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A Sustainable Approach to Sunscreen Plant-Derived Starch as a Natural SPF Booster

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1. Introduction

As public awareness of the harmful effects of ultraviolet (UV) radiation increases, the demand for high-protection sunscreens continues to rise. Traditionally, achieving higher sun protection factor (SPF) values has relied on increasing the concentration of chemical UV filters or mineral blockers. However, these approaches present notable drawbacks, including potential skin irritation, environmental concerns, and formulation instability [1-2]. Consequently, there is growing interest in developing environmentally friendly, safe and efficacious sunscreen boosters that can enhance SPF without over-reliance on traditional UV filters. Such boosters not only improve sun protection efficacy but often provide additional skin benefits.

Chemical UV filters function primarily by absorbing and dissipating UV radiation as lower-energy light, whereas mineral blockers and powder-based boosters reflect and scatter UV radiation via physical mechanisms as illustrated in Fig. 1 [3-4] .

Plant-derived flavonoids and polyphenols, owing to their conjugated molecular structures, can similarly absorb UV radiation, offering protective effects comparable to synthetic filters [5]. Furthermore, their antioxidant and anti-inflammatory activities provide added protection against UV-induced skin damage [6-7]. Nevertheless, practical challenges—including poor solubility, dark coloration, strong odor, susceptibility to oxidative discoloration, and high costs—limit the large-scale use of these natural compounds in sunscreen formulations. Thus, the exploration of alternative plant-based materials with better physicochemical stability, sensory properties, and cost-effectiveness holds significant importance for advancing the development of next-generation, eco-friendly sunscreen formulations.

Starch is commonly used in cosmetic formulations as a texturing agent and skin sensation regulator, but its potential synergistic effects in sunscreen products remain largely unexplored. This study systematically evaluated two plant-derived starches (tapioca starch and corn starch) through integrated in vitro and in vivo experiments, preliminarily elucidating the structure-activity relationship between starch micromorphological characteristics and SPF enhancement effects. Specifically, we evaluated whether the two types of starches can reduce the content of sunscreen agents while improving the SPF of the formulation, addressing the need for safer, more sustainable alternatives.

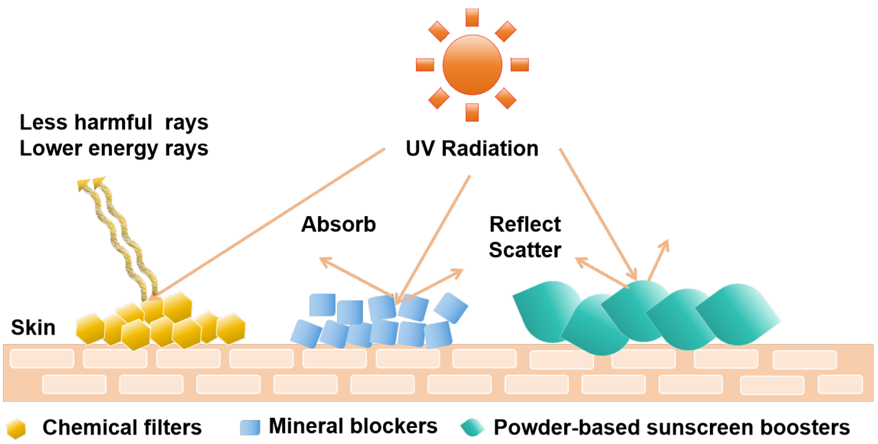


Figure 1. Mechanisms of sun protection provided by chemical filters, mineral blockers and powder-based sunscreen boosters.

2. Materials and Methods

2.1. Materials

The corn starch used in this study was obtained from Nouryon Chemicals (Ningbo) Co., Ltd., with the INCI name *Zea Mays* (Corn) Starch. The tapioca starch was sourced from Nouryon Surface Chemistry AB. Zinc oxide (ZnO) was purchased from Changzhou Nano-materials S&T Co., Ltd. All other ingredients used in the experimental formulations were of cosmetic-grade quality.

