Essential Oil Infused Pain Relief Bandages for Musculoskeletal disorders (MSDs): Medical Textile Innovation

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Abstract

Ayurveda, the traditional Indian system of medicine, emphasizes holistic healing through the use of natural resources and lifestyle balance, with polyherbal formulations playing a central role in enhancing therapeutic efficacy and reducing toxicity. This review explores the relevance of polyherbal Ayurvedic formulations and essential oils in the management of musculoskeletal disorders (MSDs), focusing on skin-mediated drug delivery mechanisms. The structure of human skin and its major drug penetration pathways intercellular, transcellular, and appendageal—are discussed, highlighting the dominant role of the intercellular lipid pathway in transdermal absorption. The use of penetration enhancers to overcome the stratum corneum barrier is also examined. Essential oils such as eucalyptus, lavender, and rosemary, known for their analgesic and anti-inflammatory properties, are reviewed for their potential in MSD management. Furthermore, the concepts of oleophilicity and oleophobicity are analyzed in relation to textile and bandage modification for improved oil delivery and fluid management. Advanced surface engineering approaches combining chemical modification and micro/nanostructuring are shown to enhance oil absorption or repellency as required. Overall, the integration of Ayurvedic polyherbal oils with engineered textile-based delivery systems presents a promising, non-invasive strategy for effective pain relief and musculoskeletal therapy.

Keywords: Ayurveda; Polyherbal formulation; Essential oils; Musculoskeletal disorders (MSDs); Penetration enhancers; Medical textile; Pain relief Bandages.

1. Introduction

Traditional healing systems continue to gain global attention as complementary approaches to modern healthcare, particularly in the management of chronic pain conditions. Ayurveda offers a holistic approach by combining natural plant-based formulations with principles that support long-term wellness rather than symptomatic relief alone. Polyherbal preparations are central to this approach, as the synergistic action of multiple herbs enhances therapeutic outcomes. Musculoskeletal disorders remain a major cause of pain and functional limitation worldwide, creating a significant challenge to public health due to their persistent nature, impact on mobility, and effect on quality of life. The United Nations and the World Health Organization (WHO) recognized the global significance of MSDs when they designated the years 2000–2010 as the "Bone and Joint Decade" on January 13, 2000, in Geneva, Switzerland. Topical therapies provide targeted relief and are well suited for long-term use when compared to systemic medications.

Essential oil–based formulations have gained attention due to their dual role in providing pain relief and improving skin permeation. At the same time, advances in functional textiles enable better control over oil absorption and repellency, improving application efficiency and user comfort. The convergence of Ayurvedic polyherbal therapy, essential oil technology, and smart textile design presents a novel and promising strategy for effective management of musculoskeletal discomfort.

2. Polyherbal Formulation in Indian Ayurveda

Ayurveda, the traditional system of medicine of India, is rooted in the philosophy of preventing suffering and promoting a long, healthy life. It believes in restoring balance within the body by using natural elements, while also encouraging a healthy lifestyle to prevent disease recurrence. Herbal medicine has a long global history and was practiced in ancient Chinese, Greek, Egyptian, and Indian civilizations. Even today, the World Health Organization estimates that nearly 80% of the world's population depends on traditional medicine for primary healthcare. India, one of the world's richest centers of biodiversity, is home to about 45,000 plant species, of which nearly 15,000 are medicinal. Traditional communities use around 7,000–7,500 of these plants to treat various ailments. A key strength of Ayurveda lies in polyherbalism—the use of single or multiple herbs in combination. Classical texts such as the Sarangdhar Samhita emphasize that combining herbs in specific ratios enhances therapeutic effectiveness and reduces toxicity, as the active compounds of a single plant may not be sufficient alone. This story of Ayurveda highlights how the wisdom of polyherbal formulations continues to play a vital role in improving treatment outcomes and advancing traditional medicine. [1]

3. Oil Penetration Mechanism

The skin is made up of three layers: epidermis, dermis, and hypodermis**.** The epidermis is the outermost layer and acts as the main protective barrier of the skin. The dermis, located beneath the epidermis, provides strength, elasticity, and support. It contains blood vessels, nerves, sweat glands, sebaceous glands, and hair follicles, and helps regulate body temperature while supplying nutrients to the epidermis. Adipose (fat) and connective tissue make up the majority of the hypodermis, the deepest layer of skin. In addition to supporting blood arteries and neurons, it offers insulation, cushioning, and energy storage. [2]

