Review

Exploring the Potential of Nanotechnology in Cosmetics: Incorporating Natural Ingredients for Enhanced Skin Benefits

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Exploring the Potential of Nanotechnology in Cosmetics: Incorporating Natural Ingredients for Enhanced Skin Benefits

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Abstract: This article presents a comprehensive overview of the utilisation of nanotechnology in the cosmetics industry, with a specific focus on developing nanoparticles for the efficient delivery of active ingredients through skin penetration. The review delves into incorporating natural ingredients in cosmetics, exploring their therapeutic properties and the advantages and limitations associated with their use. Furthermore, the article examines the benefits of integrating natural ingredients into skincare products to enhance skin conditions, highlighting the application of nonfibrous technology in areas such as UV protection, anti-ageing effects, moisturisation improvement, and wound healing. Ultimately, the article emphasises the immense potential of nanotechnology to create innovative opportunities and positive societal impacts across various industries.

Keywords: nanotechnology; nanofibers; active ingredients; skincare products; encapsulation methods; electrospinning

1. Introduction

Nanotechnology is a rapidly growing field in the cosmetics industry that involves manipulating materials at the nanoscale to create nanoparticles that can penetrate the skin and deliver active ingredients more effectively [1]. Nanotechnology involves studying substances at the molecular and atomic levels, focusing on objects and structures calibrated on a nanometre scale, which is one billionth of a meter (10^{-9} m) [2]. For comparison, the diameter of an influenza virus is 100 nm, whereas the thickness of human hair is approximately 100 μm [3].

Nanotechnology in cosmetic products has led to innovative products with improved performances [4]. Natural products are commonly used in cosmetics because of their therapeutic properties and minimal side effects [5]. Despite this, the safety of nanoparticles in cosmetic products is a concern, and further research is needed to fully understand their impact on human health and the environment [6].

Herbal cosmetics offer advantages such as better patient tolerance [7], minimal side effects [8], renewable sources of medication [7], extensive availability [9], and cost-effectiveness [10]. Nevertheless, it also has disadvantages, such as slower growth in demand, testing difficulties and limited availability, strict manufacturing procedures and a lack of standardisation in ingredients and techniques [11]. Skin is the primary barrier that shields the body from various free radicals [12]. Various sources produce free radicals, such as UV rays, dust, chemicals, and air pollution [13].

People of all ages seek premium skincare products for flawless, youthful skin. The quality and density of extracellular matrices and the provision of cells to connective tissues influence the concept of ideal skin [14]. Skin conditions such as acne, abnormal pigmentation, and xerosis can indicate skin pathology [15]. Nutritional deficiencies can cause skin lesions; however, combining cosmetic skin

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care products and over-the-counter (OTC) treatments can help individuals improve their skin health and appearance [16]. By following a regimen that includes both products, consumers can rebuild their skin and achieve a more beautiful complexion [17]. Natural ingredients are substances derived from natural sources, such as plants or minerals, without synthetic or artificial additives, such as coconut oil, shea butter, or lavender essential oil [10]. Incorporating natural ingredients into skin care products improves skin conditions [18]. Nanotechnology is used in various ways in skincare products to provide benefits such as UV protection [19], anti-ageing effects [20], improved moisturisation [21], and wound healing [10].

Nanomaterials are increasingly being used in various industries, including cosmetics [22], pharmaceuticals [23], and dermatology [24]. In cosmetics, nanomaterials are used as hair conditioners [25], serums [26], moisturisers [27], shampoos [28] for damaged hair, skin-lightening creams, and anti-ageing creams [4].

Nanofibrous technology allows for the encapsulation of nanoparticles, which then act as a drug delivery substrate, allowing the active components to reach deeper layers of the skin, where they can have the most effect [15]. For these reasons, nanofibrous technology is gaining popularity in cosmetics and medicine.

This study endeavours to investigate the potential of nanotechnology in the cosmetics field by incorporating natural ingredients to amplify skin benefits. By filling the existing research gap, it aims to elucidate the effective utilisation of nanotechnology in seamlessly integrating natural ingredients into cosmetic formulations. This research offers novel insights into the application of nanotechnology and presents a fresh perspective on harnessing the potential of natural ingredients in skincare. The findings of this study hold promise for advancing our understanding of how nanotechnology can revolutionise the use of natural ingredients in skincare and pave the way for innovative approaches in cosmetic product development.

2. Natural active ingredients

Table 1 presents a compilation of scientifically backed active ingredients derived from natural sources, curated for their potential effectiveness in addressing various skin types. Specifically, for individuals with dry skin, the following ingredients are recommended: aloe vera (Aloe barbadensis), chamomile (Matricaria chamomilla), calendula (Calendula officinalis), lavender (Lavandula angustifolia), coconut oil (Cocos nucifera), jojoba oil (Simmondsia Chinensis), shea butter (Butyrospermum parkii), olive oil (Olea europaea), rosehip oil (Rosa canina), and witch hazel (Hamamelis virginiana). These ingredients have been identified for their potential to provide soothing, moisturising, and hydrating effects, offering a natural approach to alleviate dryness and promote improved skin health [29]. Furthermore, cosmeceuticals have the ability to regulate the distribution of their active ingredients by forming a thin film on the skin, facilitating targeted and precise delivery [8]. This controlled release mechanism enables the recommended ingredients for normal, oily, and combination skin types, such as niacinamide, vitamin C, hyaluronic acid, green tea extract, salicylic acid, tea tree oil, zinc, witch hazel, alpha hydroxy acids, jojoba oil, to exert their beneficial effects in specific areas as needed. By incorporating such advanced delivery systems, cosmeceuticals can optimise the efficacy of these ingredients, ensuring their effective penetration into the skin and enhancing their desired outcomes [30].

Table 1. Active Ingredients from Natural Sources for Different Skin Types.

Skin Type	Active Ingredient	Benefits	References
Dry skin	Aloe vera	Moisturises and soothes dry skin and helps restore the natural skin moisture barrier.	[30]
	Chamomile	It has anti-inflammatory properties and soothes dry, irritated skin.	[31]
	Calendula	Helps to hydrate and heal dry, damaged skin.	[32]
	Lavender	Has calming properties and soothes dry, itchy skin.	[33]
	Coconut oil	Has moisturising properties and helps to soothe and hydrate dry skin.	[34]
	Jojoba oil	Helps to moisturise dry skin without leaving a greasy residue	[35]
	Shea butter	Has deeply moisturising properties, helps to soothe and nourish dry skin	[36]
	Olive oil	Contains antioxidants and moisturising properties, helps to hydrate and protect dry skin	[37]
	Rosehip oil	Contains essential fatty acids and vitamin A, helps to hydrate and rejuvenate dry skin	[38]
	Witch hazel	Has astringent properties, helps to tighten and tone dry, ageing skin	[39]
Normal skin	Niacinamide	Helps improve skin texture and tone, reduces the appearance of fine lines and wrinkles, and strengthens the skin barrier	[40]
	Vitamin C	Helps brighten and even out skin tone, promotes collagen synthesis, and protects against environmental damage	[41]
	Hyaluronic acid	Provides deep hydration and helps retain moisture in the skin, improving skin elasticity and firmness.	[42]
	Green tea extract	Has anti-inflammatory and antioxidant properties, helps protect against UV damage, and promotes healthy skin ageing	[43]
	Retinoids	Helps stimulate collagen production, improves skin texture and tone, and reduces the appearance of fine lines and wrinkles	[44]
Oily skin	Salicylic acid	Helps unclog pores, reduces oiliness, and prevents breakouts	[45]
	Tea tree oil	Has anti-inflammatory and antimicrobial properties, helps reduce acne and oiliness	[46]
	Zinc	Helps regulate sebum production, has anti-inflammatory and antimicrobial properties, and promotes wound healing.	[47]
	Witch hazel	Has astringent properties that can help tighten and tone oily skin, reduces inflammation and irritation	[39]
Combination	Niacinamide	Helps regulate sebum production, improves skin texture and tone, and strengthens the skin barrier.	[40]
	Hyaluronic acid	Provides deep hydration to dry areas while being lightweight enough not to exacerbate oiliness in the T-zone	[42]
	Vitamin C	Helps brighten and even out skin tone, promotes collagen synthesis, and protects against environmental damage	[41]