2.2. Micromorphological Characterizations of Starches and ZnO

Scanning electron microscopy (SEM) was employed to investigate the surface morphology and microstructural features of the starches and ZnO powder. Samples were mounted onto conductive adhesive tapes, sputter-coated with gold, and subsequently imaged using a Hitachi SU8600 SEM. This technique provides high-resolution insights into material surface characteristics, which are critical for understanding their properties, behaviors, and potential applications [8].

2.3. Experimental Sunscreen Preparation

Sunscreen samples were prepared as oil-in-water emulsions using a combination of Bis-Ethylhexyloxyphenol Methoxyphenyl Triazine, Ethylhexyl Salicylate, Ethylhexyl Triazone, Diethylamino Hydroxybenzoyl Hexyl Benzoate, Ethylhexyl Methoxycinnamate, and Methylene Bis-Benzotriazolyl Tetramethylbutylphenol as the active sunscreen agents. Methylene Bis-Benzotriazolyl Tetramethylbutylphenol accounted for 50% of the total sunscreen agent content. Other formulation components included Aqua, Decyl Glucoside, Propylene Glycol, and Xanthan Gum. For sample preparation, Phase A was heated to 75-80 °C and stirred for 20 minutes until completely dispersed. Simultaneously, Phase B was heated to 80-85 °C and stirred until fully dissolved, then added to Phase A under homogenization and emulsification for 5 minutes at the same temperature. Afterward, Phase C was incorporated, and the mixture was cooled below 45 °C with continuous stirring, followed by the sequential addition of Phase D, Phase E, and Phase F to obtain the final sunscreen emulsions.

Experimental groups included: S0 (base sunscreen formula without starch), ST (sunscreen formula containing tapioca starch), SCn (formulas containing varying concentrations of corn starch), and SDn (formulas with increased sunscreen agent content designed to match the SPF performance of SCn samples). The detailed compositions of the experimental samples listed in Table 1.

Table 1. Information on Sunscreen Formula Samples (wt%)

Phase	Ingredient (INCI name)	S0	ST	SC1	SC2	SD1	SD2
A	Aqua	To 100	To 100	To 100	To 100	To 100	To 100
A	Acrylates/C10-30 Alkyl Acrylate Crosspolymer	0.1	0.1	0.1	0.1	0.1	0.1
A	Xanthan Gum	0.08	0.08	0.08	0.08	0.08	0.08
B	Potassium Cetyl Phosphate	1	1	1	1	1	1
B	Diisopropyl Sebacate	6	6	6	6	6	6
B	Bis-Ethylhexyloxyphenol Methoxyphenyl Triazine	1	1	1	1	1.5	1
B	Ethylhexyl Salicylate	4	4	4	4	4	4.5
B	Ethylhexyl Triazone	1	1	1	1	1	1.5
B	Diethylamino Hydroxybenzoyl Hexyl Benzoate	3	3	3	3	3.5	3
B	Ethylhexyl Methoxycinnamate	7	7	7	7	7	8.5
B	Cetearyl Alcohol Cetearyl Glucoside	0.5	0.5	0.5	0.5	0.5	0.5
B	C14-22 Alcohols C12-20 Alkyl Glucoside	2.2	2.2	2.2	2.2	2.2	2.2
B	Peg-60 Hydrogenated Castor Oil	0.5	0.5	0.5	0.5	0.5	0.5
B	VP/Eicosene Copolymer	1	1	1	1	1	1
C	Aqua	0.5	0.5	0.5	0.5	0.5	0.5
C	Arginine	0.08	0.08	0.08	0.08	0.08	0.08
D	Methylene Bis-Benzotriazolyl Tetramethylbutylphenol Aqua Decyl Glucoside Propylene Glycol Xanthan Gum	4	4	4	4	4	4
E	Butylene Glycol	5	5	5	5	5	5
E	Tapioca Starch Polymethylsilsesquioxane	0	3	0	0	0	0
E	*Zea Mays* (Corn) Starch	0	0	3	5	0	0
F	preservative	0.4	0.4	0.4	0.4	0.4	0.4

2.4. SPF Value Determination

The in vitro SPF values were determined according to international testing methods established by the U.S. Food and Drug Administration (FDA) and the European Cosmetics, Toiletries and Perfumery Association (COLIPA). Sunscreen samples were applied at a dosage of 0.75 ± 0.01 mg/cm² onto 5cm × 5cm polymethyl methacrylate (PMMA) diffusion plates and measured using a UV-2000s spectrophotometer. Three plates were tested per sample, and the SPF value was calculated as the average of the three measurements.

