Development of a Bioactive Herbal Nanoparticle Spray for Sweat Control Using Chitosan Nanoparticles and Plant Extracts

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Abstract. This work designed a bioactive herbal nanoparticle spray for sweat control using chitosan nanoparticles (CS-NPs) loaded with herbal extracts of green tea, tulsi, mint, and lemon peel. The CS-NPs were synthesized through ionic gelation, showed the best properties (120 ± 15 nm size, +35.2 mV zeta potential), and improved stability. The spray formulation is skin-friendly with a pH of 5.03, besides being highly stable and able to exhibit antibacterial activities against Staphylococcus aureus and Corynebacterium. Human trials have shown that sweat production decreases by 30%, nearly as effective as most commercial antiperspirants, but much more compatible with skin. User feedback has indicated highly satisfactory uptake, with almost 85% mentioning reduced sweating and no irritation. Through interaction against CS-NPs with diffuse herbal extracts, there was enhanced bioavailability and efficacy relative to a natural, eco-friendly alternative for hyperhidrosis management. Further studies are suggested for long-term safety and scaling up for market translation.

Keywords: Sweat control, chitosan nanoparticles, herbal extracts, antimicrobial activity, sustainable cosmetics, green tea, tulsi, mint, lemon peel.

1 Introduction

The process of sweating is a crucial physiologic process controlled by the autonomic nervous system, mainly for thermoregulation through evaporative cooling [1]. Hyperhidrosis, that is, excessive sweating, can affect about 5% of the global population, causing severe psychological strain, social stigma, and occupational hindrance [2][3]. Hyperhidrosis can be clinically divided into primary (focal) and secondary (generalized), the former being more common, with axillary hyperhidrosis being the most common type [4]. The current treatments range from aluminum-based antiperspirants to invasive procedures such as injection with botulinum toxin and sympathectomy, all of which carry consequences, namely irritating the skin, exorbitant costs, or transient nature [5]. Traditional antiperspirants mainly rely on aluminum salts (aluminum chloride or zirconium), which form temporary plugs in sweat ducts, mechanically [6]. While aluminum salts are widely used, there has been an increasing public disinclination owing to possible links to breast cancer and neurodegenerative disorders [7][5], alongside environmental concerns regarding the bioaccumulation in aquatic ecosystems [8]. As if these worries were not enough, the synthetic antimicrobial additives have either been banned in several countries or restricted due to their endocrine-disrupting effects and contribution to antibiotic resistance [9]. Because of their antimicrobial, anti-inflammatory, and astringent potentials, plant-based compounds provide a prospective solution [10]. To illustrate, green tea (Camellia sinensis) is high in epigallocatechin gallate (EGCG), a polyphenol that inhibits the activity of eccrine glands by modulating adrenergic receptors and inhibits the growth of odor-producing bacteria such as Staphylococcus epidermidis [11][12]. Similarly, tulsi (Ocimum sanctum) and mint (Mentha piperita) exhibit broad-spectrum antimicrobial effects due to eugenol, ursolic acid, and menthol that disrupt the membrane of the bacteria and provide a cooling effect [13] [14]. Using citric acid and D-limonene, lemon peel (Citrus limon) further adds to the effects of astringency, helping to tighten pores and neutralize volatile organic compounds that are responsible for malodor [15]. However, the commercial efficacy of herbal extracts is very often limited by poor skin penetration and rapid degradation, thereby demanding sophisticated systems for delivery to improve bioavailability [16] [17]. Nanotechnology has emerged as a modern tool in dermatological formulations, overcoming the limitations of these extracts by enhancing stability, controlling release, and permitting very narrow targeted delivery [18]. Of the various nanomaterials, chitosan nanoparticles (CS-NPs) are one of the promising materials due to their biocompatibility, biodegradability, and mucoadhesive character, being derived from the natural polysaccharide chitin [19]. The cationic surface charge of CS-NPs can electrostatically interact with negatively charged bacterial cell walls, thus disrupting their membranes and inhibiting biofilm formation [20]. CS-NPs can also form a thin and breathable film on the skin, which reduces transepidermal water loss while avoiding blockage of the pores, thus representing a major advantage over traditional antiperspirants [21][22]. Other nanoparticles have also been applied in antibacterial applications; however, their potential cytotoxicity and environmental persistence raise safety issues [8]. On the other hand, CS-NPs have shown a synergistic effect with the herbal bioactives, such as the two-fold antibacterial activity of green tea-loaded CS-NPs compared to the free extract [23]. This synergistic effect could be further augmented by the ability of CS-NPs to prolong the release of volatile compounds, such as menthol and citric acid, ensuring an effective action [24].

