

Article

SVX Spider Silk-Inspired Biopolymer and Enhanced Cosmetics Efficacy

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Abstract: The cosmetics industry is undergoing a shift towards sustainability and efficacy, driven by consumer demand for eco-friendly and safe products. This paper introduces SVX, a spider silk-inspired raw material intended to transform cosmetic formulations. Produced through fermentation, SVX is a biopolymer composed of self-assembled proteins characterized by a porous structure for delivering active ingredients safely to the skin. The study utilized in vitro and ex vivo methods to assess SVX's ability to protect against oxidative stress, enhance skin hydration, and support ingredient delivery. Safety assays, including the HET-CAM, patch test, and HRIPT, demonstrated that SVX is non-irritating and safe for topical application. Additionally, FTIR analysis confirmed SVX's capacity for sustained release of active ingredients, such as hyaluronic acid, over an 8 h period. Results showed that SVX significantly improved skin barrier protection and exhibited superior antioxidant properties compared to control formulations. Its biocompatibility, along with a vegan and biodegradable composition, aligns with the principles of sustainability, with over 60% biodegradability achieved within 10 days. Furthermore, SVX displayed antioxidant efficacy approximately 130 times greater than L-ascorbic acid, based on DPPH assay results. These findings suggest that SVX offers a versatile and sustainable solution for skincare formulations, combining environmental responsibility with benefits for skin health and performance.

Keywords: SVX; protein; spider silk; biotechnology; cosmetic innovation; sustainability; fermentation; vegan biopolymer; smart delivery system; green chemistry; biodegradability



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1. Introduction

The cosmetics industry stands at a pivotal juncture, navigating a landscape defined by evolving consumer preferences, stringent regulatory standards, and an increasing emphasis on sustainability [1–8]. In this context, the quest for cosmetics that not only enhance beauty and longevity but also adhere to principles of environmental responsibility and safety is of great importance [9–12]. Consumers are seeking products that align with their ethical values, eschewing harmful chemicals and embracing eco-friendly formulations that promote both personal wellness and planetary health [13–15].

Against this backdrop, the cosmetics industry faces several unmet needs, prompting a paradigm shift towards solutions rooted in green chemistry and sustainability [16,17]. One pressing demand is for cosmetics crafted through eco-friendly practices, devoid of harmful chemicals, and compatible with vegan lifestyles [18–23]. SVX (INCI: *sr-(Tetrapeptide-74 Hexapeptide-40 Expression Vector pMBP-parallel 1 Polypeptide-1 Spider Polypeptide-1 Spider Polypeptide-5)*), offers a potential solution to these unmet needs [24–28].

SVX, a novel raw material, represents a convergence of technology and sustainability [29–31]. Produced through a fermentation process utilizing biotechnology processes, SVX is a large biopolymer composed of about 470,000 protein monomers that self-assemble into particles of approximately 0.7 microns. This biopolymer, with its non-penetrative

yet porous structure, offers a novel approach to cosmetic formulation, providing safe and effective delivery of active ingredients without compromising skin integrity [32–36].

Moreover, SVX is intended to answer the industry's commitment to eco-friendly practices. As a sustainable and vegan biopolymer, SVX underscores the potential for cosmetics to be both effective and responsive to environmental concerns. Furthermore, SVX boasts antioxidant properties, surpassing conventional antioxidants such as vitamin C in efficacy. By forming a protective network on the skin, SVX acts as a shield against free radicals, oxidative stress, and environmental pollutants, offering multifaceted benefits for cosmetics applications [37].

Recombinant proteins, encompassing growth factors, chemokines, and structural and membrane proteins, are increasingly in demand due to their purity, their efficacy, and their ability to be produced in greater amounts. In cosmetics, they are prized for their ability to rejuvenate skin, repair wounds, and improve wrinkles, owing to their effect on collagen. In haircare, they are known to improve shine and health. The appeal of recombinant proteins in beauty products is further bolstered by their ability to be produced without animal sources, making them suitable for vegan formulations. These proteins can also be used in products sold in regions with stringent regulations, such as Europe, where materials isolated directly from human cells are forbidden in cosmetics [38].

In light of these developments, there is a growing need to explore the multifaceted potential of SVX in cosmetic formulations. This paper endeavors to unravel the properties and applications of SVX, shedding light on its potential role as a transformative raw material in the cosmetics industry. Through analysis and empirical evidence, this paper aims to elucidate the benefits of SVX, from its impact on skin physiology to its efficacy as a smart delivery system for sensitive ingredients [38]. By examining SVX through a scientific lens, this paper seeks to underscore its potential as a game-changer in cosmetic innovation, paving the way for a more sustainable and conscientious approach to skin and hair care [39–45].