Drugs can enter the skin through three main pathways: intercellular, transcellular, and appendageal. The intercellular pathway is the most common route, where drugs pass between skin cells (corneocytes) through lipid spaces. This pathway can allow relatively large and hydrophilic molecules. In the transcellular pathway, drugs pass directly through the skin cells, crossing lipid membranes, so only small and lipophilic drugs can use this route. The appendageal pathway delivers drugs through hair follicles, sweat glands, and sebaceous glands, allowing larger, polar, or ionizable molecules, but its contribution is limited because these structures cover only a very small area of the skin (~0.1%). [2]

The skin's structure is a factor that affects transepidermal penetration. Overcoming the Stratum corneum (SC), the outermost layer of the non-viable epidermis, is the main barrier to active chemical penetration through the skin. (SC) acts as a rate-limiting lipophilic barrier to prevent transepidermal water loss and the absorption of chemical and biological contaminants. Only a few routes exist for active compounds to penetrate the epidermis: transcellular (intracellular) penetration through the SC's corneocytes, penetration through the SC's intercellular spaces, and appendage penetration through hair follicles, sebaceous, and/or sweat glands. While lipophilic permeants travel through the SC via the intercellular route and hydrophilic substances partition preferentially into the intracellular domains, most molecules pass through the SC by both pathways. However, it is generally accepted that the intercellular pathway serves as the primary avenue and significant obstacle to the majority of medications' penetration. [3]

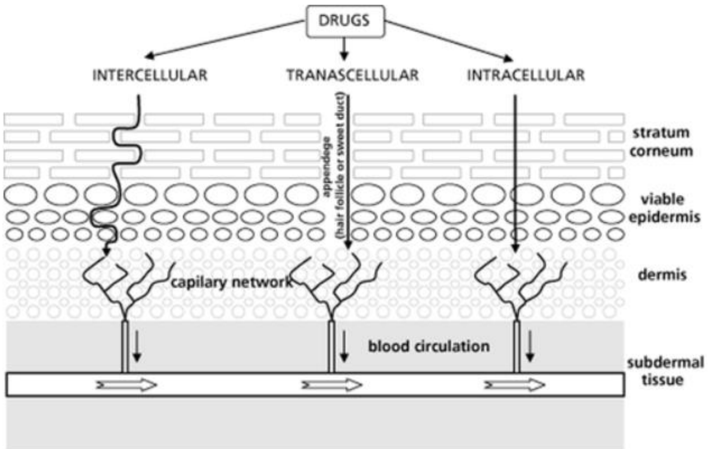

Figure 1: Drug permeation routes across the skin [3]

3.1. Penetration enhancer:

Penetration enhancers, sometimes referred to as sorption promoters or accelerants, are substances that can improve drug penetration through the skin by reversibly reducing the skin barrier's resistance. Transdermal drug delivery has attracted a lot of interest during the last two to three decades because of its many potential advantages. However, the skin's protective function makes it difficult for most medications to be absorbed via the skin. In order to reversibly lower the barrier function of the stratum corneum, skin penetration enhancers are commonly utilized in the field of transdermal medication delivery. Numerous chemical substances have been demonstrated to improve the skin permeation of medicinal medications thus far. [4]

3.2. Mode of action of penetration enhancers

Skin penetration enhancers may work on the skin using one or more of the following techniques. The first mechanism that has been suggested is solvent action. The penetration enhancers may cause the skin-tissue components to become soluble or plasticized. According to the second proposed mechanism, enhancers promote drug diffusivity through the lipid domain by altering the highly ordered lamellar structure through interactions with intercellular lipids. The third recommended strategy involves the interaction of enhancers with intracellular proteins to promote drug penetration through the corneocyte layer. The fourth proposed mechanism is an increase in the partitioning of drugs, co-enhancers, or co-solvents into the stratum corneum. [4]