For in vivo determination, the procedure followed the "Safety and Technical Standards for Cosmetics 2015" guidelines issued in China. Sunscreens were applied at a dosage of 2.00 ±

0.05 mg/cm² to a 5 cm × 8 cm area of human skin, and SPF values were measured using a Solar Light Model 601 device. Samples selected for in vivo testing were based on the outcomes of the in vitro SPF assays. The in vivo SPF evaluation was conducted on the back of a single human subject, enabling a targeted preliminary assessment of the samples' real-world sun protection efficacy based on prior in vitro data.

2.5. SPF Increase Rate and Sunscreen Agent Reduction Rate

The SPF increase rate was calculated using the following formula:
SPF Increase Rate (%) = ((SPF − SPF) / SPF) × 100%,
where SPF is the SPF value of the sample containing starch, and SPF is the SPF value of the starch-free control sample.
The sunscreen agent reduction rate was determined according to the formula:
Reduction Rate (%) = ((P − P) / P) × 100%,
where P is the total amount of sunscreen agents in the starch-free control sample, and P is the total amount of sunscreen agents in the starch-containing sample.

3. Results

3.1. Micromorphological Characteristics of Starches and ZnO

SEM images (Fig. 2) reveal that tapioca starch and corn starch possess comparable particle sizes, with both exhibiting surfaces characterized by small pores. As shown in Fig. 2, tapioca starch particles are predominantly spherical or hemispherical shape (Fig. 2a and b), whereas corn starch particles are predominantly irregular polyhedrons (Fig. 2c and d) [9-10]. In contrast, ZnO exhibits the smallest particle size among the three materials and displays a similarly irregular morphology (Fig. 2e and f). Notably, the surface morphology of corn starch more closely resembles that of ZnO, suggesting potential similarities in their physical interactions with UV radiation.

3.2 SPF Value and SPF-Boosting Effect

In vitro evaluations showed that the SPF value of the starch-free sunscreen base (S0) was 53. The sunscreen sample containing 3% tapioca starch (ST) exhibited a marginally increased SPF value of 54. In contrast, samples SC1 and SC2, containing 3% and 5% corn starch respectively, achieved significantly higher SPF values of 80 and 78 (Fig. 3a). Relative to the base sample S0, the ST sample showed almost no SPF-boosting effect, whereas SC1 and SC2 demonstrated substantial SPF increases of 50.1% and 46.3%, respectively (Fig. 3b). The SPF-boosting performance of corn starch was markedly different from that of tapioca starch.

Furthermore, for comparison, samples SD1 and SD2, which incorporated higher amounts of sunscreen agents without starch addition, reached SPF values of 79 and 81, respectively (Fig. 3a). Compared with SD1 and SD2, the sunscreen agent reduction rates achieved by samples SC1 and SC2 were 5.0% and 12.5%, respectively (Fig. 3c), indicating that the addition of corn starch can achieve similar SPF enhancement with lower active ingredient content.