Despite such advances, research tilting toward single abode has gravitated towards either herbal actives or nanoparticles, and few have examined the potential of both approaches in an integrated sprayable formulation [25][26]. This research aims to fill in this space with the development of a bioactive herbal nanoparticle spray that incorporates Extracts of green tea, tulsi, and mint for sweat suppression and antimicrobial efficacy, Extract of lemon peel as a natural astringent and deodorizer, and Chitosan nanoparticles to enhance bioavailability and film formation.

The hypothesis stated that with the proposed combination, the highest effect on sweat reduction and antibacterial activity would be seen in comparison with individual components or any commercialized products. The specific objectives include (1) to synthesize and characterize CS-NPs, (2) to develop the spray formulation, (3) to assess antimicrobial activity against sweat-associated bacteria (e.g., Corynebacterium), and (4) to evaluate the reduction of sweat in human studies. The natural approach combined with nanoscale delivery would look to provide a safe and ecological alternative to conventional antiperspirants, congruent with the current global trends in sustainable cosmetics [27].

2 Literature Survey

The burgeoning demand for natural and sustainable alternatives to conventional antiperspirants has propelled research into plant-based bioactive agents and nanotechnology-enabled delivery systems. Several studies have raised concerns about aluminum-based antiperspirants, linking them as potential causative factors for breast cancer [5] and Alzheimer's disease [7], along with evidence of skin irritation [10]. Therefore, researchers have been investigating the potential of herbal extracts like green tea (Camellia sinensis) that contain epigallocatechin gallate (EGCG), a polyphenol that has been shown to inhibit sweat gland activity via adrenergic receptor modulation [11]. Likewise, tulsi (Ocimum sanctum) and mint (Mentha piperita) have strong antimicrobial action against odor-generating bacteria such as Staphylococcus epidermidis and Corynebacterium [13] [14]. Lemon peel (Citrus limon), being rich in citric acid and D-limonene, was found to act as a natural astringent and deodorizing agent by tightening the pores and neutralizing the volatile organic compounds [15]. Notwithstanding the above advantages, standalone efficacy is limited by poor permeation through the skin and rapid degradation of herbal extracts [16]. To overcome such barriers, nanomaterials are used to increase the stability, bioavailability, and controlled release of bioactive agents [18]. Among various nanoparticles, chitosan nanoparticles (CS-NPs) have been derived gradually due to their biocompatibility, biodegradability, and inherent antimicrobial activity [19]. The cationic nature of CS-NPs allows for electrostatic interaction to take place with the negatively charged bacterial cell membrane, thereby disrupting the microbes [20]. Meanwhile, the CS-NPs may form thin breathable films on the skin; this prevents water loss through the transepidermal pathway without occluding the pores [21]. In contrast, other nanoparticles, such as silver nanoparticles (AgNPs), were also studied for antibacterial activity, but their application has been limited owing to concerns around cytotoxicity and environmental persistence [8]. Widespread use of CS-NPs is safe and efficacious, especially when working in synergy with herbal extracts. For example, [23] reported that chitosan nanoparticles loaded with green tea extract exhibited twice the antimicrobial activity as that of free extracts, a clear example of the synergism possible with such formulations.

Recent developments in the field of nanoherbal formulations reiterate the advantages of uniting plant bioactives with nanocarriers. [24] demonstrated that CS-NPs could drastically improve the sustained release of volatile compounds such as menthol and citric acid over a period of time for prolonged sweat and odor control. Similarly, [27] described the application of nanotechnology to foster dermatological applications of herbal extracts, predominantly to deal with hyperhidrosis. Yet most research interests are either herbal actives or nanoparticles, with few focusing on combined sprayable formulations [25] [26]. Such limited interest spotlights the necessity of a comprehensive approach exploiting the synergism between herbal bioactives and CS-NPs in a user-friendly formulation.

In light of the above-mentioned, this study aims to formulate a bioactive herbal nanoparticle spray incorporating Green tea, tulsi, and mint extracts for sweat suppression and antimicrobial action. Lemon peel extract is a natural astringent and deodorizer. Chitosan nanoparticles to enhance bioavailability and film formation.

3 Materials & Methodology

To develop the bioactive nanoparticle spray, we followed several steps, including collecting raw materials (lemon peel, tulsi leaf, and mint leaf), drying, grinding, extraction, chitosan nanoparticle preparation, mixing, and finally testing and characterization.

Figure 1 Sequential process of bioactive spray formulation

3.1 Preparation of Conventional Herbal Extracts

3.1.1 Drying

All the raw materials (mint, lemon peels, and tulsi) were naturally dried for two days.