4. Musculoskeletal Disorders (MSDs)

Musculoskeletal disorders (MSDs) are a group of diseases that impact the locomotor system, which includes the muscles, bones, joints, and tendons. [4] Musculoskeletal conditions comprise more than 150 diseases and syndromes. MSDs commonly arise due to sudden physical exertion or prolonged exposure to risk factors such as repetitive movements, excessive force, vibration, and awkward postures. Although they vary widely in their pathophysiology, they are anatomically related and commonly associated with pain and reduced physical function. These conditions range from acute, short-term disorders to chronic, lifelong diseases, including osteoarthritis, rheumatoid arthritis, osteoporosis, and low back pain. The prevalence of many musculoskeletal conditions increases significantly with advancing age, and several are influenced by lifestyle factors such as obesity and physical inactivity. The global rise in the aging population, along with widespread lifestyle changes, is expected to substantially increase the burden of musculoskeletal disorders on individuals and society. [5] Rheumatoid arthritis (RA), osteoarthritis (OA), low back pain (LBP), neck pain (NP), and gout are common types of MSDs. These conditions can cause physical dysfunction, depressed symptoms, and other long-term health problems like cardiovascular diseases. They are characterized by joint pain, stiffness, and limited mobility. [4]

Musculoskeletal disorders (MSDs) are widespread worldwide and represent one of the leading causes of long-term pain and disability, affecting millions of individuals. MSDs involve conditions of the muscles, nerves, tendons, joints, cartilage, and other supporting structures of the upper and lower limbs, neck, and lower back. These disorders result in pain and discomfort that significantly interfere with daily activities. The global importance of MSDs was acknowledged by the World Health Organization (WHO) and the United Nations, which declared the period from 2000 to 2010 as the “Bone and Joint Decade” in 13 January 2000 at Geneva, Switzerland. [5]

5. Role of Essential Oils in Managing MSD

Musculoskeletal disorders (MSDs) represent a significant global public health concern, as they lead to chronic pain, physical disability, and a reduced capacity to work. These disorders affect various parts of the body, including the back, neck, shoulders, limbs, joints, and surrounding tissues. The primary objective of the treatment is to alleviate pain and improve stiffness, thereby enhancing overall physical function. [7]

Painkillers can have major adverse effects, particularly when used for extended periods of time (in chronic conditions) and at high dosages. Because it can lower the dosage of required analgesic medications or extend the duration of an effective treatment before it loses its effectiveness in pain management. A well selected, evidence-based phytotherapy may be helpful in the treatment of pain. [7]

Essential oils (EOs) are complex secondary metabolites produced by aromatic plants and consist primarily of low–molecular weight, apolar or semi-polar volatile compounds. Terpenoids form the largest class of these constituents, while phenolic compounds are also prominent. Typically, an essential oil contains between 10 and 50 chemically diverse components, including hydrocarbons and oxygenated compounds such as alcohols, ketones, aldehydes, ethers, and esters. The biological activity of an essential oil is largely determined by its chemical composition, although individual components, such as menthol or camphor, may exhibit strong bioactivity on their own. Essential oils are most commonly administered through inhalation or topical application, with massage being a widely used method. Both the aroma and tactile stimulation play a role in activating the parasympathetic nervous system, promoting relaxation and subsequently reducing pain intensity. [7]

Essential oils such as lavender, peppermint, rosemary, eucalyptus, and chamomile have traditionally been used in the management of musculoskeletal disorders (MSDs). Their application aims to reduce musculoskeletal pain and inflammation while enhancing blood circulation. These oils also exhibit cooling and local anesthetic properties, promote muscle relaxation, and help alleviate depression associated with chronic pain. The analgesic effects of various essential oils have been demonstrated in several animal studies, in which the oils were commonly administered orally or intraperitoneally. [7]

5.1. Types of Essential Oils Used:

5.1.1 Eucalyptus Oil:

Eucalyptus [Eucalyptus globulus Labill (E. globulus)] is a tall, evergreen shrub that may reach a height of

250 feet and is a member of the Myrtaceae family. Its oil has been used to energize and regulate the neurological system, which is responsible for headaches, neuralgia, and debility. The essential oil of this plant are widely known for their ability to treat rheumatoid arthritis as well as aches and pains in the muscles and joints. The antibacterial, anti-inflammatory, anti-proliferative, and antioxidant properties of eucalyptus oil have been proven. Additionally, it can be used to treat wounds, cuts, burns, herpes, lice, insect repellent, and insect bites. The outcomes are encouraging and may be used to treat complex illnesses in people with different causes.

