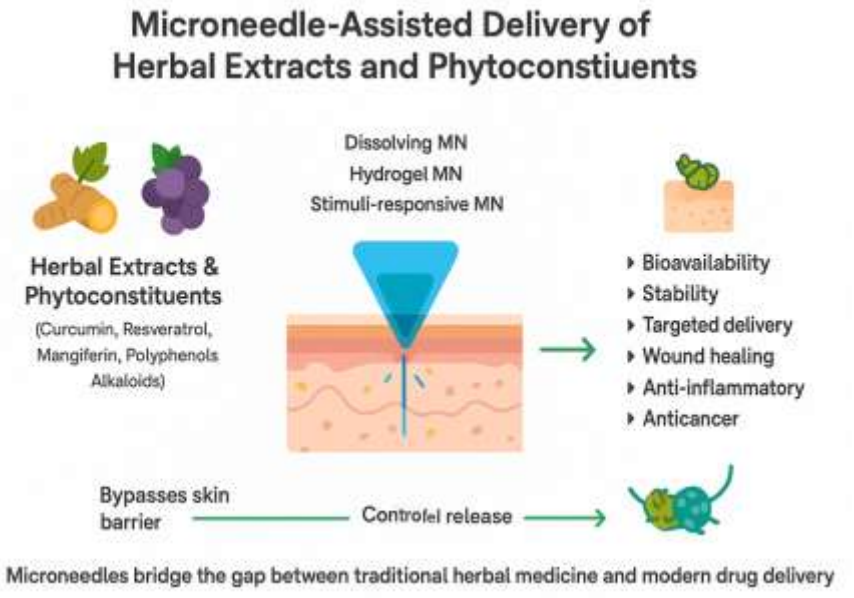

Figure 1 : Microneedle bridge the gap between traditional herbal medicine and modern drug delivery

NEED OF THE WORK

Despite their extensive use in traditional medicine, herbal extracts and phytoconstituents face major challenges in modern therapeutics due to poor aqueous solubility, chemical instability, rapid metabolism, and limited systemic absorption following oral administration [8]. Even with topical application, the stratum corneum acts as a strong barrier that restricts the penetration of large or hydrophilic phytomolecules such as flavonoids, polyphenols, and alkaloids, resulting in subtherapeutic concentrations at the target site [9]. Conventional dosage forms, including creams,

gels, and patches, often fail to provide adequate drug penetration, limiting their clinical efficacy [10].

Transdermal drug delivery offers several advantages, such as bypassing hepatic first-pass metabolism, providing sustained release, and improving patient compliance; however, its success relies on overcoming the skin's barrier properties [11]. Microneedles (MNs) have emerged as an innovative solution by creating transient microchannels that permit efficient transport of herbal compounds into deeper skin layers without pain or tissue injury [12].

Recent studies have demonstrated that MN-mediated delivery of phytoconstituents such as curcumin, resveratrol, and mangiferin significantly enhances dermal deposition, pharmacological activity, and controlled release compared to conventional systems [13–15]. Curcumin-loaded dissolving MNs show superior wound healing and anticancer efficacy [13], resveratrol nanocrystal MNs improve dermal delivery and anti-inflammatory effects [14], and ROS/pH-responsive mangiferin MNs provide controlled release for infected wound therapy [15].

However, most studies remain at the preclinical or proof-of-concept stage, and challenges related to large-scale manufacturing, stability, patient acceptability, and regulatory approval persist [16,17]. Addressing these issues is essential to translate the pharmacological benefits of herbal compounds into clinically viable therapies. Therefore, a comprehensive review of microneedle-assisted delivery of herbal extracts and phytoconstituents is required to summarize current progress, highlight limitations, and identify future directions [18].