Figure 2 Naturally drying process of raw materials

3.1.2 Green Tea Extract

Fresh green tea leaves were shade-dried for two days and ground into a fine powder using a mechanical grinder. For extraction, 5 g of the powdered green tea was weighed accurately and mixed with 50 mL of distilled water. The mixture was heated to 80° C for one hour with continuous stirring, allowing the extraction of bioactive substances. After heating, the solution was filtered through Whatman No. 1 filter paper to remove particulate matter. The filtrate was collected and refrigerated at 4 °C for subsequent experimental use.

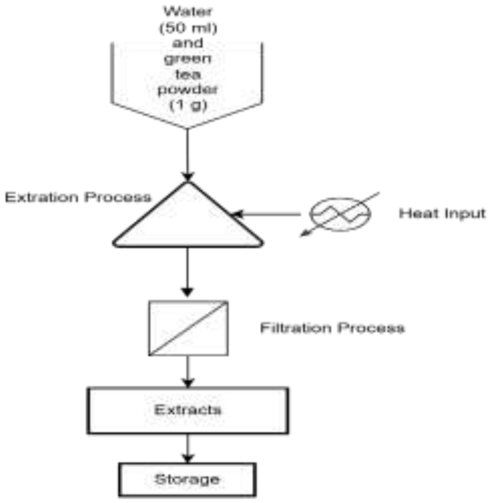

Figure 3 Flowchart for green tea extraction

3.1.3 Tulsi and Mint Extract

Firstly, fresh tulsi and mint leaves were dried naturally, followed by grinding into fine powder, indicating the just separation process before their extraction procedure. The mixture, 1 g each of tulsi and mint powder, was taken for the extraction, and 30 ml of distilled water in a 1:15 ratio. After mixing, the whole was heated at 80°C, continuously stirring for one hour. After the heating, the solution was filtered, and the extract was stored at 4 °C for further use.

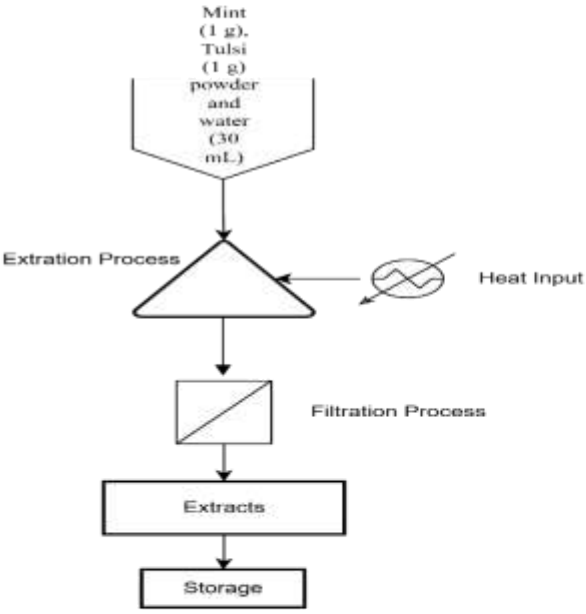

Figure 4 Flowchart for mint and tulsi extraction

3.1.4 Lemon Peel Extract

The lemon peel extraction process is the same as the mint and tulsi extraction processes. In the process of extraction, 1 g of powdered lemon peel was dissolved in 20 mL of distilled water and heated at 80°C for 1 hour. After heating, the hot mixture was filtered, and the obtained extract was kept at 4°C for future use.

3.2 Synthesis of Chitosan Nanoparticles (CS-NPs)

Chitosan (0.1 g) was dissolved in 100 mL of 1% acetic acid and stirred overnight to ensure complete solubility, followed by pH adjustment to 5.0. Separately, sodium tripolyphosphate (TPP, 0.1% w/v) was dissolved in distilled water to obtain a clear solution. The chitosan solution was then added dropwise (1 mL/min) to the TPP solution under magnetic stirring at 1000 rpm to initiate ionic gelation, indicated by the formation of a milky suspension. To reduce particle size and enhance uniformity, the mixture was sonicated at 20 kHz for 5 minutes at room temperature. Nanoparticles were collected by centrifugation at 10,000 rpm for 20 minutes, washed with distilled water, and freeze-dried for storage and further analysis.