2. Materials and Methods

2.1. SVX Production

Fermentation process: SVX's one-step fermentation process represents an advancement in biotechnology. Using recombinant DNA technology, a patented DNA code inspired by spider silk DNA is engineered into bacteria that synthesize SVX. Bacteria produce SVX in a controlled fermentation process. The downstream process includes the purification of SVX from the bacteria. This scalable and controlled process, with high batch-to-batch consistency and purity, eliminates the need for extracting or depleting natural resources, further solidifying SVX as a sustainable potential solution for the cosmetic industry [46].

2.2. SEM Image Analysis

Instrument: Analytical high-resolution scanning electron microscope Apreo 2S by Thermo Fisher Scientific (Waltham, MA, USA).

Cryo-SEM: The instrument is equipped with the system PP3010 (manufactured by Quorum Technology, Lewes, UK), permitting fast cooling of samples down to cryogenic temperatures, their fracture, coating, and SEM imaging at controlled temperatures.

Sample preparation: Prior to the SEM imaging, the samples were iridium-coated for 1 min using the Quorum Q150V S Plus Sputter Coater (Quorum Technology, UK). This coater is designed to produce fine-grain “cool” coatings, achieving thin coatings of 2–3 nm without charging effects in SEM. Iridium and gold-palladium coatings are available for different types of samples.

2.3. Biodegradability Test

Biodegradability assessment: The biodegradability of SVX was assessed by Bio-EC labs following OECD 301 B guidelines. This study aimed to determine the biodegradability

of raw material ingredients by evaluating the production of CO₂ or dissolved organic carbon (DOC) over a minimum of 28 days in a liquid environment [47].

Test conditions:

- Sample preparation: The test was performed on a 10% SVX (*w/w*) dispersion in water.
- Test system: The biodegradability of organic compounds by microorganisms in an aquatic medium was examined using a static test system. This test system included an inorganic medium, with the organic compound serving as the sole nominal source of carbon and energy (with a theoretical concentration of 10 to 20 mg/L of carbon), and a mixed inoculum from an urban wastewater treatment plant. The final blend of this test system contained less than 30 mg/L of suspended matter.
- Incubation: The mixture was stirred in test vessels exposed to a CO₂-free airflow for approximately 28 days at a temperature of 22 °C ± 2 °C. The test duration could be extended by two weeks if degradation had commenced but had not yet reached a plateau.

CO₂ measurement:

- CO₂ trapping: Carbon dioxide generated during microbial degradation was collected in external vessels containing a barium hydroxide solution and subsequently quantified via titrimetric analysis.
- CO₂ calculation: The measured CO₂ was compared to the theoretical amount (CO₂Th) and expressed as a percentage. CO₂ capture occurred in the first vessel containing the barium hydroxide solution, positioned close to the test blend. The remaining vessel was exchanged for one containing a freshly prepared barium hydroxide solution.
- Barium hydroxide volume: The volume of barium hydroxide in the vessels ranged from 250 to 300 mL, depending on the interval between the two measurements.

Final analysis:

- Post-incubation: On the 28th day, about 1 mL of concentrated hydrochloric acid was added to each test vessel to decompose carbonates and bicarbonates. The obtained values were referenced as the “28 bis” incubation day.

This detailed methodology ensured accurate and reliable measurement of the biodegradability of the 10% SVX (*w/w*) dispersion in water, reinforcing its suitability as a sustainable ingredient in cosmetic formulations.

2.4. Safety Assessments

Safety assessments of SVX were conducted by Bio-EC labs (Longjumeau, France) and include the following tests:

Patch test: Evaluated the cutaneous compatibility of SVX fibers. The fibers were applied to the external face of the arm for 48 h on 22 volunteers. Post-application, the skin condition was assessed.

Human repeat insult patch test (HRIPT): Determined allergic reactions to SVX biopolymer and SVX-based anti-wrinkle serum on 50 healthy subjects. Ten applications with a sealing patch were examined up to 48 h after removal.

Phototoxicity: An *in vitro* method was used to assess the phototoxic potential of SVX fibers (Phototoxicity testing methods and applications, Cosmetics Europe, 1997).

Ocular irritation: Assessment was conducted using the hen’s egg chorioallantoic membrane (HET-CAM) method.

Ethical conduct of the study: The study adhered to the principles of good clinical practice as outlined in the ICH Topic E6 “Note for Guidance and Good Clinical Practice” (CPMP/ICH/135/95), along with the Helsinki Declaration (1964, WMA) and its subsequent revisions. It was conducted according to the sponsor’s defined standard operating procedures and study protocol. All recorded study events were reported, with data accuracy and compliance with the protocol verified and confirmed by study participants.