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	Alpha-hydroxy acids (AHAs)	Help exfoliate dead skin cells, improve skin texture and tone, and reduce the appearance of fine lines and wrinkles.	[40]
	Jojoba oil	A similar structure to the natural skin sebum helps regulate oil production and hydrates dry areas.	[35]

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UV radiation exposure accounts for approximately 90% of skin ageing [48]. The skin's ageing process can also be influenced by lifestyle factors such as smoking and sleeping habits, exposure to pollution and poor diet [49]. The first signs of skin ageing include dryness, wrinkling and loss of elasticity [50]. In the pursuit of preventing or decelerating the onset of early signs of skin ageing, various modern interventions have emerged [51]. While traditional topical formulations, including emulsions, suspensions, solutions, gels, powders, and aerosols, continue to be widely employed for delivering active ingredients to the skin, advancements in scientific research have opened up new avenues for innovative approaches [52]. These novel interventions aim to enhance the efficacy of anti-ageing treatments by harnessing cutting-edge technologies, such as nanotechnology, microencapsulation, and targeted delivery systems. By leveraging these advancements, scientists and researchers can devise formulations that optimise active ingredients' bioavailability, stability, and controlled release, thereby maximising their impact on skin health and rejuvenation [53–55]. Traditional topical skin care formulations may have limitations that affect their safety and efficacy [56]. Researchers have developed various nanomaterials to overcome these limitations to facilitate drug delivery [57]. Using nanomaterials to develop skin care products is an ongoing process in the healthcare and cosmetics industries, potentially creating new opportunities and positive impacts on society and various industries [58]. Nano-sized drug delivery systems are being studied to improve the delivery of active pharmaceutical ingredients (APIs) in nano-products such as cosmetics and pharmaceuticals [59]. The skin is a barrier, and the administration of APIs can be challenging because of the complex physiological layers with different polarities [60]. Various active ingredients in cosmetic products can prevent, delay and treat skin ageing [61]. Nanofibers have been studied as potential solutions to address the challenges of transdermal drug delivery [62]. Skin care products that use nanotechnology, including nano-products, have demonstrated promising results in delivering active ingredients into the skin [7,9,43,53].

3. Skin structure

The epidermis, dermis, and subcutaneous layers constitute the skin's largest organ. **Figure 1** shows the structure of the skin. The epidermis regenerates continually and contains keratinocytes and other cells that divide at the base and move toward the surface [63]. As part of the natural process, skin cells undergo apoptosis and contribute to forming the outermost layer of the epidermis, known as the stratum corneum [64]. Melanocytes, specialised cells in the skin, produce melanin, a pigment responsible for skin colouration and a protective shield against UV radiation [65]. The dermis houses sweat glands, which release perspiration through ducts, enabling the body to regulate its temperature [66].

Additionally, dermal hair follicles play a role in temperature regulation [67]. These cellular components and mechanisms contribute to maintaining the functionality and protection of the skin, ensuring its vital role in thermoregulation [68]. Sebaceous glands generate sebum, an oil that protects hair from bacteria and dust and creates the skin surface layer with perspiration [13,14].

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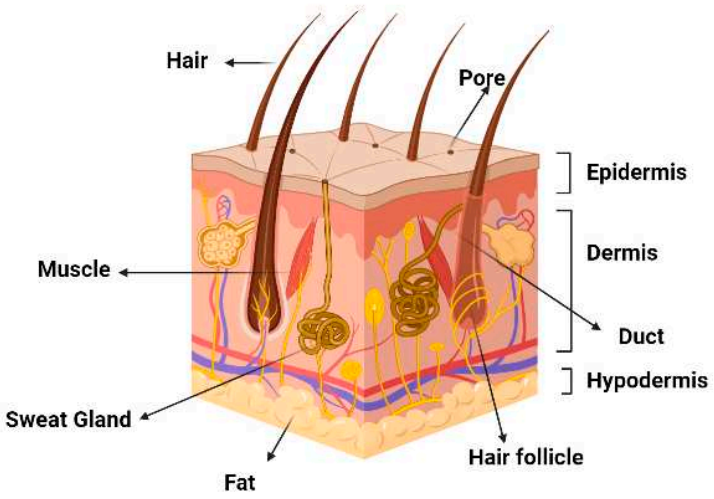

Figure 1. Anatomy of the Skin [69].

3.1. Keratinocytes

The epidermis, the outermost layer of the skin, consists mainly of keratinocytes and acts as a protective barrier, maintaining moisture levels and shielding the skin from external factors [70]. It has a layered structure, with the youngest cells in the basal layer and the oldest cells on the surface [71]. Stem cells in the basal layer continuously regenerate and renew the skin, while the granular layer synthesises lipids, proteins, and carbohydrates, forming multi-coloured granules [63]. The outermost layer of flattened and inactive cells is called the stratum corneum (SC) [72].

Skin tone can be dull or tired, and darker-skinned people can describe it as *"ashy"* due to this buildup caused by a lack of natural enzymes that break down dead skin cells [73]. Keratinocytes can be converted into cancerous cells by losing their ability to survive programmed cell death, or a process called apoptosis squamous cell carcinoma (SCC) or basal cell carcinoma (BCC), depending on the location of the affected cells, which reproduce and produce multiple copies of themselves, resulting in the formation of squamous cell carcinoma (SCC) or basal cell carcinoma (BCC) is more commonly observed in individuals who have a history of significant sun exposure cancers of these types of cancer are usually treated with surgery, which can result in scarring antioxidants and retinoids, according to some studies, may help prevent the formation of SCCs and BCCs. [74,75].

3.2. Fibroblasts

Fibroblasts are located in the middle layer of the skin over the muscle and fat layers [76]. Fibroblasts are vital cells in skin ageing because they secrete collagen, elastin, and hyaluronic acid (HA), which affect the appearance of skin collagen, elastin, and HA, the skin's thickness, volume, elasticity, and strength are dependent on fibroblasts. After all, they contain the cellular organelles that produce collagen, elastin, and HA, which are essential skin components [77,78].

3.2.1. Collagen

Collagen is the primary component of connective tissue and is a group of proteins characterised by their unique triple-helix structure [79]. The dermis contains 11 out of 18 types of collagen [80]. The most prevalent protein found in humans is Type I collagen, whereas Type I, III, and VII collagen are the most significant types of collagen in the skin [81]. Fibroblasts produce collagen in a pre-formed state that acts as a scaffold or structure, providing structural support and strength to the skin. As skin ages, it contains lower amounts of Type I and Type III collagen than young skin. [82]. laser treatments, light therapy, and injectable hyaluronic acid (HA) products have been shown to increase collagen production in the skin [83–86].

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3.2.2. Elastin

Elastin is a crucial element of the extracellular matrix of connective tissue and consists of two primary components: fibrillin and tropoelastin [87]. Fibroblasts separate fibrillin and tropoelastin components, and the skin must assemble them to form mature elastin fibrils that provide elasticity to the skin [88]. After puberty, the skin has trouble producing functional elastin; therefore, ageing skin sags and loses its elasticity [88]. Aged skin exhibits reduced levels of functional elastin compared to younger skin. Presently, there are no topical or injectable medications that effectively stimulate the synthesis of functional elastin in the skin [89,90].