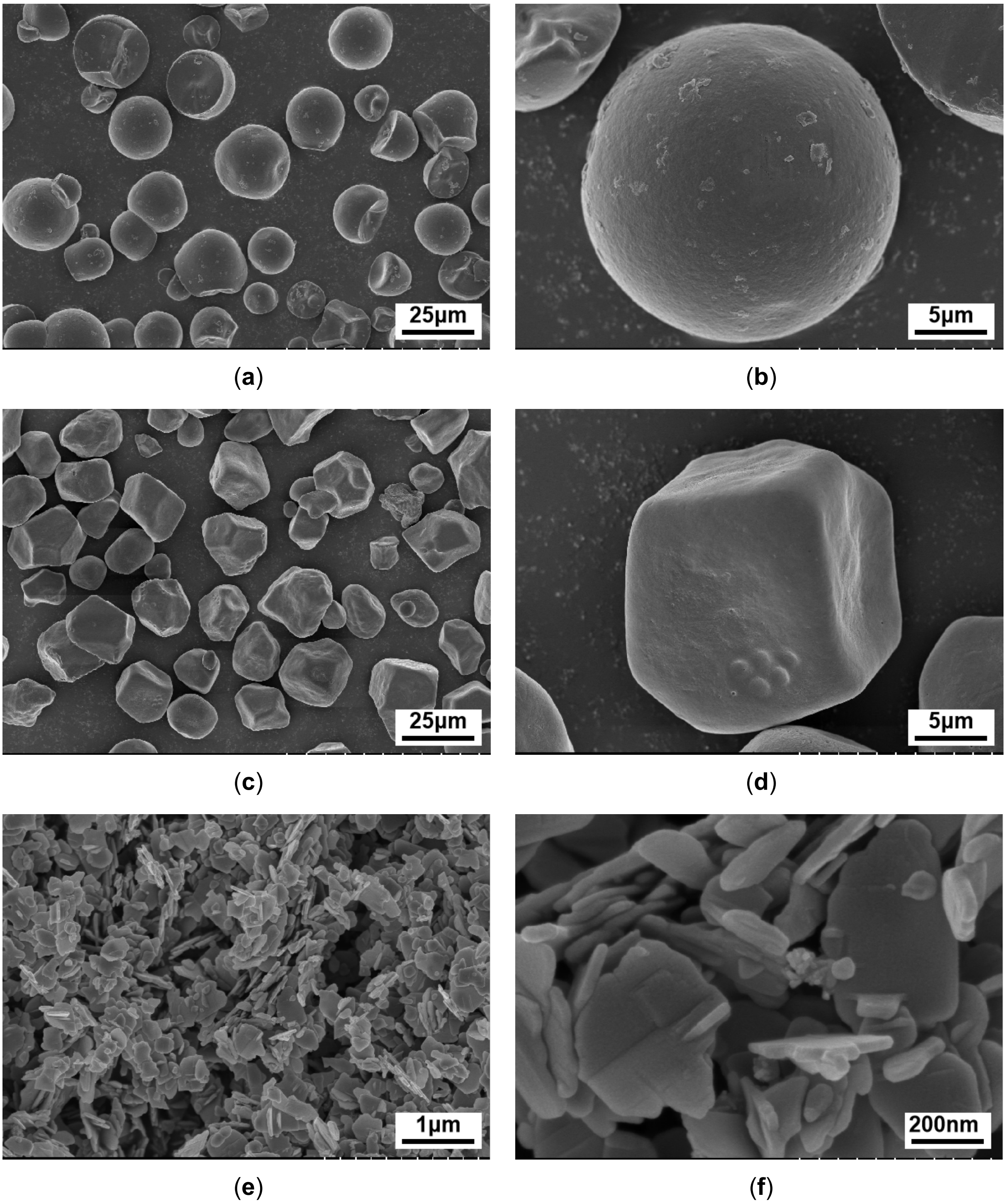
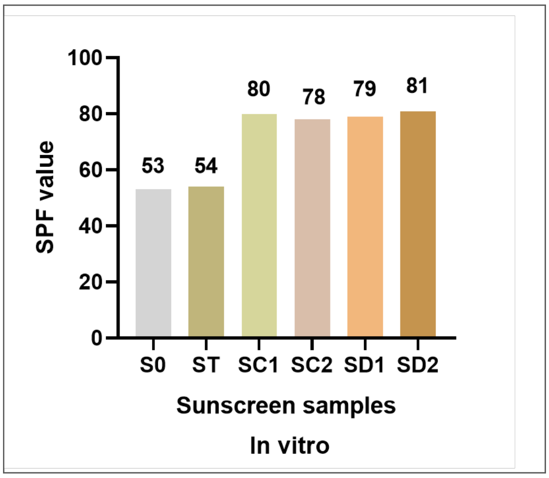


Figure 2. SEM images at varying magnifications: (a, b) Tapioca starch showing spherical or hemispherical particles; (c, d) Corn starch exhibiting irregular polyhedral particles; (e, f) ZnO with irregular morphology.