Scope of tests compliant with:

- Regulation of the European Parliament and the Council (EC) No. 1223/2009 of 30 November 2009 on cosmetic products.
- Cosmetics Europe—The Personal Care Association (previously COLIPA) Guidelines “Product Test Guidelines for Assessment of Human Skin Compatibility 1997”.
- Cosmetics Europe—The Personal Care Association (previously COLIPA) Guidelines for Evaluation of the Efficacy of Cosmetic Products 2008.
- “Appraisal of Safety of Chemicals in Foods, Drugs and Cosmetics” by J.H. Draize, published by the Association of Food and Drug Officials of the United States.

Ethical committee:

In line with the procedures of the investigating center, the protocol, informed consent form, and preclinical information concerning the investigational product SVX were submitted to the center’s internal committee. The committee ensured that the project met the conditions of optimal scientific rigor, assessed its general relevance and the suitability between the aim followed and the means implemented, and gave an opinion on the protection of the test subjects. The study began after the approval of the survey committee.

2.5. Antioxidant Activity

DPPH assay: Antioxidant activity was evaluated by Bio-EC labs using the DPPH method, compared to L-ascorbic acid (vitamin C). The test measures the ability of an antioxidant to reduce the DPPH radical, with absorbance read at 517 nm using a UV-MC2 spectrophotometer (SAFAS, Monaco). Results were expressed as vitamin C equivalent antioxidant capacity (VCEAC) in mmol/L [29,48].

The DPPH (2,2-diphenyl-1-picrylhydrazyl) assay is widely used to evaluate the antioxidant activity of various substances. It is based on the ability of antioxidants to donate hydrogen atoms or electrons to neutralize DPPH radicals, resulting in a color change that can be quantitatively measured. The underlying principle of the DPPH assay supports its use in assessing antioxidant activity because the capacity to scavenge free radicals is a hallmark of antioxidant behavior [19–21].

Concentration of SVX: A 1% SVX (*w/w*) dispersion in water was used.

Dilutions prepared: 1/500, 1/1000, 1/1500, 1/2000, 1/2500, 1/3000, and 1/4000.

EC50 Values: The concentration required to achieve a 50% antioxidant effect (EC50) for L-ascorbic acid is 0.3 mM. For SVX, the dilution necessary to achieve a 50% antioxidant effect (EC50) is 1/2500.

2.6. Environmental Pollution Modeling

Pollution modeling: Carbon black particles (PM2.5–10) were used to model environmental pollution. These particles were procured from Sigma-Aldrich (St. Louis, MI, USA) and applied to a skin model made from polyurethane. The polyurethane served as a skin model, with a 30 mm diameter circle marked on its surface.

Application procedure:

1. Formula application: 100 mg of the tested formula was applied within the marked circle using circular motions, allowing the solvents to evaporate.
2. Pollution application: Carbon particles were applied to achieve a concentration of 3 mg/cm² on the surface.
3. Washing process: The sample was then washed under running water for 20 s.
4. Scrubbing process: The polyurethane model was scrubbed with a brush for 20 s and washed again for an additional 20 s under running water.

Analysis: Each step was monitored using ImageJ analysis (version 1.53k) and delta L measurements, with five repetitions conducted for accuracy.

2.7. Hair Experiments

Experiments involving hair used European blond virgin hair:

Hair denaturation temperature: Measured using differential scanning calorimetry (DSC) with heating steps of 20 °C per minute from 100 °C to 300 °C under a nitrogen flow of 60 mL/min. The DSC-1 instrument is by Mettler Toledo (Greifensee, Switzerland). The crucibles are standard aluminum with a volume of 40 µL.

2.8. Slow-Release Mechanism and Protection Studies

Materials: Pure retinol was purchased from Sigma-Aldrich. Retinol 50 C Complex, a commercially available retinol complex, was obtained from BASF (Ludwigshafen, Germany). Hyaluronic acid (PrincipHYAL[®]) was provided by ROELMI Group (Lombardy, Italy).

Retinol stability measurement: Retinol stability was measured using a spectrophotometer.

FTIR analysis of hyaluronic acid (HA) release:

Complex creation: A complex of SVX:HA was created and monitored by FTIR techniques.

Measurement: An experiment to demonstrate the gradual release of hyaluronic acid was conducted using FTIR, comparing two peaks: the SVX peak at 1624 cm⁻¹ and the HA peak at 1010 cm⁻¹.

2.9. Statistical Analysis

All experimental data were analyzed using a two-sample t-test to assess the significance of differences between test groups. A two-tailed test with equal variance was applied, where the first two arguments correspond to the two datasets being compared, the third argument (2) represents a two-tailed test, and the fourth argument (2) indicates equal variance (homoscedastic). A *p*-value of less than 0.05 was considered statistically significant.

