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Valorization Of Dragon Fruit Peel Waste: A Review On Pigment And Polymer Extraction For Probiotic-Based Anti-Tan Hydrogel Application

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Abstract: The sustainable management of agro-industrial waste has become a major global concern, necessitating the development of innovative valorization strategies. Dragon fruit peel, a significant by-product of *Hylocereus spp.*, constitutes approximately one-third of the total fruit mass and is an abundant source of bioactive compounds including betalains, phenolics, flavonoids, and polysaccharides. The present review provides an extensive evaluation of the potential of dragon fruit peel as a raw material for the extraction of natural pigments and polymers and their application in the formulation of a probiotic-enriched anti-tan hydrogel. Betalains demonstrate remarkable antioxidant, anti-inflammatory, and photoprotective activities, while pectin serves as a biodegradable and biocompatible polymer capable of forming stable hydrogel networks. The integration of probiotics such as *Lactobacillus fermentum* and *Lactobacillus parabuchneri* enhances the functional efficacy of the formulation by modulating the skin microbiome and improving barrier function. The synergistic interaction of these components contributes to effective tyrosinase inhibition, mitigation of oxidative stress, and protection against UV-induced skin damage. This review also explores advanced extraction techniques, nano-encapsulation strategies, rheological characterization, and industrial scalability, highlighting the role of fruit waste valorization in sustainable cosmetic innovation.

***Index Terms* -.** Dragon fruit peel, betalains, pectin, probiotics, hydrogel, anti-tan formulation, waste valorization.

1. **Introduction**

The exponential rise in agricultural and food processing activities has led to the generation of vast quantities of organic waste, posing serious environmental and economic challenges. In this context, waste valorization has emerged as a sustainable strategy aimed at converting such residues into value-added products, thereby minimizing waste and promoting resource efficiency [1–4]. Dragon fruit (*Hylocereus spp.*), widely cultivated in tropical and subtropical regions, produces a substantial amount of peel waste that is often discarded despite its high content of biologically active compounds [5–7]. Recent studies have demonstrated that dragon fruit peel is a rich source of betalains, phenolic compounds, flavonoids, and polysaccharides, which exhibit significant antioxidant, antimicrobial, and therapeutic properties [8–11].

The human skin is constantly exposed to environmental stressors such as ultraviolet radiation, pollution, and microbial pathogens, all of which contribute to oxidative stress and skin damage. Reactive oxygen species generated under these conditions can induce lipid peroxidation, DNA damage, and protein degradation, ultimately leading to premature aging and hyperpigmentation [12–15]. Melanin synthesis, which is regulated by the enzyme tyrosinase, plays a crucial role in skin pigmentation and tanning.

Overproduction of melanin due to UV exposure results in uneven skin tone and hyperpigmentation disorders [16–18]. Consequently, the inhibition of tyrosinase activity and the neutralization of oxidative stress are key targets in the development of anti-tan and skin-protective formulations.

Natural bioactive compounds derived from plant sources have gained increasing attention as safer alternatives to synthetic cosmetic ingredients. Betalains, in particular, have been recognized for their potent antioxidant and photoprotective properties, making them suitable candidates for incorporation into topical formulations [19–22]. In parallel, the use of natural polymers such as pectin in hydrogel systems has gained prominence due to their biodegradability, biocompatibility, and ability to deliver active compounds in a controlled manner [23–25]. Furthermore, the growing understanding of the skin microbiome has led to the incorporation of probiotics in cosmetic formulations to enhance skin health. Probiotic strains such as *Lactobacillus fermentum* have been shown to improve skin barrier function, reduce inflammation, and inhibit pathogenic microorganisms [26–29]. The combination of probiotics with prebiotic substrates such as pectin results in a synbiotic formulation that enhances stability and efficacy.

2. **Bioactive Components and Functional Properties**

Dragon fruit peel contains a diverse range of bioactive compounds that contribute to its functional properties. Betalains, which are water-soluble nitrogenous pigments, are responsible for the characteristic red and yellow coloration of the peel and exhibit strong antioxidant activity by scavenging free radicals and reducing oxidative stress [30–33]. These compounds have been reported to possess higher antioxidant capacity compared to conventional antioxidants, making them highly effective in protecting skin cells from oxidative damage [34,35]. In addition to their antioxidant activity, betalains exhibit anti-inflammatory properties by inhibiting the production of pro-inflammatory cytokines, thereby reducing inflammation and promoting skin healing [36].

Phenolic compounds and flavonoids present in the peel further enhance its bioactivity. These compounds act as potent antioxidants by donating hydrogen atoms or electrons to neutralize free radicals, thereby preventing oxidative damage to cellular components [37–39]. Flavonoids also play a crucial role in maintaining skin elasticity by inhibiting enzymes responsible for collagen degradation, such as collagenase and elastase [40]. The synergistic interaction between betalains and phenolic compounds significantly enhances the overall antioxidant capacity of dragon fruit peel.