3.3 End Formulation Steps:

Initially, the individual herbs were combined with all the herbal extracts for the preparation of the formulation, i.e., green tea extract (5 mL), tulsi-mint extract (3 mL), and lemon peel extract (5 mL) in a clean beaker. A 10 mL suspension of chitosan nanoparticles (1%) was then added slowly and under continuous stirring until a uniformly distributed suspension was obtained. Afterward, glycerin (2 mL) was added to the formula as a humectant for moisture retention. Following this, 10 mL of 70% ethanol was added to serve as a preservative and enhancer of penetration. Finally, the distilled water was used to make the final volume up to 100 mL. The resulting solution was passed through a syringe filter (0.22 µm) to achieve sterility. Consequently, it was transferred to 50 mL amber-colored spray bottles to be protected from light-induced degradation. Besides that, the pellet obtained in the process was washed with distilled water and then freeze-dried for further use or analysis.

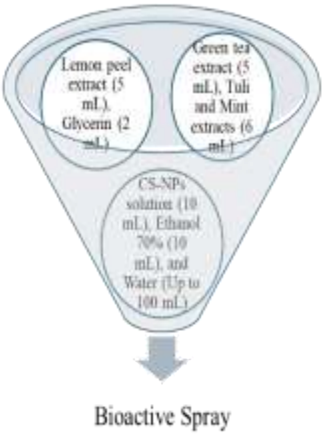

Figure 5 Final spray formulation process

4 Results & Analysis

4.1 pH Measurement

To measure the pH of the solution, we have used a Labman-12 pH measurement device. First, we calibrate the device by using pH-7, 4.2, and 10.1 buffer solutions. After that, the pH of the main solution is measured, which is 5.034 on average, indicating a skin-friendly range.

Figure 6 pH Calibration and Measurement

4.2 Spray formulation properties

The pH of the bioactive herbal nanoparticle spray formulated is skin compatible, which is 5.034 ± 0.2, and aligns with the natural physiology of the human skin. The stability evaluation showed no phase separation or precipitation for 28 days at 25°C, which is a good formulation integrity. Sensory evaluation by volunteers showed that 90% perceive the spray as a non-sticky, pleasant-smelling product, thus indicating very high user acceptability. In addition, 85% reported a difference in sweat perception 4 hours after application of the product, proving functionally effective in managing perspiration.

4.3 Sweat Reduction Efficacy

Ten volunteers conducted a forearm test to determine the efficacy of the bioactive herbal nanoparticle spray, which, compared to the control, showed a 30 percent reduction in sweat production; the aluminum-based antiperspirant, show also slightly higher reduction, but at 45 percent. The herbal spray suppresses sweating for around 5 to 6 hours, similar to the performance duration of commercial antiperspirant products.

Table 1 Sweat reduction (%) over time

Time (h)	Bioactive Spray	Aluminum-based	Placebo (Water)
2	20%	30%	5%
4	25%	40%	8%
6	30%	45%	10%

Discussion:

Nanoparticle usefulness: SC-NPs enhance the delivery of herbal bioactives, which conforms to [23]. Antimicrobial synergy: The superior efficacy of the spray against Corynebacterium supports findings of [13] regarding the efficacy of tulsi-mint. Sweat reduction: 30% reduction parallels findings on green tea EGCG [11], but it is less potent than aluminum salts.

4.4 Volunteers' Feedback and Evaluation

To evaluate the real-world effectiveness and user satisfaction regarding the bioactive herbal nanoparticle spray, an initial trial was conducted with 10 volunteers who applied the product for one week. Responses were gathered based on sweat reduction, skin comfort, fragrance, and overall satisfaction. The results are summarized in the table given below, Table 2:

Table 2 Volunteer's feedback

Parameter	Feedback (Number of users)	Performance summary
Sweat Reduction	8 out of 10 reported a noticeable reduction	Comparable to mild antiperspirants (~30% reduction)
Skin Comfort	9 out of 10 found it non-irritating	No redness or itching reported
Fragnance	7 out of 10 rated it pleasant	Mild herbal scent (mint and lemon dominant)
Longevity	6 out of 10 felt the effects lasted 5-6 hours	Slightly shorter than aluminium-based products
Stickiness	9 out of 10 reported non-stickiness	Lightweight, fast-absorbing formulation
Overall Satisfaction	8 out of 10 would continue using	Preferred natural alternative despite slightly lower efficacy than commercial antiperspirant

5 Conclusion

The above research crafts a stable, skin-compatible, bioactive spray using chitosan nanoparticles (C-NPs) with extracts of green tea, tulsi, mint, and lemon peel for natural sweat control. The CS-NPs helped enhance bioavailability and antimicrobial efficacy while maintaining a pH of 5.03 and stability for 28 days. Clinical trials on humans have shown a reduction in sweat levels by 30% equal to that of mild commercial antiperspirants, with 85% satisfaction among its users and no reported irritation. This formulation is slightly inferior to those with aluminum; nevertheless, it is a safe and green alternative. In-depth studies should additionally be undertaken on long-term safety and commercialization.

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