3. Results

3.1. SVX—General Information

SVX is a novel raw material in the cosmetics industry, characterized by its unique properties and production methodology. SVX is synthesized through a fermentation process utilizing bacteria, resulting in the formation of particles with dimensions akin to bacteria themselves, approximately 0.7 microns (Figure 1). The significance of this size lies in its non-penetrative nature, ensuring that SVX remains on the skin's surface without causing irritation or adverse reactions. Due to its relatively large size, high surface area, and porous structure, SVX is potentially an ideal encapsulation and carrier for various active and sensitive ingredients commonly employed in cosmetics [39–45].

The benefits of SVX extend beyond its physical characteristics. As a sustainable and vegan biopolymer, SVX embodies the principles of green chemistry, aligning with the industry's shift towards eco-friendly formulations [49–56].

SVX further distinguishes itself by being readily biodegradable (Figure 2), aligning with the increasing emphasis on sustainability within the cosmetics field. This feature underscores SVX's commitment to environmental responsibility, offering a green alternative in cosmetic formulations without compromising efficacy or safety [57].

SVX represents an advancement in cosmetic raw materials, distinguished by its properties and safety profile. Testing has affirmed SVX's suitability for cosmetic applications, ensuring both efficacy and safety for consumers.

SVX has successfully undergone safety evaluations, including patch testing and human repeat insult patch testing (HRIPT). In patch studies, SVX demonstrated non-irritant properties after 48 consecutive hours of application on 22 volunteers' external arm surfaces. Similarly, in HRIPT studies involving 50 healthy subjects, both SVX raw material and final product SVX-based anti-wrinkle serum exhibited no dermal irritation or sensitization, indicating their safety for human use. Furthermore, evaluations of SVX's ocular irritation potential through in vitro methods, specifically utilizing the hen's egg test on the chorioallantoic membrane (HET-CAM), revealed a moderately irritant classification for SVX. However, it is noteworthy that the irritation observed was within acceptable limits, ensuring minimal risk to ocular tissues. Additionally, assessments of SVX's phototoxic

potential through in vitro tests yielded favorable results, with SVX categorized as “non-phototoxic”. This signifies SVX’s compatibility with prolonged exposure to light, ensuring its safety for use in cosmetic formulations intended for daytime application.

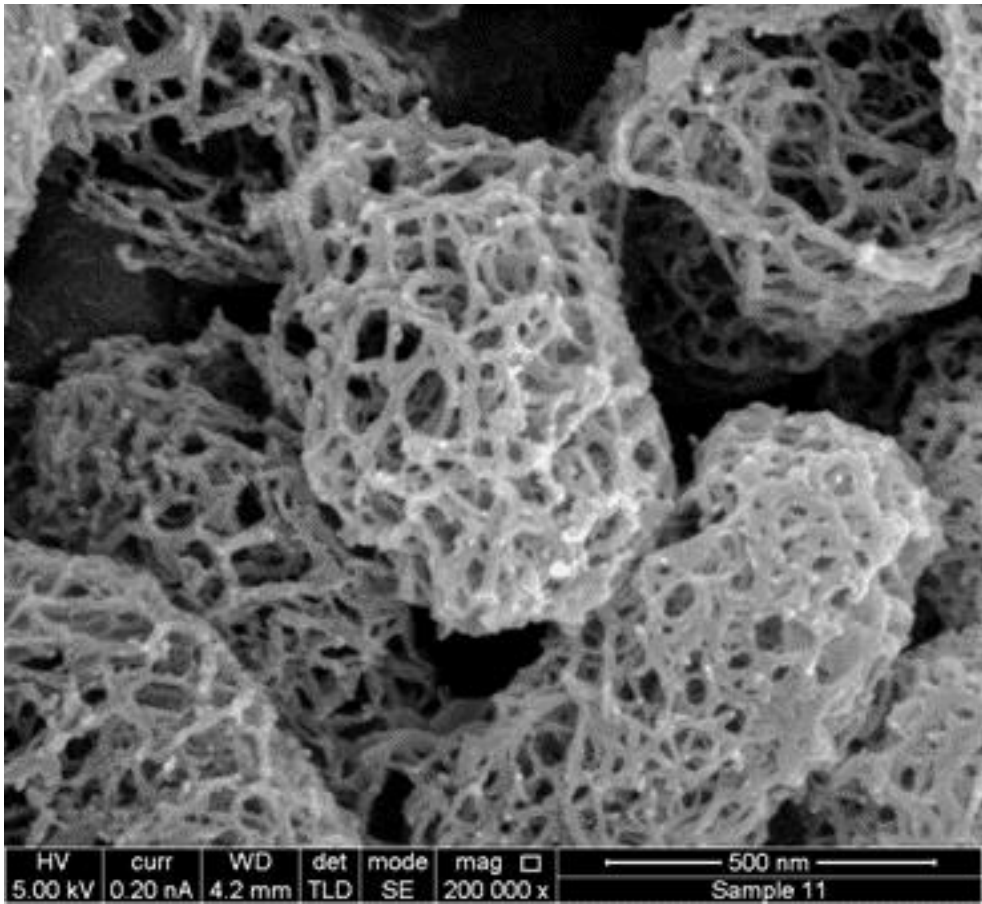


Figure 1. SEM analysis of SVX composed of 470,000 proteins.