OBJECTIVES

The objectives of this review are formulated to provide a comprehensive understanding of microneedle-assisted delivery of herbal extracts and phytoconstituents:

- To discuss microneedle technology in terms of design, fabrication methods, and mechanisms of skin permeation.
- To summarize herbal extracts and phytoconstituents (such as curcumin, resveratrol, mangiferin, aloe vera, green tea polyphenols, and others) that have been successfully delivered using microneedles.
- To analyze therapeutic applications of phytoconstituent-loaded microneedles in areas such as wound healing, cancer therapy, metabolic disorders, anti-inflammatory treatments, and dermatological conditions.
- To evaluate the formulation strategies used to improve the stability, solubility, and release profile of phytochemicals in microneedle systems, including nanoparticles, nanocrystals, lipid carriers, and polymeric scaffolds.
- To identify challenges and limitations in scaling up microneedle-based herbal formulations, including safety, patient acceptability, manufacturing feasibility, and regulatory perspectives.
- To highlight future prospects of integrating nanotechnology, stimuli-responsive systems, and smart microneedle designs for enhancing herbal drug delivery.

GLYCOSIDES:

1. Glycyrrhizin:

Glycyrrhiza glabra extract, rich in glycyrrhizic acid and flavonoids, showed anti-inflammatory and antiproliferative effects when delivered via chitosan or hyaluronic acid-based microneedles, offering promising treatment for psoriasis and rheumatoid arthritis through enhanced dermal delivery and controlled release [19,20].

2. Ginsenosides:

Traditional Chinese medicine phytochemicals, such as flavonoids and saponins, exhibit poor solubility and absorption. Microneedles enhance their bioavailability and stability by bypassing first-pass metabolism, enabling efficient transdermal delivery for chronic and metabolic disorders [21].

3. Hesperetin:

A hyaluronic acid-based dissolvable microneedle patch loaded with hesperetin nanostructured lipid carriers enhanced drug stability, skin penetration, and bioavailability, offering controlled release and improved therapeutic efficacy for obesity and metabolic disorders with minimal side effects and better patient compliance.[22]

4. Emodin:

A PDA-enhanced dissolving microneedle patch loaded with emodin co-precipitate enabled rapid NIR-triggered drug release, improved skin penetration, and reduced obesity markers in rats by enhancing lipid metabolism, offering a safe, effective, and innovative approach for obesity and metabolic disorder management.[23]

5. Salicin:

Salicylic acid-loaded microneedle and hydrogel acne patches enhance drug penetration, show strong antibacterial action against *P. acnes*, and reduce irritation. These minimally invasive, patient-friendly systems improve treatment efficacy, stability, and cosmetic acceptability for managing various acne types effectively.[24].

6. Digoxin:

A MEMS-based hollow microneedle micropump system made of PDMS and PMMA enabled precise, painless, and controlled delivery of potent drugs like digoxin. It ensured accurate dosing, reduced infection risk, and improved safety and comfort in chronic cardiac therapy.[25]

TABLE : 1 Overview of Glycosides

Sr.No.	Phytoconstituents	Biological Source	Microneedle Application	References
1	Glycyrrhizin / Glycyrrhizic acid	*Glycyrrhiza glabra* (Licorice)	Treatment of psoriasis and skin disorders (via GgE-loaded chitosan microneedles) - Methotrexate delivery for rheumatoid arthritis using glycyrrhizic acid-modified carbon dots in dissolving MNs	[19,20]
2	Ginsenosides (Rg3, Rb1)	*Panax ginseng*	Treatment of alopecia (Rg3-liposome-loaded MNs) - Synergistic treatment of hypertrophic scars (with asiaticoside and L-carnosine)	[21]
3	Hesperidin / Hesperetin	Citrus fruits (esp. *Citrus sinensis*, *Citrus aurantium*)	Delivery of HES-loaded nanostructured lipid carriers (NLCs) via HA-based MNs for obesity and metabolic disorders	[22]
4	Emodin	*Rheum tanguticum*, *Aloe barbadensis*, *Polygonum cuspidatum*	Emodin-loaded dissolving MNs with PDA for enhanced fat metabolism under NIR irradiation in obesity management	[23]

5	Salicin / Salicylic Acid	*Salix* spp. (Willow bark), commonly used in salicylic acid form	Poly(ionic liquid)-based microneedle acne patches for direct, localized delivery - Treatment of various acne types (cystic, nodular, inflammatory)	[24]
6	Digoxin	*Digitalis lanata*	MEMS-based hollow microneedle integrated with micropump for precise, painless, subcutaneous/IV delivery of digoxin	[25]

FLAVANOIDS:

1. Quercetin:

Quercetin-loaded microneedles enhanced solubility, dermal penetration, and therapeutic efficacy for wounds, keloids, alopecia, and melanoma through controlled, localized release with minimal side effects. These versatile systems improved healing, angiogenesis, and antioxidant effects, offering promising potential for dermatological therapies. [26–29]

2. Luteolin:

Luteolin-loaded microneedles with colostrum-derived exosomes and propolis enable sustained ocular delivery for glaucoma, lowering intraocular pressure, improving antioxidant activity, and ensuring biocompatibility and dropless therapy with enhanced bioavailability.[30]

3. Myricetin:

Myricetin–humic acid–magnesium nanodrug microneedles exhibit photothermal, antibacterial, and antioxidant effects, promoting rapid healing of drug-resistant wounds with high biosafety, strong mechanics, and excellent infection control under NIR irradiation.[31]

TABLE: 2 Overview of Flavanoids

Sr No.	Phytoconstituent	Biological Source	Microneedle Applications	References
1	Quercetin	*Camellia sinensis* (tea) Theaceae	Quercetin-loaded microneedles for deeper skin delivery in wounds, scars, alopecia, melanoma.	[26-29]
2	Luteolin	*Thymus vulgaris* (Thyme) Lamiaceae	Luteolin-exosome microneedles for sustained, dropless ocular drug delivery in glaucoma.	[30]
3	Myricetin	*Myrica gale* (Sweet gale), *Myrica rubra* (Chinese bayberry) Myricaceae	Myricetin-loaded microneedles for drug-resistant wound healing and NIR light photothermal activation.	[31]

TERPENOIDS:

1. Oregano oil:

Oregano essential oil-loaded mucin microneedles (OEO@muMN) provide targeted, minimally invasive therapy for hypertrophic scars by reducing collagen deposition, fibroblast proliferation, and inflammation, improving scar architecture, and showing strong clinical translation potential.[32]

2. Menthol:

Menthol-enhanced microneedles improve transdermal delivery of poorly permeable drugs like asiatic acid by creating microchannels and

disrupting the stratum corneum, increasing local drug retention, therapeutic efficacy, and skin penetration for dermatological applications.[33]

3. Borneol:

Borneol-loaded microneedles enhance transdermal and brain delivery of tetramethylpyrazine, improving systemic absorption, blood–brain barrier penetration, and neuroprotection in stroke models, offering a minimally invasive strategy for cardiovascular and neurological therapies.[34]

TABLE:3 Overview of Terpenoids

Sr. No.	Phytoconstituent	*BIOLOGICAL SOURCE*	Microneedle Application	References
1	Oregano oil	*Origanum vulgare* (Oregano) Lamiaceae	Oregano oil microneedles for targeted, pain-free hypertrophic scar management.	[32]
2	Menthol	*Mentha piperita* (Peppermint) Lamiaceae	Menthol-hydrogel microneedles to boost transdermal delivery of pharmacological agents.	[33]
3	Borneol	*Dryobalanops aromatica* (Camphor tree) Dipterocarpaceae	Borneol microneedles (with iontophoresis) for enhanced brain and systemic drug absorption.	[34]

PHENOLIC COMPOUNDS:

1. Curcumin:

Curcumin, the main polyphenol in turmeric (*Curcuma longa*), exhibits potent antioxidant, anti-inflammatory, anticancer, and wound-healing properties. Despite poor bioavailability, advanced delivery systems like microneedles enhance absorption and therapeutic efficacy, making curcumin a promising natural therapeutic agent[.35-46]

2. Resveratrol:

Resveratrol, a natural polyphenol found in grapes, peanuts, and berries, exhibits antioxidant, anti-inflammatory, cardioprotective, and neuroprotective effects. Dissolving microneedle systems significantly enhance its solubility, bioavailability, and transdermal delivery for chronic disease treatment [47-57].

3. Carvacrol:

Carvacrol, a phenolic monoterpenoid from oregano and thyme, shows potent antimicrobial, anti-inflammatory, and antioxidant activity. Carvacrol-loaded microneedles improve solubility, stability, and wound healing through enhanced skin penetration and controlled release, offering promise for infection control and tissue repair [58,59,60].