3.2.3. Hyaluronic Acid

Hyaluronic acid (HA) is a glycosaminoglycan abundantly present in the dermis [91]. It is a sugar molecule capable of binding to water up to 1,000 times its weight, aiding the skin's ability to attract and retain moisture, thereby maintaining its volume [92]. HA plays vital roles in cell development, membrane receptor function, and cell adhesion while also crucial for skin hydration [21,21]. With age, the levels of HA in the joints and skin decrease, resulting in a decline in skin plumpness [93]. HA is the active component in dermal fillers like Restylane and Juvéderm [94]. The study conducted by Poetschke et al. [95] aimed to assess the efficacy of the daily application of hyaluronic acid-containing anti-wrinkle creams on wrinkle depth, skin tightness, and elasticity. The findings revealed significant improvements in wrinkle depth and skin tightness following consistent use for over 3 months. However, due to limitations in the study design, conclusive evidence regarding the efficacy of hyaluronic acid could not be established.

4. Encapsulation methods

Encapsulation in cosmetics involves the encapsulation of active ingredients within small particles or spheres composed of polymers, lipids, or other materials, serving to protect the active ingredient from degradation or evaporation and enabling controlled release over time, thereby enhancing the stability and efficacy of cosmetic products and facilitating the delivery of vitamins, antioxidants, and peptides to the skin [95].

5.1. Polymer-based nanoparticles

Polymeric nanoparticles are small and have unique properties that make them useful for various applications, including drug delivery. They can improve drug stability, provide controlled release, enhance drug-tissue interaction, and reduce adverse effects by improving the therapeutic index, making them suitable for various fields [20]. Polymer-based nanoparticles are spherical nanocarriers that are available in nanocapsules and nanospheres. The former has a hollow core surrounded by a polymeric layer, while the latter has a polymeric matrix that extends from the body to the surface. Molecule location is determined by its chemical structure; in other cases, the active molecule's location is determined by its chemical structure; in other cases, it can be adsorbed or grafted onto the particles' surface. [10,11,23]. Chitosan, alginate, and proteins like albumin are some of the most extensively studied natural polymers in polymeric nanoparticles for drug delivery [50]. Several synthetic polymers have been extensively studied to produce polymeric nanoparticles, with polylactide-polyglycolide, polylactide, polycaprolactones, and polyacrylates being some of the most widely explored [31]. Polymer-based nanoparticles have attracted much attention in various applications, particularly drug delivery systems. Nanoparticles have unique properties that enhance drug stability, controlled release, drug-tissue interaction, and reduced adverse effects, thereby raising the therapeutic index [96]. In addition to their applications in drug delivery systems, polymer-based nanoparticles have garnered significant attention in the cosmetic industry [97]. Provide promising opportunities for improving the quality and performance of cosmetic products. Cosmetics can achieve improved stability, controlled release, and targeted delivery of beneficial compounds to the skin by incorporating active ingredients into polymer-based nanoparticles [98].

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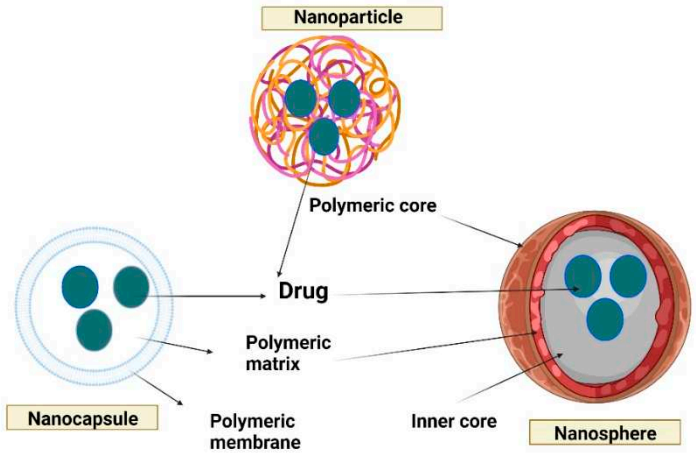

Figure 2. Schematic representation of the structure of nanocapsules and nanospheres (arrow stands for the presence of drug/bioactive within the nanoparticles).

5.2. Nanoprecipitation method

Nanoprecipitation is a rapid and reproducible technique that produces submicron particles with a well-defined size distribution in a single step [99]. The initial publication on this technique was authored by Fessi et al. [20]. Nanoprecipitation occurs when an organic solution containing a polymer not soluble in water is mixed with water (the non-solvent phase) during nanoprecipitation [100]. Combine, but the resultant mixture is a poor solvent for the chosen polymer, causing it to precipitate immediately through solvent diffusion, a technique known as solvent diffusion [13]. Nanocapsules are made using the same technique, except oil is included in the organic phase to form an internal oily core [9]. Nanoprecipitation has several advantages, including simplicity, speed, consistency, and the ability to scale up the process [1].

In addition, the nanoprecipitation technique eliminates the need for a stabiliser or high-energy production for charged polymers. A significant drawback of this method is the low loading efficiency for hydrophilic drugs due to the hydrophobic nature of the nanoparticle matrix [42]. The nanoparticle matrix's water-repellent properties can hinder the absorption of water-soluble drugs in the nanoprecipitation technique [100]. Nevertheless, several strategies have been proposed to enhance the incorporation of these substances [46].

5.3. Simple emulsion evaporation method

Vanderhoff et al. introduced a straightforward emulsification evaporation technique for producing polymeric nanoparticles.[45]. In this technique, pharmaceutical drugs and polymers are initially dissolved in a volatile organic solvent that is insoluble in water. Subsequently, nanoparticles are formed through the process, yielding a homogeneous dispersion of drug-polymer particles [101]. The emulsion solvent evaporation technique produces nanoparticles, wherein an organic polymer solution is emulsified with an aqueous phase containing a stabiliser [102]. The polymer precipitates and nanoparticles are formed by applying high-shear stress and stirring, resulting in a well-dispersed system [103]. Hydrophobic drugs have a high encapsulation rate but can result in polydisperse particles and are less effective than hydrophilic drugs [20]. Ruiz et al. investigated the impact of sonication parameters on the preparation of polymeric nanoparticles using the emulsion-solvent evaporation technique. The study optimised the conditions for obtaining polymeric nanoparticles with polylactic acid (PLA), achieving particle sizes ranging from 110 to 240 nm and PDI values between 0.09 and 0.32. Power was found to have the most significant influence on particle size and PDI, followed by sonication

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time and the number of sonication cycles—the optimised PLA nanoparticles indicated excellent size homogeneity and potential for developing targeted nano formulations [104].

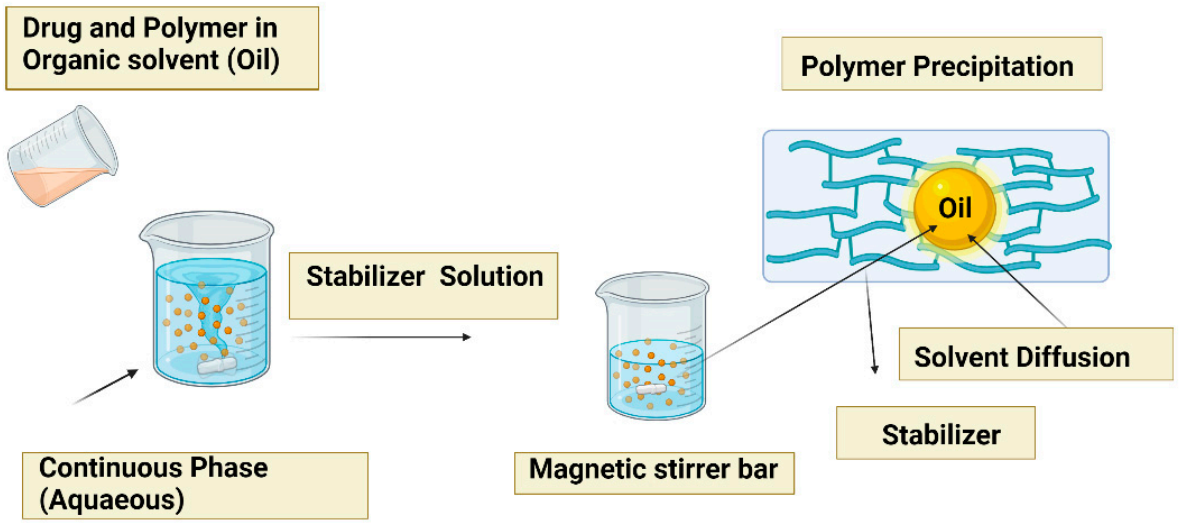

Figure 3. Preparation of nanocapsules by emulsion diffusion method.