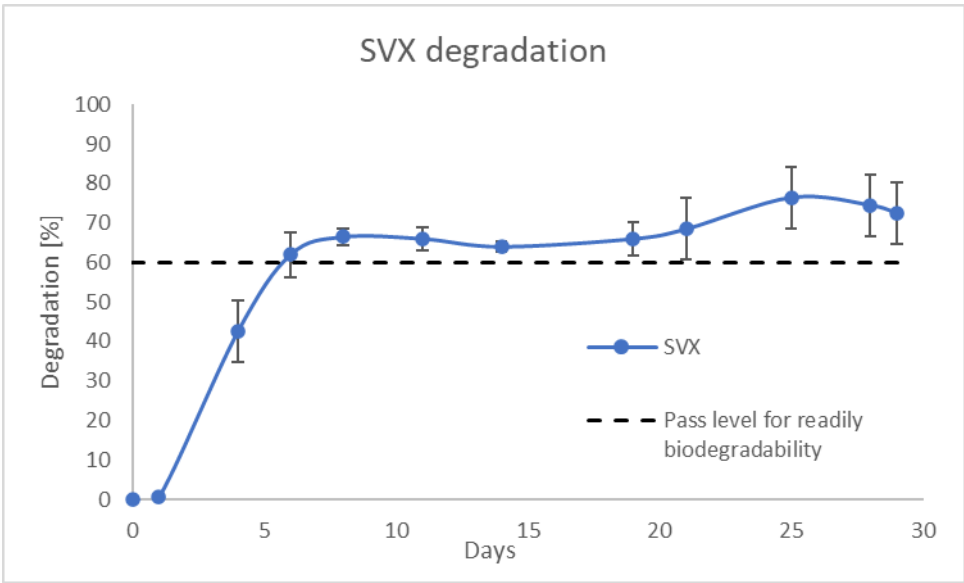


Figure 2. SVX is readily biodegradable, SVX biodegradable at 73%.

With its proven safety profile and multifaceted potential benefits, SVX emerges as a candidate for innovative and sustainable cosmetic formulations, intended to meet the evolving needs of consumers seeking effective, eco-friendly skincare solutions.

3.2. SVX—Antioxidant

Building upon SVX's antioxidant properties, this section presents findings from the 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay, a widely recognized method for evaluating antioxidant activity [58]. By quantifying SVX's ability to neutralize free radicals and inhibit oxidative damage, this section underscores the antioxidant potential of SVX and its implications for skincare formulations (Figure 3).