4. Apigenin:

Apigenin, a flavonoid found in parsley and chamomile, shows antioxidant, anti-inflammatory, and dermatoprotective effects. It enhances skin barrier integrity, reduces cytokine-mediated inflammation, and relieves pruritus, making it useful in atopic dermatitis treatment [61,62].

5. Hypericin:

Hypericin, a bioactive compound from *Hypericum perforatum*, exhibits antidepressant, antiviral, and anticancer effects. Microneedle-assisted delivery enhances solubility, stability, and dermal

penetration, improving photodynamic therapy efficacy for skin cancers and targeted treatments [63,64].

6. Epigallocatechin gallate (EGCG):

Epigallocatechin gallate (EGCG), a major green tea catechin, exhibits antioxidant, anti-inflammatory, and antimicrobial effects. Microneedle-assisted delivery enhances skin penetration, bioavailability, and therapeutic efficacy, showing promise in psoriasis, acne, hair regeneration, and oxidative stress-related skin disorders [65,66].

7. Celastrol (Ce):

Celastrol (Ce), a triterpenoid from Chinese medicinal herbs, exhibits antioxidant and anti-inflammatory effects. Microneedle-delivered Ce-loaded nanozymes enhance skin penetration, scavenge ROS, reduce cytokines, and alleviate psoriatic symptoms, offering a promising minimally invasive psoriasis therapy [67,68].

8. Polyphenol:

Polyphenols are plant-derived compounds with antioxidant, anti-inflammatory, and immunomodulatory effects. They promote wound healing, cardiovascular and neuroprotection, tissue regeneration, and mood regulation, offering a holistic therapeutic approach for oxidative stress and inflammation-related disorders [69,70].

9. Eugenol:

Eugenol is a phenolic compound from clove and other herbs, exhibiting antimicrobial, anti-inflammatory, analgesic, antioxidant, and local anesthetic effects. It is effective in dental care, wound healing, and biofilm-related infections, making it valuable for therapeutic use [71].

10. Mangiferin:

Mangiferin from *Mangifera indica* exhibits antioxidant, anti-inflammatory, antimicrobial, and pro-angiogenic effects. ROS/pH-responsive microneedle delivery enhances wound healing, biofilm eradication, and macrophage polarization, offering a promising precision therapy for infected wounds [72,73].

TABLE:4 Overview of Phenolic Compounds

Sr.No.	Phytoconstituents	Biological Source	Microneedle Application	References
1	Curcumin (Diferuloylmethane)	*Curcuma longa* (Turmeric rhizome, Zingiberaceae)	Nanosuspension-based dissolving MNs ↑ solubility, absorption, bioavailability; useful in skin disorders, inflammation, cancer.	[35-46]
2	Resveratrol (Res)	*Polygonum cuspidatum*, grapes, peanuts, mulberries, berries	PVP-based dissolving MNs (↑ solubility, 75% release/24h); hyaluronic acid MNs (anti-arthritic); SLN-MNs (Parkinson's, sustained release, neuroprotection).	[47-57]
3	Carvacrol (monoterpenoid phenol)	Essential oils of thyme, oregano, marjoram, coriander	Nanoparticle-loaded dissolving MNs for wound healing; ↑ solubility, controlled release; accelerates closure, reduces infection, promotes angiogenesis.	[58,59,60]
4	Apigenin / Betanin	*Petroselinum crispum* (parsley), chamomile, celery, onions / *Beta vulgaris* (beetroot)	Hyaluronic acid MNs (rapid release, barrier repair, ↓ cytokines, atopic dermatitis); dissolvable MNs (sustained release, antioxidant, anticancer).	[61,62]
5	Hypericin (phenolic, anthraquinone)	*Hypericum perforatum* (St. John's Wort)	MN patches enhance dermal delivery; improve PDT efficacy in skin cancers; hollow MNs superior to topical; also for viral & inflammatory disorders.	[63,64]