5.4. Double emulsion evaporation method

The double emulsion evaporation method, also known as the water-in-oil-in-water (W/O/W) method, is a widely used encapsulation technique for the preparation of nanoparticles. It is beneficial for encapsulating hydrophilic (water-soluble) substances, such as drugs and proteins, within a hydrophobic nanoparticle matrix. [16]. Encapsulation in the double emulsification evaporation method involves homogenising an oily phase (O) that typically consists of a polymer solution dissolved in an organic solvent containing the required hydrophobic drug, with an aqueous phase (W1) containing a hydrophilic drug. In the second step, the first W1/O emulsion is emulsified in another aqueous phase (W2) containing a suitable stabiliser using high-shear homogenisation or low-power sonication to create a double emulsion (W1/O/W2). While this approach can encapsulate both hydrophilic and hydrophobic drugs, it has several drawbacks, including low colloidal stability of the resulting particles, high shear stirring, which can lead to emulsion fragmentation, foam formation, and polydisperse particles more significant than a micron in size [40]. Iqbal et al. demonstrated that by optimising process parameters, such as ultrasound exposure time, amplitude, outer aqueous phase volume, PCL content, and PVA concentration, they successfully prepared biodegradable PCL nanoparticles with reduced particle size and spherical morphology using the double emulsion solvent evaporation method combined with power ultrasound [105].

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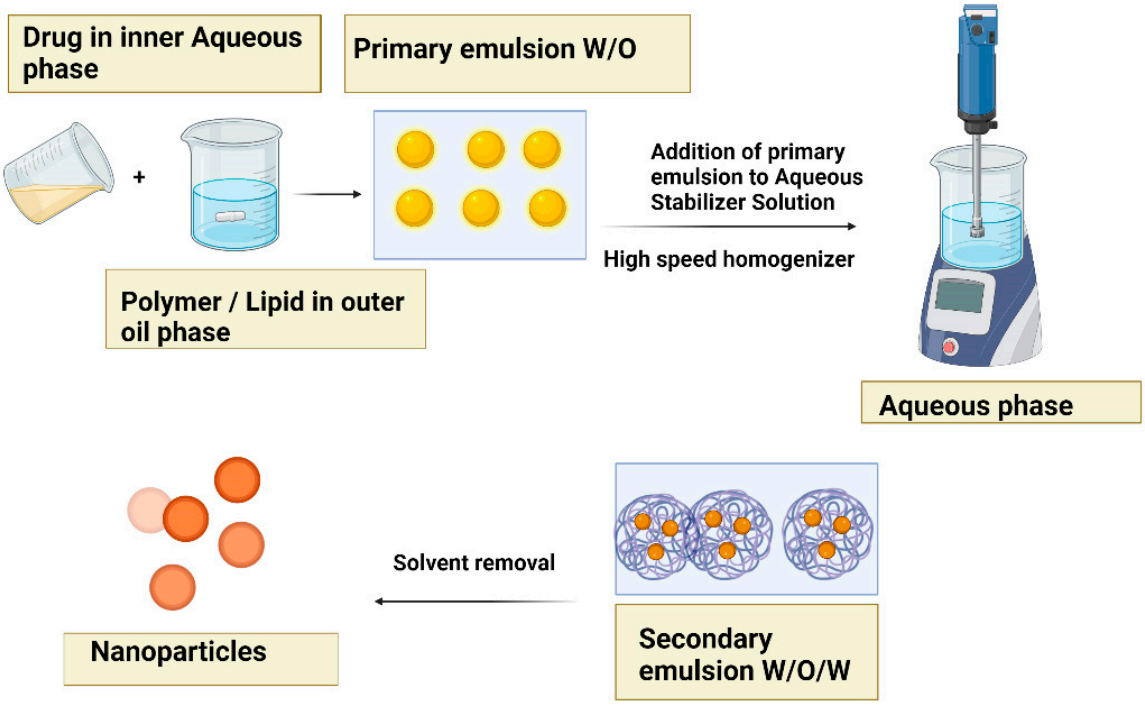

Figure 4. The schematic diagram for the double emulsion solvent evaporation method.

5.5. Ionic gelation

Ionic gelation is a widely employed technique for the formulation of polymeric nanoparticles or microparticles, characterised by crosslinking a water-soluble polymer utilising a compatible ionic crosslinking agent [20]. This method involves establishing ionic interactions between the polymer chains and the crosslinking agent, leading to forming a gel-like network structure [106]. Through careful control of the reaction conditions, such as the selection of appropriate polymers and crosslinkers, as well as their concentrations and reaction parameters, the resulting particles' size, shape, and stability can be tailored to meet specific requirements [107]. Giri et al., ionotropic gelation involve the formation of nanoparticles through the interaction between polyelectrolytes and counter ions, where chitosan polysaccharide is dissolved in an aqueous acidic solution to obtain the cation of chitosan. This cationic solution is subsequently added drop-wise to a polyanionic tripolyphosphate solution under continuous stirring, resulting in ionic gelation and precipitation of chitosan as spherical particles [108].

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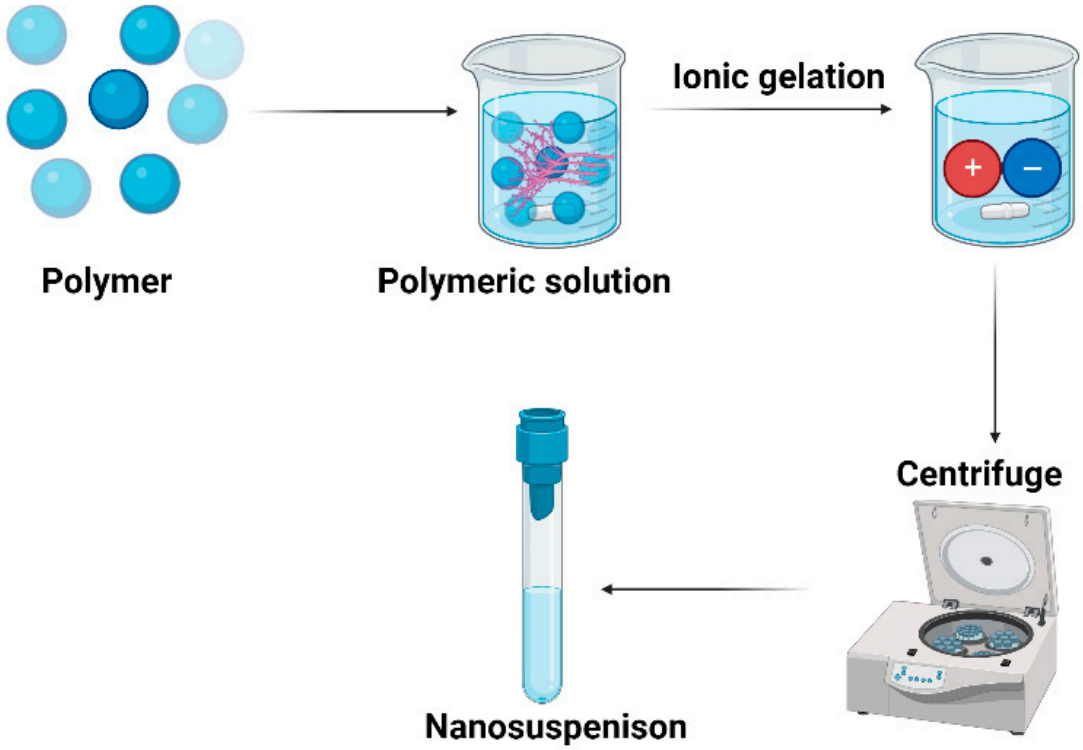

Figure 5. A schematic illustration of ionic gelation reaction.