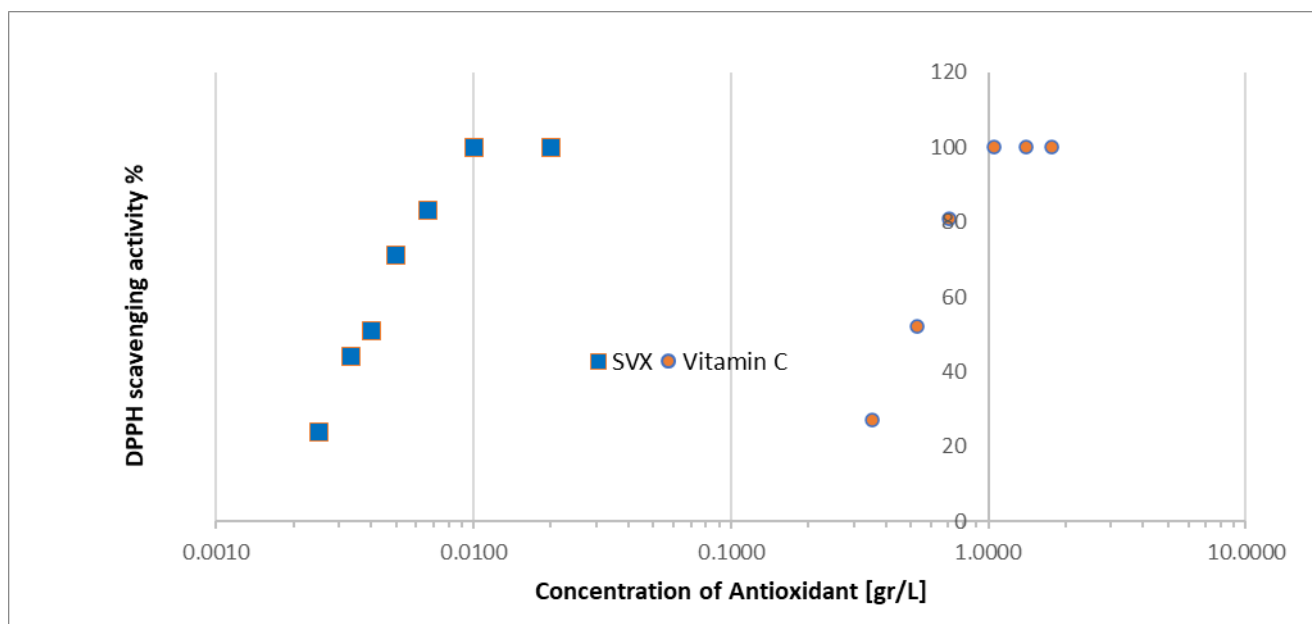


Figure 3. The graph represents the antioxidant activity of SVX compared to L-ascorbic acid, using the DPPH radical scavenging assay (logarithmic scale). The scavenging activity is measured by the percentage of DPPH radicals neutralized at varying concentrations of SVX and L-ascorbic acid. SVX demonstrates approximately 130 times more potent radical scavenging activity at equivalent concentrations compared to L-ascorbic acid.

To evaluate the antioxidant activity of SVX in comparison to L-ascorbic acid, a DPPH assay was conducted. This assay is based on the capacity of antioxidant compounds to reduce DPPH by hydrogen transfer, resulting in a measurable discoloration of the solution. The extent of this reaction is proportional to the antioxidant capacity of the tested substances. In this experiment, both SVX and L-ascorbic acid were exposed to DPPH radicals in parallel, with their scavenging activities being monitored.

The DPPH scavenging activity of L-ascorbic acid indicates that the concentration required to achieve a 50% antioxidant effect (EC₅₀) is 0.3 mM, establishing it as a potent antioxidant. Figure 3 illustrates the DPPH scavenging activity of SVX, where the dilution necessary to achieve a 50% antioxidant effect (EC₅₀) is 1/2500. This dilution highlights the potency of SVX as an antioxidant.

Further analysis revealed that the antioxidant activity of the SVX 1% in water at 1/2500 dilution corresponds to a vitamin C equivalent antioxidant capacity (VCEAC) of 0.3 mM. When converting the concentration of SVX and vitamin C to [g/mol], the concentration of vitamin C is 0.53 g/L and the concentration of SVX is 0.04 g/L, where both items achieve a 50% antioxidant effect (EC₅₀). The ratio between the concentrations is 130, meaning that SVX is approximately 130 times more powerful as an antioxidant than L-ascorbic acid.

SVX showcases antioxidant properties that extend beyond skin protection, offering comprehensive potential benefits for cosmetic formulations. Its antioxidant ability plays a pivotal role in safeguarding against oxidative stress and preserving the integrity of various cosmetic products.

Studies have underscored SVX’s efficacy in neutralizing free radicals, mitigating the detrimental effects of oxidative damage on the skin. Furthermore, SVX’s antioxidant capacity extends to preserving color integrity, particularly in haircare formulations. By combatting oxidation, SVX serves to prevent color fading, ensuring long-lasting vibrancy and vitality of hair dyes.

The antioxidant properties of SVX position it as a potentially versatile ingredient in cosmetic formulations, offering not only skin protection but also color preservation benefits. As oxidative stress continues to be a significant concern in the cosmetics industry, SVX emerges as a possible solution for enhancing product stability and longevity, thereby meeting the evolving needs of consumers seeking effective and enduring cosmetic solutions.

3.3. SVX—Barrier and Protection

Through its unique properties, SVX creates a protective layer [59–63] on both skin and hair, guarding against various environmental stressors. Studies have demonstrated SVX’s ability to fortify the skin’s barrier function, enhancing its resilience against external aggressors such as pollutants [64–69] and free radicals (Figure 4, Table 1).