5.1.2 Lavender Oil:

Lavender (Lavandula officinalis Chaix.), a member of the Lamiaceae family, is a widely valued aromatic garden herb. Lavender essential oil exhibits antibacterial and antifungal activity against numerous microorganisms. It is well documented for its use in treating abrasions, burns, stress, headaches, skin disorders, and muscle pain, as well as for promoting new cell growth and supporting immune function.

5.1.2 Rosemary Oil:

Rosemary (Rosmarinus officinalis Linn.), a member of the Lamiaceae family, is an aromatic shrub that produces small pale blue flowers during late spring or early summer and grows up to approximately 90 cm in height. It occurs in three varieties—silver, gold, and green-striped—of which the green variety is primarily used for medicinal purposes. The plant is rich in bitter compounds, resins, tannic acid, and volatile oils. It contains anti-inflammatory and analgesic (pain-relieving) properties. Additionally, the oil supports cardiovascular health by helping to regulate blood pressure and slow arterial hardening. Traditionally, it has been used during winter to alleviate rheumatic pain aggravated by cold. Rosemary oil also acts as an effective skin tonic, and promotes hair growth. [8]

6. Oleophobicity:

The term "oleophobic" describes a material's physical characteristic of having no attraction for oils. Oleophobic materials prevent oils from penetrating or sticking to them. These materials are frequently utilized in the creation of coating materials that prevent corrosion. [9] Oleophobicity is the ability of a surface to repel oils and prevent them from wetting it. This feature is especially important for textiles that are exposed to oil on a regular basis. Oleophobic textiles are important in a number of important areas: By limiting oil absorption, which can cause material deterioration, these textiles extend the durability of fabrics, as oils don't stick to the surface, they make cleaning procedures simple**,** and by preventing stains from forming, they enhance the aesthetic attractiveness of textiles.

Oleophobic, superoleophobic, and omni/amphiphobic coatings are essential for a variety of applications, including chemicals, oil/water separation media, self-cleaning surfaces, and anti-oil coatings, bio-adhesive surfaces, anti-blocking substances, shields, and more. [11]

6.1 Oleophobic fabrics:

- **Definition:** Fabrics that repel oils and low surface tension liquids, preventing wetting. The term "phobic" denotes “fear” or repulsion. [14]
- **Mechanism:** Low surface energy coatings combined with micro/nano-scale roughness lead to a non-wetting Cassie–Baxter state, where oil droplets remain nearly spherical.[11]
- **Examples:** Textiles coated with fluorinated polymers, perfluoroalkyl silanes, silica nanoparticles, PDMS, or engineered with hierarchical micro/nanotextures. [11]

7. Oleophilicity:

Oil and other non-polar liquids exhibit a strong attraction toward oleophilic materials. In contrast to hydrophilicity, the term oleophilic originates from Greek, where oléum means oil and philéō means to love. This property where oleophilic polymers or surfaces preferentially attract and absorb oil - is widely exploited in technical textiles for separating oil–water mixtures. Oleophilicity ensures high separation efficiency in many industrial applications, such as coalescence filters, oil skimmers, and exhaust air purification systems. From a chemical perspective, oleophilicity is closely related to lipophilicity, as lipophilic substances readily dissolve in fats and oils and generally show low affinity for polar solvents. [12]

An oleophilic material is therefore defined as a material that has a strong affinity for oils. Such materials may be synthetic, including polystyrene and polyurethane, or natural, such as kapok fiber, rice husk, and coconut coir. [13]

7.1 Oleophilic fabrics:

- **Definition:** Fabrics that attract and absorb oils or non-polar liquids. The term "philic" denotes “loving” or affinity towards a substance.[14]
- **Mechanism:** Have higher surface energy relative to the oil, facilitating spreading and absorption.[11]
- **Examples:** Untreated natural fibers like cotton, or fabrics coated to selectively absorb oil in oil–water separation membranes.[11]