6	Epigallocatechin gallate (EGCG)	*Camellia sinensis* (green tea)	Dissolving MNs (PVA/HA-based); psoriasis therapy, hair regrowth (follicle activation), acne (↓ lipids, antibacterial, anti-inflammatory), wound healing.	[65,66]
7	Celastrol (triterpenoid)	*Tripterygium wilfordii* (Thunder God Vine)	Nanozyme-MNs (Ce@TA-Fe); mimic SOD/CAT enzymes, remove ROS; potent antioxidant/anti-inflammatory; effective in psoriasis (↓ PASI, keratinocytes).	[67,68]
8	Polyphenols (multiple phenolic compounds)	Fruits, vegetables, tea, coffee, cocoa, berries, *Lycium barbarum*	MNs enable antioxidant, anti-inflammatory, neuroprotective, wound-healing, cardiovascular protection; localized, controlled transdermal delivery.	[69,70]
9	Eugenol (allylbenzene phenolic)	*Syzygium aromaticum* (clove – main); also *Ocimum sanctum*, cinnamon, nutmeg, bay leaves	Incorporated into MN formulations for antimicrobial, antifungal, and biofilm disruption【109】; enhances wound healing and infection control【108】; applied in dental/oral MN patches for pain relief and antiseptic effects【110】; versatile phytoconstituent for herbal MN systems【111】.	[71]
10	Mangiferin (C-glucosylxanthone)	*Mangifera indica* L. (mango; family Anacardiaceae) – mainly in leaves, bark, fruit.	Dual ROS/pH-responsive MN system with PLGA microspheres + chitosan–gallic acid hydrogel + silver coating ; enables stimuli-responsive release in infected wounds; antibacterial action, ROS scavenging, macrophage M2 polarization, angiogenesis; enhances collagen deposition, re-epithelialization, and tissue regeneration; promising in wound infection management and antibiotic resistance.	[72,73]

TANNINS:

1. Catechin:

Catechin's poor stability and bioavailability can be improved using microneedle arrays. PVA-based microneedles containing 10% gelatin microspheres showed the highest catechin release (84.4% at 24 h), demonstrating the effect of microsphere concentration on release kinetics [74].

2. Green Tea:

Green tea (*Camellia sinensis*) extract–loaded hyaluronic acid microneedles provide sustained antibacterial activity and promote wound healing. GT/HA microneedles achieved up to 95% bacterial growth reduction and enhanced wound closure, offering a biodegradable, effective alternative for infection control [75].

3. Pomegranate:

The nano-pomegranate millineedle platform integrates electrodynamic therapy, cuproptosis, and immune activation for oral cancer treatment. It enhances ROS generation, induces apoptosis, and suppresses tumor growth with minimal side effects, offering a multifunctional therapeutic strategy [76].

4. Grape:

Microneedle impedance sensors offer a non-destructive, real-time method to monitor grapevine water potential, enhancing irrigation efficiency and grape quality. This technique supports

sustainable viticulture by optimizing water use and improving vineyard management practices [77].

5. Nuts:

Nuts are nutrient-rich foods offering cardioprotective, antioxidant, and anti-inflammatory benefits. Microneedle-based delivery of peanut allergens has shown potential for allergy desensitization, highlighting novel therapeutic applications beyond nutrition [78].

TABLE:5 Overview of Tannins

Sr.No.	Phytoconstituent	Biological Source	Microneedle Application	References
1.	Catechin	Green tea (Camellia sinensis), cocoa, fruits	Controlled catechin release (84.4% in 24 h) using gelatin microspheres	[74]
2.	Green Tea Extract (Catechins)	Leaves of Camellia sinensis	Antibacterial wound therapy, reducing infection	[75]
3.	Pomegranate (Punica granatum)	Family Lythraceae; cultivated in Mediterranean, Middle East	Oral cancer treatment using Pt@DLMSN + copper ionophore microneedles	[76]
4.	Grapes (Vitis vinifera)	Cultivated in Mediterranean, Europe	Monitoring grapevine water potential to optimize irrigation in viticulture	[77]
5.	Nuts	Almonds, walnuts, cashews, pistachios, peanuts (legume, but nutritionally considered nut)	Used in microneedle-based cutaneous immunotherapy with peanut allergens for allergy desensitization; potential role in immune modulation. Also provide systemic health benefits: cardioprotective, anti-inflammatory, antioxidant, glycemic control, BP regulation, weight management, longevity.	[78]

ALKALODS:

1. Nicotine:

Nicotine, an alkaloid from *Nicotiana tabacum*, is therapeutically used in Nicotine Replacement Therapy. Transdermal patches deliver nicotine steadily, reducing cravings and withdrawal symptoms, making them effective aids for smoking cessation [79].