5.6. Supercritical fluid method

The methods frequently require toxic solvents and surfactants that can pose risks to the environment and physiological systems [20]. As a result, current research have been focused on exploring safer techniques to produce carriers for various applications. One such approach that has piqued the interest of many researchers is the use of supercritical fluids, considered environmentally friendly solvents [39]. Revercheon et al. emphasised the application of supercritical fluid-based techniques for synthesising a wide range of nanostructures, including nanofibers, nanotubes, nanowires, nanoparticles, and other nano-architectures [109]. Byrappa et al. investigated the versatile capabilities of supercritical fluids (SCFs) in the fabrication of advanced nanomaterials, encompassing carbon nanotubes, fullerenes, magnetic particles, quantum dots, phosphors, nanocomposites (such as peptide/hydroxyapatite), and gold nanoshells. These nanomaterials hold significant potential for various biomedical applications, including drug delivery, imaging, sensing, and cancer theranostics [110]. Supercritical fluid technology emerges as a promising approach in the formulation of drug carriers, offering notable advantages such as utilising environmentally friendly solvents [111]. Supercritical CO_2 is a commonly used fluid used in the supercritical antisolvent process to instantaneously precipitate particles from a drug and polymer dissolved in a liquid solvent [112]. However, this technique has some limitations, including the need for specialised equipment and higher costs for routine use [28].

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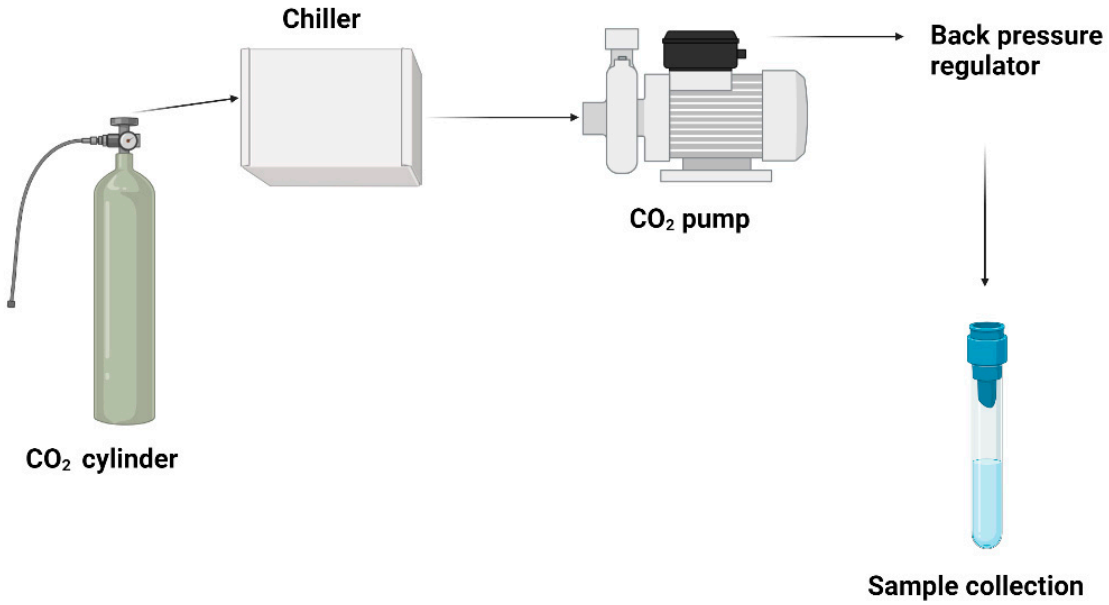

Figure 6. Flow diagram of supercritical fluid extraction system.

6. Electrospinning for encapsulated active ingredients

Electrospinning produces ultrafine fibres characterised by a high surface area to volume ratio, making them well-suited as encapsulation materials [113]. These fibres can serve as a delivery system for controlled release applications or as a scaffold for tissue engineering purposes by incorporating active ingredients into the polymer solution prior to electrospinning [114]. Conversely, electrospinning involves the creation of nanofibers by subjecting polymer solutions or melts to an electric charge [115]. Both methodologies can be employed for delivering active ingredients to the skin and may be combined to enhance efficacy and achieve targeted delivery [116]. **Figure 7** illustrates the encapsulation technique, wherein active ingredients are encapsulated within a protective outer shell, followed by the electrospinning of the prepared solution.

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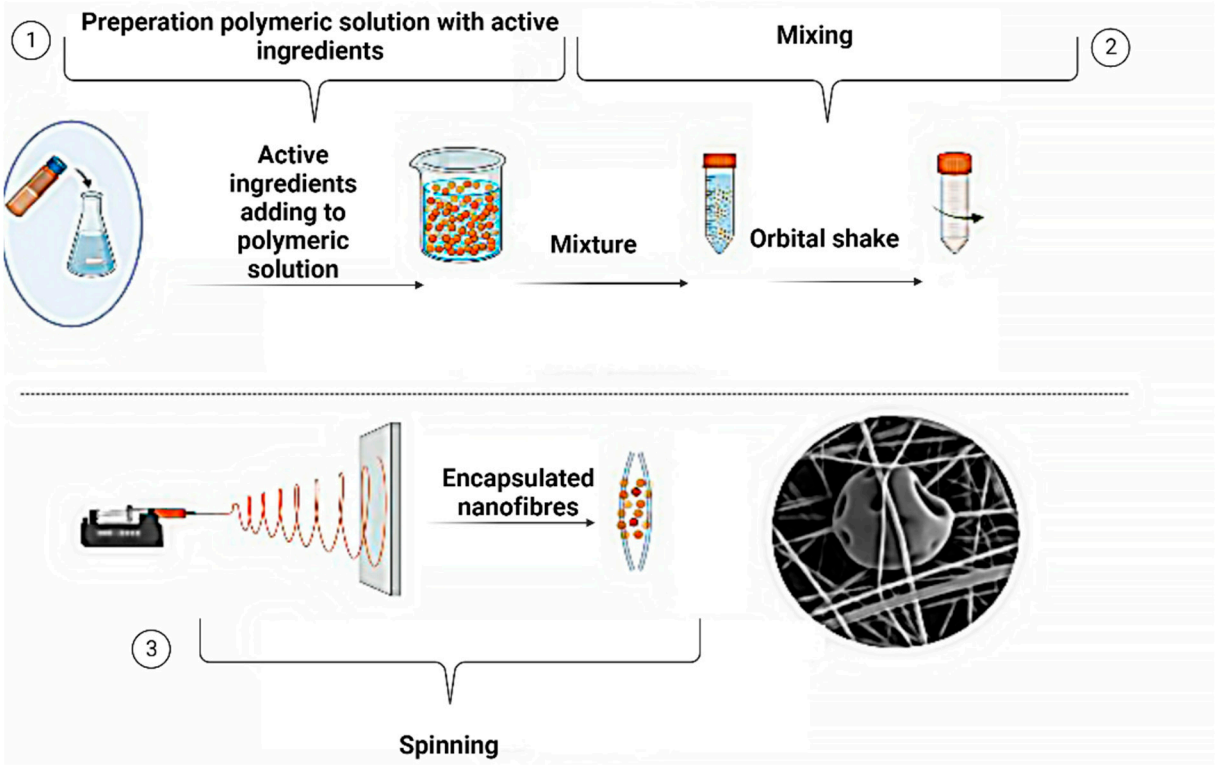

Figure 7. Encapsulated nanofibers with active ingredients.