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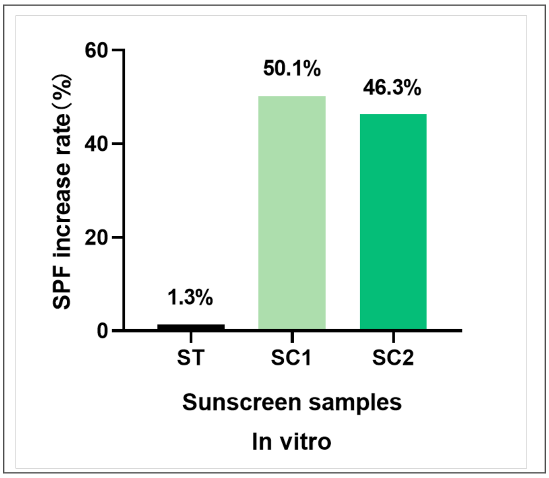

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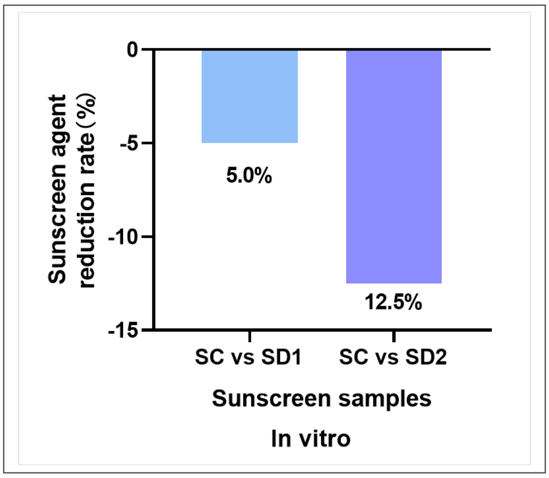

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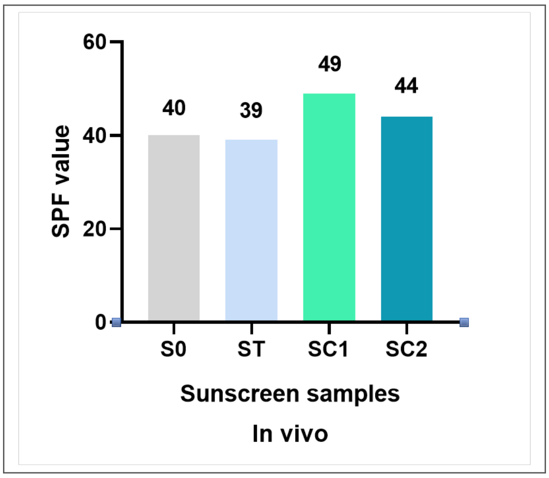
Figure 3. In vitro results of SPF value and SPF-boosting effect tests: (a) SPF values of sunscreen samples; (b) SPF increase rates of sunscreen samples; (c) Comparison of sunscreen agent reduction rate between sample SC and SD1, and SC and SD2.

3.3. Clinical Trials

Based on the results of the in vitro tests, samples S0, ST, SC1, and SC2 were selected for the in vivo human sunscreen assay. The in vivo SPF values are as follows: sample S0 exhibited an SPF of 40, sample ST had an SPF of 39, sample SC1 had an SPF of 49, and sample SC2 had an SPF of 44 (Fig. 4a). Compared to the SPF value of sample S0, sample ST showed no SPF-enhancing effect. Notably, the SPF increase rates of samples SC1 and SC2 were 22.5% and 10.0%, respectively (Fig. 4b). These clinical in vivo results are consistent with the in vitro findings, confirming that corn starch provides a much stronger SPF-boosting effect compared to tapioca starch.