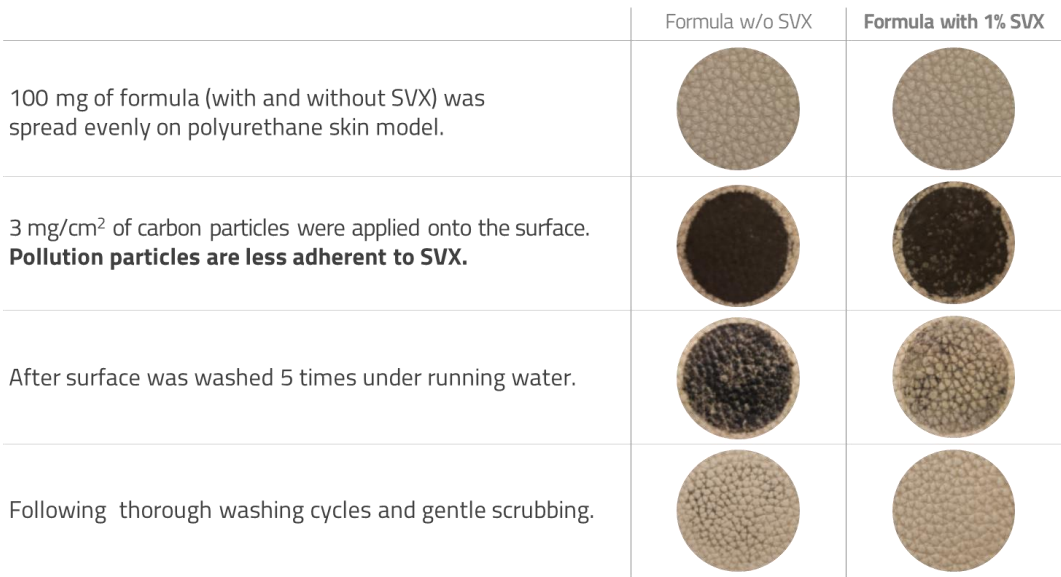


Figure 4. SVX acts as a protective barrier against environmental damage.

Table 1. Antipollution measurements.

Skin Model Tone	Formula w/o SVX (n = 7), Mean (SEM) ¹	Formula with 1% SVX (n = 7), Mean (SEM) ¹	p Value
Before application of pollution particles	142.1 (0.6)	141.7 (0.9)	0.5172
Immediately after application of pollution particles	35.6 (1.2)	40.5 (3.4)	0.0194
After 5 washes under running water	59.2 (3.7)	97.1 (3.9)	3×10^{-7}
After gentle scrubbing	117.1 (9.8)	138.2 (4.6)	2×10^{-3}

¹ Measured by ImageJ (version 1.53k).

SVX not only serves as a shield for the skin but also extends its protective benefits to hair strands. Through its properties, SVX creates a formidable protective layer on both skin and hair, guarding against various environmental stressors.

SVX imparts a protective shield on hair fibers, safeguarding against extreme temperatures and preventing color fading. This protective layer acts as a barrier, shielding the hair from the damaging effects of heat styling tools and environmental stressors, thereby promoting hair health and vitality (Table 2).

Table 2. Heat damage. Temperature denaturation measurement.

Hair Type	Temperature of Denaturation [°C] ¹ , n = 3
Hair before heat damage	256.7 (1.3)
Hair treated with formula with SVX after heat damage	246.8 (0.9)
Hair treated with formula without SVX after heat damage	233.9 (1.0)
Unprotected hair after heat damage	227.6 (1.5)

¹ Measured by DSC.

Table 2 demonstrates the efficacy of SVX in protecting hair fibers from heat damage, as evidenced by temperature denaturation measurements. Hair treated with a formula containing SVX after heat damage shows a denaturation temperature of 246.8 ± 0.9 °C, which is significantly higher than the 233.9 ± 1.0 °C observed in hair treated with a formula lacking SVX. This 12.9 °C difference ($p < 0.0001$) underscores the enhanced protective effect of SVX against heat. Furthermore, untreated hair exposed to heat damage denatures at a much lower temperature of 227.6 ± 1.5 °C, highlighting the substantial protection afforded by SVX.

In the color fading experiment (results shown in Figure 5, Table 3), fresh-colored hair was dipped into chlorinated water to demonstrate the damaging effects of pool water. The unprotected hair almost lost all its pigment, reverting to its natural color and becoming dry and brittle. Hair treated with a formula without SVX lost a significant amount of pigment and became very dry. However, the hair treated with the formula containing SVX retained almost the same color as freshly colored hair and maintained a smooth, soft texture. The difference in ΔE values of hair between the treatment with the formula containing SVX and the formula without SVX is 13.2 ($p < 0.0001$), underscoring the significance of SVX as a critical component for effective color protection. This experiment underscores the protective qualities of SVX, highlighting its effectiveness in preserving hair color and texture against harsh environmental conditions. SVX’s ability to shield hair from oxidative damage and moisture loss underscores its potential as a valuable ingredient in haircare formulations aimed at prolonging color longevity and enhancing hair health.



Figure 5. Color fading following exposure to chlorinated and salt water for 3 days. SVX-coated hair samples showed only minimal fading.

Table 3. Total color change under the extreme oxidative conditions of pool water.