6.1. Electrospinning methods

Electrospinning is a scientifically established process that utilises an electric field to induce the transformation of a charged polymer solution or melt into finely spun fibres [117]. The process commences with preparing a polymer solution, which is subsequently loaded into a syringe or spinneret apparatus [118]. The polymer solution is carefully extruded through a needle or spinneret orifice, subsequently experiencing the influence of a high-voltage electric field [117]. This causes the solution to become charged and form a Taylor cone at the tip of the needle [113]. As the electric field strength increases, the surface tension of the solution is overcome, and a charged jet is ejected from the cone [119]. The jet undergoes a whipping motion as it travels towards a grounded collector, and as it dries, it solidifies into a continuous nanofiber [120]. The diameter of the fibres can be controlled by adjusting the concentration of the polymer solution [121], the flow rate [122], and the strength of the electric field [118]. The electrospinning process is versatile and can be used with various polymers, including synthetic and natural materials. It has numerous applications in tissue engineering [123], drug delivery [124], filtration [125], energy storage [126], and sensors [3]. Several electrospinning approaches that can be used to encapsulate active ingredients and nanofiber productions are given in **Figure 8**.

Nanofiber encapsulation is an attractive approach for incorporating drugs into polymer carriers; it allows for precise control over the size and morphology of the resulting fibres. **Figure 9** shows various cross-sections of electrospun fibres form that can be used to encapsulate active ingredients.

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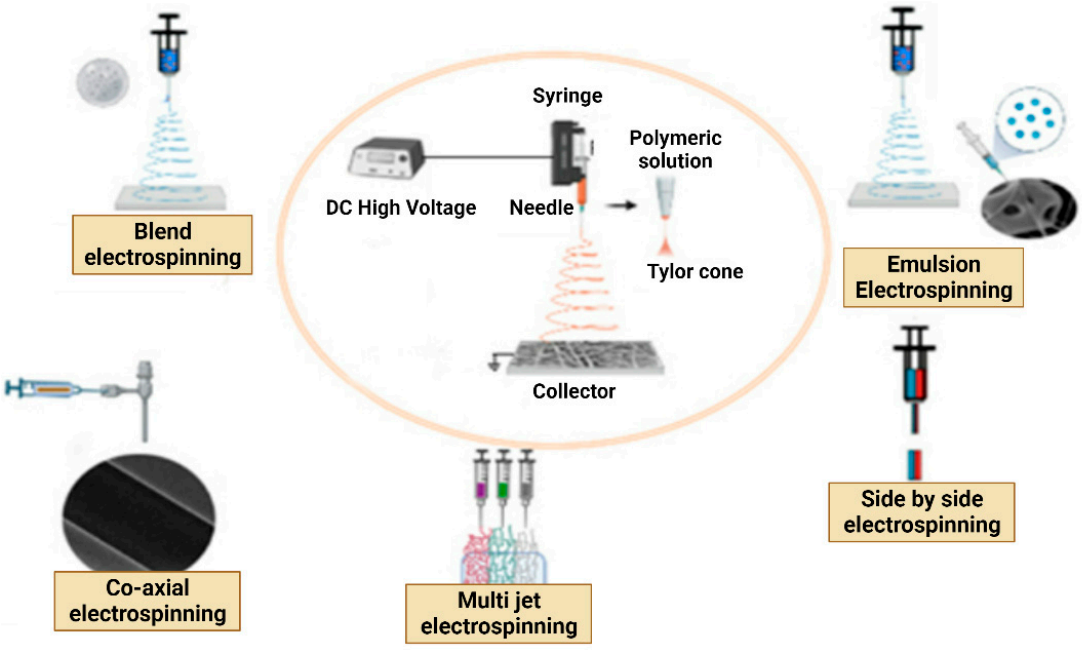

Figure 8. Schematic representation of various methods for incorporating drugs into a polymer carrier using electrospinning.

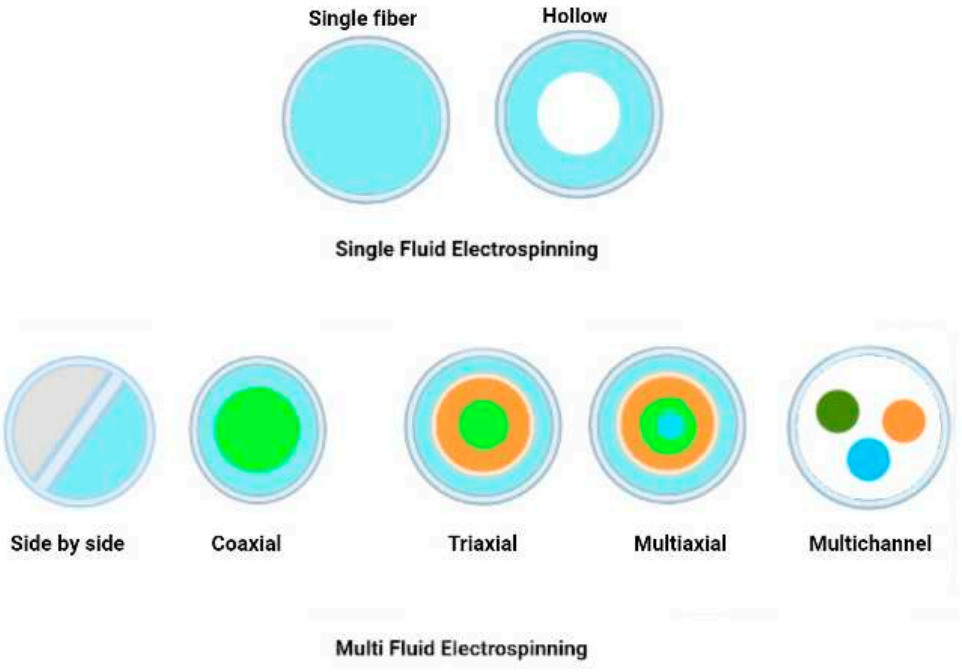

Figure 9. Cross-sections of electrospun fibres form for active ingredients encapsulation.

6.1.1. Single Fluid Electrospinning

Blend Electrospinning

This approach involves dissolving the drug and the polymer carrier in a suitable solvent to create a homogenous spinning solution. Electrospinning this solution can achieve a wide range of drug release profiles, ranging from very rapid (within seconds) to sustained release over weeks or even months. The

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choice of solvent, polymer and processing conditions can be optimised to achieve the desired release profile for a particular drug and delivery application [47]. The main weakness of this approach is the commonly observed burst release phenomenon [30].

Emulsion Electrospinning

Emulsion electrospinning is a scientifically established technique to fabricate core-shell nanofibers, enabling the encapsulation of growth factors, proteins, and drugs within the core region to enhance drug stability and improve bioavailability [127]. Forming a stable emulsion necessitates three crucial components: an oil phase, a water phase, and surfactants/emulsifiers, all of which influence the drug-release properties of the resulting fibres based on their respective compositions [128]. Typically, a hydrophobic polymer is dispersed in an organic solvent (oil phase), while hydrophilic compounds are dispersed in water, ensuring the desired characteristics of the emulsion for successful electrospinning. [20]. Tao et al. successfully manufactured polycaprolactone/carboxymethyl chitosan/sodium alginate fibres using emulsion electrospinning with minimal organic solvents. The resulting fibres positively impacted osteoblast viability and osteogenesis [41].