2. Naloxone:

Naloxone, a semisynthetic opioid antagonist from *Papaver somniferum*, rapidly reverses opioid-induced respiratory depression. Hollow microneedle delivery achieves comparable or superior absorption to intramuscular injections, offering a faster, user-friendly option for overdose management [80].

3. Aconitum sinomontanum:

Microneedle-assisted nanostructured lipid carriers enhance transdermal delivery of Aconitum sinomontanum alkaloids, improving absorption, bioavailability, and analgesic and anti-inflammatory effects while reducing cardiotoxicity, offering a safe and effective strategy for clinical application [81].

4. Colchicine:

Colchicine, a tricyclic alkaloid from *Colchicum autumnale*, treats acute gout and inflammatory disorders. Microneedle-assisted transdermal

delivery improves bioavailability and reduces gastrointestinal side effects, offering a safer, effective alternative to oral therapy [82].

5. Matrine, Oxymatrine:

Sophora flavescens contains alkaloids and flavonoids with anti-inflammatory, anticancer, antiviral, and immunomodulatory effects. Dissolving microneedle delivery enhances therapeutic efficacy, reduces systemic side effects, and offers promise for clinical applications such as psoriasis treatment [83].

6. Sinomenine:

PVP-based dissolving microneedles enable localized transdermal delivery of sinomenine, enhancing skin and systemic bioavailability, reducing gastrointestinal side effects, and improving therapeutic efficacy for rheumatoid arthritis compared to conventional gels or oral formulations [84].

7. Berberine:

Berberine-loaded liposomes-in-hydrogel microneedles enhance psoriasis treatment by bypassing the stratum corneum, providing controlled release, reducing inflammation, and improving skin penetration, offering a safe and effective alternative to conventional systemic or topical therapies [85].

8. Pilocarpine:

Dissolvable microneedle patches delivering pilocarpine provide a minimally invasive, effective alternative to iontophoresis for cystic fibrosis sweat testing, improving sweat yield, diagnostic accuracy, and tolerability, particularly in infants and resource-limited settings [86].

TABLE:6 Overview of Alkaloids

Sr No.	PHYTO-CONSTITUENTS	BIOLOGICAL SOURCE	MICRONEEDLE APPLICATION	References
1	Nicotine	*Nicotiana tabacum* (Tobacco)	Transdermal patches for Nicotine Replacement Therapy (NRT) – sustained release, reduced cravings	[79]
2	Naloxone	Semisynthetic (from *Papaver somniferum* via thebaine)	Hollow microneedles for opioid overdose reversal – rapid absorption, improved accessibility	[80]
3	Lappaconitine, Ranaconitine	*Aconitum sinomontanum*	MN-assisted NLCs for arthritis & inflammation – enhanced absorption, reduced cardiotoxicity	[81]
4	Colchicine	*Colchicum autumnale* (Autumn Crocus)	Transdermal MN delivery for gout and inflammatory diseases – improved safety and compliance	[82]
5	Matrine, Oxymatrine	*Sophora flavescens*	Dissolving MNs for psoriasis, cancer, asthma – localized delivery, reduced systemic toxicity	[83]
6	Sinomenine	*Sinomenium acutum*	PVP-based dissolving MNs for rheumatoid arthritis – better bioavailability, local action	[84]
7	Berberine	*Berberis* spp.	Transdermal MN delivery for gout and inflammatory diseases – improved safety and compliance	[85]

8	Pilocarpine	*Pilocarpus jaborandi*	Dissolving MN patches for sweat induction (CF diagnosis) – alternative to iontophoresis	[86]

CONCLUSION:

Microneedle technology offers a promising solution for herbal drug delivery by enhancing solubility, permeability, and bioavailability of phytoconstituents like curcumin, resveratrol, and mangiferin. It enables painless, controlled, and targeted transdermal delivery, improving therapeutic outcomes in various diseases. However, challenges in large-scale production, stability, and clinical validation persist. Continued multidisciplinary research and standardization are vital to translate this innovative approach into practical phytopharmaceutical therapies.

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