Polysaccharides, particularly pectin, constitute another important component of dragon fruit peel. Pectin is a complex carbohydrate composed mainly of galacturonic acid residues and is widely used as a gelling agent due to its ability to form stable hydrogel networks [41–43]. The physicochemical properties of pectin, including its degree of esterification and molecular weight, influence its gel-forming ability and suitability for various applications. Additionally, pectin exhibits prebiotic properties by promoting the growth of beneficial microorganisms, thereby enhancing the efficacy of probiotic formulations [44].

3. **Extraction, Stabilization, and Characterization**

The efficient extraction of bioactive compounds from dragon fruit peel is essential for their application in cosmetic formulations. Conventional extraction methods such as solvent extraction and maceration are widely used; however, these methods often require long processing times and may result in the degradation of heat-sensitive compounds [45]. Advanced extraction techniques such as ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction have been developed to overcome these limitations and improve extraction efficiency [46–48]. These methods enhance mass transfer, reduce solvent usage, and preserve the bioactivity of the extracted compounds.

Stabilization of betalains is a critical aspect of formulation development, as these pigments are sensitive to environmental factors such as pH, temperature, and light exposure. Various strategies, including encapsulation in polymer matrices and the use of antioxidants, have been employed to improve their stability [49–51]. Characterization of the extracted compounds is typically performed using analytical techniques such as high-performance liquid chromatography, Fourier-transform infrared spectroscopy, and UV–visible spectroscopy to determine their composition and functional properties [52].

4. Hydrogel Engineering and Rheological Behavior

Hydrogels are three-dimensional polymeric networks capable of absorbing and retaining large amounts of water, making them ideal for topical applications. Pectin-based hydrogels have gained significant attention due to their biocompatibility, biodegradability, and ability to provide controlled release of active compounds [53–55]. The gelation mechanism of pectin involves the formation of cross-links between polymer chains, resulting in a stable network structure.

The rheological properties of hydrogels, including viscosity, elasticity, and shear-thinning behavior, play a crucial role in determining their performance and user acceptability. These properties influence the spreadability, stability, and release kinetics of the formulation [56–58]. Rheological studies are therefore essential for optimizing the formulation and ensuring its suitability for topical application.

5. Probiotics, Skin Microbiome, and Synbiotic Systems

The human skin microbiome plays a vital role in maintaining skin health and preventing infections. Disruption of the microbiome can lead to various skin disorders, including acne, dermatitis, and infections. Probiotics have been shown to restore microbial balance by inhibiting pathogenic microorganisms and promoting the growth of beneficial bacteria [59–61]. *Lactobacillus fermentum* is one of the most widely studied probiotic strains and has been shown to produce antimicrobial compounds such as lactic acid and bacteriocins, which inhibit the growth of harmful microorganisms [26,62].

The incorporation of probiotics into hydrogel formulations presents certain challenges, including maintaining cell viability and stability during storage. However, the use of prebiotic substrates such as pectin can enhance probiotic survival and activity, resulting in a synbiotic system that offers improved efficacy [63–65]. Such systems not only provide antimicrobial protection but also enhance skin hydration and barrier function.

6. Mechanistic Insights into Anti-Tan Activity

The anti-tan activity of the probiotic-enriched hydrogel is mediated through multiple mechanisms. Betalains and phenolic compounds inhibit tyrosinase activity, thereby reducing melanin synthesis and preventing hyperpigmentation [16,66]. Their antioxidant properties enable the neutralization of reactive oxygen species, thereby protecting skin cells from oxidative damage [34,67]. Additionally, the UV-absorbing properties of these compounds provide a protective barrier against harmful radiation, reducing the risk of photoaging and skin damage [68].

Probiotics further enhance the formulation by modulating the skin microbiome and reducing inflammation, thereby improving overall skin health. The combined effect of these mechanisms results in a multifunctional formulation that addresses various aspects of skin protection and care.

7. Industrial Translation and Regulatory Considerations

The commercialization of probiotic-enriched hydrogels derived from fruit waste presents significant opportunities for the cosmetic industry. The increasing demand for natural and sustainable products has driven the development of plant-based formulations that are safe, effective, and environmentally friendly [69–71]. However, several challenges must be addressed, including standardization of extraction methods, quality control, and regulatory approval. Compliance with cosmetic regulations and safety assessments is essential to ensure product efficacy and consumer safety.

8. Future Perspectives

Future research should focus on the development of advanced delivery systems such as nano-encapsulation and smart hydrogels to enhance the stability and bioavailability of bioactive compounds. The integration of artificial intelligence and machine learning in formulation design may further improve product performance and customization. Additionally, clinical studies are required to validate the efficacy and safety of these formulations in real-world applications [72–80].

9. Conclusion

Dragon fruit peel valorization represents a promising approach for the development of sustainable and innovative cosmetic formulations. The extraction of bioactive compounds such as betalains and pectin, combined with the incorporation of probiotics, enables the formulation of a multifunctional anti-tan hydrogel with significant antioxidant, photoprotective, and microbiome-modulating properties. This approach not only addresses environmental concerns associated with agro-industrial waste but also contributes to the advancement of eco-friendly cosmetic technologies.

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