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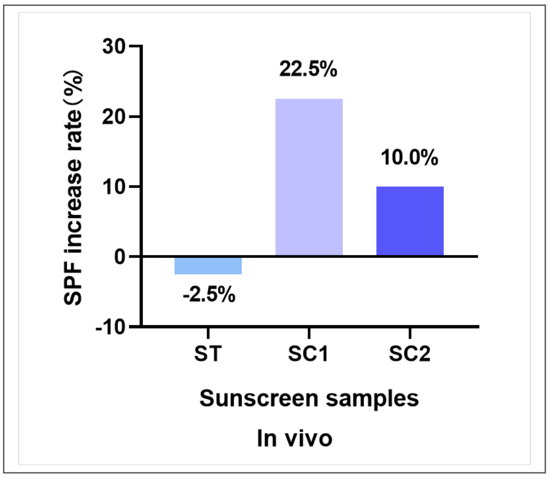

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Figure 4. Results of SPF value and SPF-boosting effect tests in vivo: (a) the SPF values of sunscreen samples; (b) SPF increase rates of sunscreen samples.

4. Discussion

Recent studies have increasingly focused on the synergistic effects of non-UV-absorbing components in sunscreen formulations, particularly sustainable materials such as starch or cellulose. While previous work [11] suggested the potential SPF-enhancing effects of corn and cassava starches, the underlying mechanisms remained unexplored. Starch-based microsponges investigated for their synergistic and sustained-release properties in sunscreen emulsions, have shown promise, although their complex preparation process limits their practical application [12]. In contrast, the present study demonstrates that native corn starch can significantly enhance SPF without requiring special processing, offering distinct advantages in terms of cost-effectiveness and production feasibility.

Moreover, this research has identified a plant-derived starch with remarkable properties as a physical UV blocker, functionally comparable to conventional ingredients like zinc oxide. Notably, this starch not only shows potential for reducing the concentration of synthetic sunscreen agents but also improves SPF efficacy, representing a sustainable and effective alternative to traditional chemical sunscreens. The environmental and dermatological benefits of this botanical ingredient are particularly significant given growing concerns about the ecological and cutaneous impacts of synthetic sunscreen components.

Comparative analysis revealed that corn starch exhibits superior SPF-enhancing effects compared to tapioca starch, which showed negligible improvement. This difference likely stems from their distinct microstructural and scattering characteristics. SEM observations indicate that corn starch's irregular polyhedral morphology may provide greater light scattering efficiency than the smooth spherical particles of tapioca starch. The uneven surfaces of corn starch increase UV diffusion pathways, thereby enhancing overall UV blocking performance. In contrast, the smooth spherical morphology of tapioca starch particles may allow more direct light transmission, reducing UV protection effectiveness. Furthermore, corn starch's irregular particle shape appears to facilitate more uniform film formation during sunscreen application, minimizing UV "hot spots," whereas tapioca starch's spherical granules tend to form looser packing arrangements that compromise film integrity.

An important finding of this study is the discrepancy between in vitro SPF measurements (showing a 50.1% enhancement with corn starch on artificial membrane) and in vivo results (demonstrating only a 22.5% improvement on human skin). This difference may be attributed to several factors: the surface properties of artificial membranes like PMMA plates differ substantially from human skin, potentially affecting starch particle distribution and light scattering efficiency; the presence of sebum, sweat, and the dynamic nature of the stratum corneum may influence starch film stability; and while in vitro tests are conducted under static conditions, real-world factors such as friction and perspiration may diminish the SPF-enhancing effects of starch during actual use. These findings highlight the importance of considering both laboratory and clinical performance when evaluating novel sunscreen ingredients.

5. Conclusion

In conclusion, our findings demonstrate that plant-derived starches, particularly corn starch, can serve as viable alternatives to conventional sunscreen agents. This discovery paves the way for the development of next-generation sunscreens that deliver high UV protection while reducing reliance on synthetic chemicals. Moreover, it opens new possibilities for creating sunscreens that are not only effective but also more environmentally sustainable and skin-friendly. To further advance this field, future research should systematically investigate a broader range of starch types and their microstructural characteristics, aiming to establish a comprehensive structure–property relationship that provides a robust, data-driven foundation for sunscreen formulation optimization.

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