6.1.2. Multi-Fluid Electrospinning

Multi-Jet Electrospinning

Multi-jet electrospinning can be implemented through two distinct methods: needleless and needle-based configurations [129]. This technique offers substantial advantages for large-scale nanofiber fabrication because it considerably enhances throughput. By enabling the simultaneous electrospinning of multiple jets, the production rate can be significantly increased, thereby facilitating the efficient manufacturing of nanofibers on a larger scale [130]. Moreover, it enables the preparation of multi-component fibre mats, wherein diverse populations of fibres fabricated from distinct materials are seamlessly integrated into a unified scaffold. This capability facilitates the development of complex and versatile structures with tailored properties, opening up possibilities for a wide range of applications in tissue engineering, filtration systems, and other fields [131]. This feature proves valuable in cases where the inclusion of multiple polymers in a formulation is necessary, but they cannot be dissolved within the same solution due to their incompatible solubilities. By employing the multi-component fibre mats produced through this technique, the simultaneous incorporation of diverse polymers becomes achievable, offering enhanced flexibility in designing materials with desired characteristics and functionalities [132]. The resulting fibre mat can deliver multiple drugs at varying rates, and the different fibre populations can also influence mechanical and cell adhesion properties [133]. However, there are some drawbacks to multi-jet spinning in the needle modality. The electric fields around the different needles can interact with each other, which can cause spinning to be erratic [134]. Determining the optimal needle arrangement poses a significant challenge in the electrospinning process. However, this obstacle can be overcome by employing needleless or auxiliary electrodes. These approaches contribute to the enhanced stability of the spinning process, thereby improving the overall quality and consistency of the resulting fibre mats [78].

Side-by-Side Electrospinning

The side-by-side electrospinning technique involves extruding multiple spinning solutions through adjacent spinnerets. This method offers a notable advantage in the form of a side-by-side Janus morphology, enabling both compartments to establish physical contact with the biological microenvironment. The efficacy of this approach relies on the precise design of the spinneret and meticulous optimisation of the electrospinning parameters [135,136]. Zheng et al., in 2021, tamoxifen, a chemotherapeutic drug, was incorporated into polymer matrices of PVP and Ethyl cellulose (EC). The research findings highlighted the significance of shape, structure, and composition in the design of functional nanomaterials. By precisely manipulating these factors, it holds promise to develop novel

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materials with enhanced drug release profiles and other desirable properties for biomedical applications [137].

6.1.3. Coaxial/Multiaxial Electrospinning

Coaxial or multiaxial electrospinning enables the fabrication of nanofibers with a core-shell or multi-layered structure. This technique involves the simultaneous electrospinning of two or more spinning solutions through concentric or parallel spinnerets [138]. The outer layer of the fiber is formed by the polymer solution dispensed from the outer spinneret, while the inner layer (core) is formed by the solution dispensed from the inner spinneret [139]. Core-shell nanofibers offer various drug and biomolecule incorporation, enabling precise modulation of drug release rates and durations for advanced drug delivery [138]. Their structure enhances mechanical properties and biocompatibility, making them suitable for biomedical applications such as drug delivery, tissue engineering, and wound healing [140]. Coaxial electrospinning allows for precise control of small drug molecule release rates from a hydrophobic matrix and enables the encapsulation of liquids within nanofiber cores [141]. Baykara and Taylan fabricated core-shell fibres using a polyvinyl alcohol (PVA) shell and a core containing Nigella sativa seed oil, renowned for its antimicrobial properties. This core-shell structure effectively regulated the release of the oil, preventing sudden bursts of release [93]. This approach can be extended to various drugs or biomolecules that necessitate controlled release rates or encounter compatibility issues with the matrix material, offering a versatile solution for tailored drug delivery systems and overcoming formulation limitations [142]. Triaxial spinning, involving three fluids, allows for the production of multilayer nanofibers [143]. Liu et al. demonstrated the application of triaxial electrospinning to encapsulate ferulic acid within cellulose acetate nanofibers, resulting in a multilayer structure. The in vitro drug release from these fibres exhibited nearly zero-order kinetics, indicating a controlled and steady release rate. This technique can be utilised to encapsulate various drugs with varying properties, and the number of layers can be adjusted to achieve the desired release profile. Triaxial electrospinning holds promise for developing drug delivery systems with improved efficacy and reduced toxicity [144]. Quad-axial electrospinning fabricates nanofibers using four simultaneous fluids, enabling precise control over composition and functionality [145]. Quad-axial electrospinning enables the fabrication of intricate multi-layered structures with improved properties and customised release profiles, revolutionising drug delivery, tissue engineering, and biomedical applications [146]. Zhang et al. [147] utilised this approach to encapsulate the antimicrobial moxifloxacin in polycaprolactone and gelatine nanofibers with a quad-axial structure. Through the incorporation of moxifloxacin into the nanofibers, quad-axial electrospinning facilitated the achievement of controlled release kinetics over an extended duration, highlighting the adaptability of this technique in the design of drug delivery strategies. With its precise control over nanofiber composition and structure, quad-axial electrospinning presents a promising avenue for developing advanced drug delivery systems with tailored release profiles [147].

7. Applications of electrospun nanofiber-encapsulated ingredients in the cosmetic industry

Electrospinning has opened up new avenues for investigating the efficacy of nanofibers in enhancing the properties of matrix materials utilised in cosmetic applications [148]. The integration of composites offers a distinct advantage by combining the strength of reinforcement with the toughness of the matrix, resulting in exceptional properties that surpass those of conventional single materials [98]. The emergence of electrospinning techniques employing biopolymers has led to innovative nano-biocomposites, distinguished by their multifaceted nature, superior functionality, and commendable environmental sustainability, making them highly promising for future applications [149]. **Table 2** summarises active ingredients electrospun into nanofibrous scaffolds for a specific skincare product, outlining their benefits for the skin. This information can aid in selecting skincare products tailored to address specific skin concerns.

Table 2. The sum of active ingredients and their benefits to the skin.

Electrospun polymers	Ingredients	Benefits for skin	Personal Care Category	References
Silk fibroin	Lanolin	Occlusive, emollient	Lipophilic	[150–152]
Chitosan, PVA	Glycerine	Anti-inflammatory, barrier recovery	Humectant, moisturiser	[153–155]
Chitosan, Gelatin, and PVA	Hyaluronic Acid	Humectant, anti-aging	Humectant, moisturiser	[42,156]
Silk fibroin	Vitamin B5 (Pantothenic Acid/Dexpanthenol)	Hydration, barrier protection, reduction of trans-epidermal water loss (TEWL), fibroblast stimulation, and re-epithelialisation.	Humectant, emollient, antiinflammatory	[157–160]
PVA, Gelatin	Urea	Anti-inflammatory, hydrating, keratolytic	Humectant, emollient	[161,162]
Chitosan,Gelatin, and PVA	Aloesin	Tyrosinase inhibition, antioxidant, anti-inflammatory	Depigmenting, sun protective (UVB)	[163,164]
PVA	Hydroquinone	Tyrosinase inhibition	Depigmenting, brightening, lightening	[165,166]
Chitosan	Emblica Extract	Antioxidant, anti-inflammatory, antipyretic, antitumor, chemo-preventive, hepatoprotective, analgesic, antibacterial	Depigmenting, anti-ageing, sunscreen	[167–170]
PVA, PCL, Chitosan	Mulberry Extract	Antityrosinase, antihyperglycemic, antitumorigenic, anti-inflammatory, antipyretic, antioxidant, anti-atherogenic, antimicrobial chemo-preventive, neuro-protective	Depigmenting	[171–173]
PVA	Vitamin C (Ascorbic Acid)	Anti-inflammatory, antioxidant, photo-protectant, depigmenting	Depigmenting	[174–176]
PVA	Niacinamide	PAR-2 inhibition, anti-inflammatory, antioxidant, anti-ageing, photoprotective	Depigmenting, exfoliant	[171,177,178]
PVA, Chitosan	Green Tea	Antioxidant, anti-ageing, antiacne, antiangiogenic, anticarcinogenic, anticarcinogenic, anti-inflammatory, antimicrobial, chemo-preventive, immunomodulatory,2photoprotective	Anti-ageing, moisturising, antiacne, anogenital wart treatment	[43,179,180]
PVA.Chitosan	Rosa Damascena	Antioxidant, antibacterial, antimicrobial, anti-inflammatory, antiseptic, and anxiolytic	Antioxidant	[181,182]