Table 1: Examples and Fabrication Methods of Oleo ‘phobic’ and ‘philic’ Textiles [11]

Type	Fabric/Base	Surface Treatment/Coating	Key Notes
Oleophilic	Cotton, polyester	Metal oxides, PDMS, PTFE	Used in oil spill absorption and oil/water separation membranes; high oil flux
Oleophobic	Silk, nylon, polyester	Fluorodecyl POSS, fluorinated polymers, silicones, nanoparticle coatings	Maintains oil repellency, stain resistance; requires micro/nano structured topography
Superoleophobic	Silk, Nylon, Polyester	Multilevel hierarchical texture (nano- and micro-), plasma treatment, electrospun nanofibers, self-assembling monolayers	Extreme repellency, low roll-off angle, self-cleaning properties

8. Industrial Applications of Oleo ‘phobic’ and ‘philic’ Fabrics

Textiles & Clothing:

- Stain-resistant and self-cleaning garments
- Outdoor gear (tents, jackets, backpacks)
- Fashion fabrics with oil/water repellency

Medical & Healthcare:

- Gowns, masks, and bedding resistant to body fluids
- Bandages maintaining hydrophobicity and/or selective oil absorption

Industrial & Automotive:

- Protective clothing, aprons, industrial covers, upholstery
- Interiors repelling oil-based stains

Filtration & Environmental:

- Oil/water separation membranes
- Air and liquid filtration resistant to oil contamination

Electronics & Consumer Goods:

- Touchscreens, OLED displays (oleophobic coatings for smudge resistance)

Bandage Modification

For medical bandages, surface modification using oleophobic or oleophilic coatings can enhance performance:

Oleophilic bandages:

- Coated with microporous hydrophobic but oleophilic polymer layers (e.g., PDMS, crosslinked PTFE).
- **Function:** Absorb lipid-rich exudates while repelling water, maintaining a dry wound environment.

Oleophobic bandages:

- Coated with nanostructured low-surface-energy polymers (fluorinated or PFAS-free alternatives like PDMS-based brushes).
- **Function:** Repel oils, blood, or bodily fluids to prevent staining, contamination, and bacterial adhesion. Can include hierarchical micro/nano textures to maintain oil repellency under pressure and shear.

Hybrid modification:

- **Layered approach:** inner oleophilic layer absorbs exudate, outer oleophobic layer prevents external contamination.
- **Example:** superoleophobic top-layer combined with absorbent hydrogel or fabric matrix.

Evaluation Metrics for Modified Textiles

- **Contact Angle Measurements:** Water and oil droplets; superoleophobicity if $\theta > 150°$
- **Roll-off Angle:** Minimum tilt angle for droplet shedding
- **Oil Absorption Tests:** Quantitative oil uptake for oleophilic layers
- **Durability Testing:** Resistance to washing, abrasion, and mechanical stress
- **Surface Characterization:** SEM, AFM to confirm micro/nanoscale textures

Key Principles in Design

- **Surface Energy Engineering:** Match surface energy below liquid surface tension to repel liquids.
- **Hierarchical Texturing:** Micro + nano-scale structures maintain composite liquid–air interface (Cassie–Baxter state).
- **Re-entrant Features:** Ensures droplets do not penetrate gaps or transition to the Wenzel fully-wetted state.
- **Non-Fluorinated Approaches:** For environmental sustainability, PFAS-free chemistries combined with hierarchical texturing to achieve oleophobicity.

9. Conclusion

Oleophilic fabrics are oil-attracting and useful for absorption/separation, while oleophobic fabrics repel oil for stain resistance and protective clothing. Oils can be applied to human skin to reach bone tissue through textile medium holding oleophilic properties. Certain oils that are good to bone tissue soothen and reliefs from pain. Advanced designs in bandages combine chemical surface modification with micro/nanoscale hierarchical textures to create durable and robust oil-repellant textiles. Oleophilic or oleophobic layers are used in bandages for wound management, fluid management and contamination prevention. The expanding medical textile sector offers increasing opportunities for innovative product development through the use of advanced technical textile materials.

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