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PVA, PLGA	Pycnogenol	Antioxidant, anti-inflammatory, anticarcinogenic, photoprotective, antimicrobial	Anti-inflammatory, hydrating	[183–185]
PVA, PLGA	Resveratrol	Antioxidant, antibacterial, anticancer, antiinflammatory, antitumorigenic, anti-tyrosinase, cardioprotective	Anti-ageing, anticancer	[186]
PVA, PLGA.Chitosan	Flaxseed Oil	Antioxidant, anti-ageing, anti-inflammatory, and antiapoptotic	Antioxidant, anti-ageing	[187–189]
PVA, PLGA	Caffeic Acid	Antioxidant, anticarcinogenic, anti-inflammatory, antimicrobial, immunostimulatory, neuroprotective, photoprotective	Antioxidant, anti-ageing	[190–193]
PLGA.PEO	Ferulic Acid	Antioxidant, anticancer, anti-inflammatory, antimicrobial, cardioprotective, neuroprotective, hepatoprotective, photoprotective, skin lightening	Antioxidant, anti-ageing, photoprotection	[192,194,195]
Cellulose acetate	Tocopherol (Vitamin E)	Antioxidant, photoprotection, wound healing	Antioxidant, moisturising, anti-ageing	[196–198]
Chitosan, PVA	Ginger	Antioxidant, anticarcinogenic, anti-inflammatory, antinausea, wound healing	Antioxidant, analgesic, photo-protectant	[199–201]
Hyaluronic acid, PEO	Honey/Propolis/Royal Jelly	Analgesic, antioxidant, antiinflammatory, antimicrobial, antitumor, antiseptic, antipyretic, antiulcer, hepatoprotective, immunomodulatory	Antioxidant, anti-ageing, photoprotection, antiseptic, wound healing	[202–205]
Chitosan, Polycaprolactone,PVA	Melatonin	Antioxidant, anticarcinogenic, anti-ageing, anti-inflammatory, anxiolytic, immunomodulatory	Antioxidant, anti-ageing	[206–208]
Pullulan	Aloe Vera	Anti-inflammatory, antioxidant, antimicrobial, immunomodulatory, laxative, wound healing	Moisturising, soothing, cooling, burning and wound healing	[30,209,210]
Polyurethane, Gelatin	Lavandula	Anti-inflammatory, antimicrobial, antiseptic, anti-colic, antispasmodic, antidepressant, sedative	Soothing, sedating, anti-inflammatory, analgesic	[211–214]
PLA	Salicylic Acid	Anti-inflammatory, pore cleansing	Cleansing, antiacne, pore minimising, exfoliating	[215,216,216]

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In the cosmetic industry, enzymes are commonly used for their ability to improve skin texture, reduce wrinkles, and enhance skin hydration [217]; enzyme immobilisation is a well-established technique used in various fields due to its ability to improve the stability, activity, and reusability of enzymes [218]. However, using free enzymes in cosmetic formulations can be challenging due to their instability and susceptibility to degradation [219].

Neutrogena and Aveeno's "active soy" formulations incorporate soy that has undergone laboratory modifications to eliminate its estrogenic components. Although these products utilise natural ingredients, they do not qualify for NPA certification due to their altered state, which aims to enhance their effectiveness [89].

8. Conclusions, Challenges, and Future Perspectives

The field of cosmetic applications has harnessed the potential of encapsulation and electrospinning techniques to facilitate the delivery of active ingredients. These methodologies offer notable benefits such as enhanced stability, safeguarding active ingredients, precise delivery targeting, and monitoring of release rates. Encapsulation and electrospinning have proven effective in extracting enzymes, vitamins, peptides, and plant extracts, employing natural polymers that resonate with consumers seeking eco-friendly and sustainable alternatives.

Nevertheless, challenges persist in encapsulation and electrospinning for cosmetic applications. Inconsistencies arise during the preparation and characterisation of encapsulated and electrospun products, resulting in variations in quality and efficiency. Developing cost-effective techniques becomes imperative to leverage encapsulation and electrospinning for large-scale production of high-quality cosmetic products. Incorporating natural and biodegradable polymers in these processes further enhances the sustainability of cosmetic products.

Prospectively, the adoption of encapsulation and electrospinning is poised for significant expansion, propelled by technological breakthroughs and escalating consumer demand for ecologically responsible and sustainable cosmetics. Nevertheless, assuring the safety and efficacy of these methodologies in cosmetic applications mandates incessant research endeavours and meticulous standardisation initiatives. Subsequent advancements will concentrate on refining encapsulation and electrospinning protocols, instituting stringent quality control measures, and deepening comprehension of their influence on product functionality and consumer contentment.

Abbreviations

APIs:	Active pharmaceutical ingredients
BCC:	Basal Cell Carcinoma
BSTI	Baumann Skin Type Index
BSTS	Baumann Skin Type System
CIR:	Cosmetic Ingredient Review
CMCS:	carboxymethyl chitosan
CO_2:	Carbon dioxide
DRNT	Dry, Resistant, Non-Pigmented, Tight skin
DRNW:	Dry-Resistant Non-Pigmented Wrinkled
DRPT	Dry, Resistant, Pigmented, Tight skin
DRPW:	Dry-Resistant Pigmented Wrinkled
DSNT	Dry, Sensitive, Non-Pigmented, Tight skin
DSNW	Dry, Sensitive, Non-Pigmented, Wrinkle-Prone skin
DSPT	Dry, Sensitive, Pigmented, Wrinkle-Prone/Tight skin
DSPW	Dry, Sensitive, Pigmented, Wrinkle-Prone skin
EC:	ethyl cellulose
FDA:	US Food and Drug Administration
HA:	Hyaluronic acid
INCI:	International Nomenclature of Cosmetic Ingredients
nm:	Nanometre
NMF:	natural moisturising factor
NPA:	Natural Products Association

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O/W/O:	Oil-in-water-in-oil
O/W:	Oil-in-water
ORNW:	Oily, Resistant, Non-Pigmented, Wrinkle-Prone skin
ORPT:	Oily, Resistant, Pigmented, Tight skin
ORPW:	Oily, Resistant, Pigmented, Wrinkle-Prone skin
OSNT:	Oily, Sensitive, Non-Pigmented, Tight skin
OSNW:	Oily, Sensitive, Non-Pigmented, Wrinkle-Prone skin
OSPT:	Oily, Sensitive, Pigmented, Tight skin
OSPW:	Oily, Sensitive, Pigmented, Wrinkle-Prone skin
OTC:	Over-the-counter
PAR-2:	Protease-activated receptor-2
PCL:	polycaprolactone
PEG:	Polyethylene Glycol
pH:	potential of hydrogen
PLA:	Poly (lactic acid)
PLA:	Polylactic acid
PVA:	Polyvinyl alcohol
PVP:	Polyvinylpyrrolidone
SA:	Sodium alginate
SC:	Stratum Corneum
SCC:	Squamous Cell Carcinoma
SLES:	Sodium lauryl ether sulphate
SLS:	Sodium lauryl sulphate
SPF:	Sun Protection Factor
TEWL:	Trans-epidermal Water Loss
UV:	Ultraviolet
UVA:	Ultraviolet A
UVB:	Ultraviolet B
VOC:	Volatile Organic Compound
W/O/W:	Water-in-oil-in-water
W/O:	Water-in-oil

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