Hair Treatment	Delta E Calculation (n = 7), Mean (SEM) ¹
Unprotected hair	23.2 (0.9)
Hair treated with formula w/o SVX	18.2 (0.5)
Hair treated with formula with SVX	5.0 (0.6)

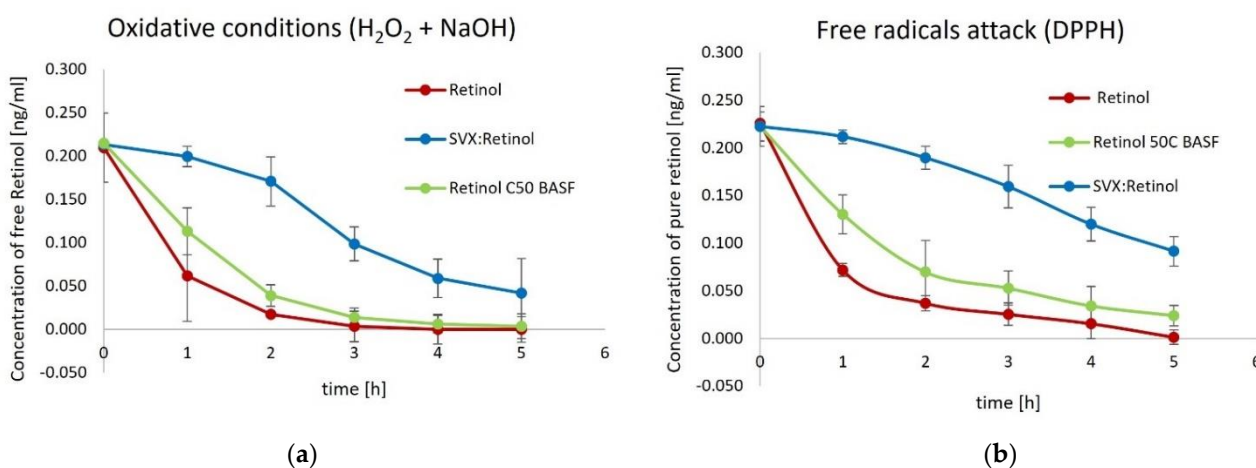
¹ Measured by ImageJ. $\Delta E = \sqrt{\{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2\}}$. ΔE is composed of the three-color units, and represents the interval between 2 points in the tri-dimensional color space—thus the difference of colors of 2 sets of L*a*b values. A high positive value indicates color is fading and/or losing the intensity.

Through its dual functionality in skincare and haircare, SVX emerges as a versatile ingredient with potential in cosmetic formulations. Its ability to create protective barriers on both skin and hair opens up new avenues for product development, catering to the diverse needs of consumers seeking effective, eco-friendly solutions for their skincare and haircare routines.

3.4. SVX—Smart Delivery System

The smart delivery system is an aspect of SVX's functionality, leveraging its properties to encapsulate and protect sensitive ingredients while enabling their controlled release [70,71]. SVX serves a dual role: It shields sensitive actives from environmental degradation and facilitates their gradual release onto the skin, enhancing efficacy and reducing potential irritation. This section presents experimental evidence supporting these capabilities.

Retinol: Retinol [72], a gold standard in skin rejuvenation, is highly sensitive to oxidation and can cause skin irritation. To evaluate the protective ability of SVX, we conducted a series of experiments exposing different retinol formulations to highly oxidative conditions (Figure 6a). Using materials including pure retinol, commercial retinol (Retinol 50C by BASF), and the SVX:retinol complex, we assessed stability in oxidative environments with hydrogen peroxide in an alkaline medium, monitored by FTIR techniques. The results clearly demonstrated that pure retinol degraded immediately, commercial retinol showed degradation over time, while the SVX:retinol complex maintained stability, preserving retinol in a fresh form. A similar experiment using a DPPH solution to expose the formulations to free radicals showed that the SVX:retinol complex had better stability compared to both pure and commercial retinol, highlighting SVX's protective capability (Figure 6b).

**Figure 6.** SVX protection of sensitive retinol: (a) under highly oxidative conditions; (b) under free radical attack.

Hyaluronic acid: In another set of experiments, we demonstrated the controlled release of hyaluronic acid (HA) using the SVX complex. SVX's porous structure, rich in various functional groups, facilitates the formation of hydrogen bonds, allowing it to absorb HA

efficiently and then release it gradually. Figure 7 shows the HA release rate from SVX in comparison to non-porous particles like silk and cellulose fibers, which can only interact with HA on the surface area. In contrast, SVX's large porous structure allows for significant absorption of HA, followed by a gradual release. The same experiments were conducted with glycolic and lactic acids, showing a similar trend. The benefit of gradual HA release is prolonged moisturization.

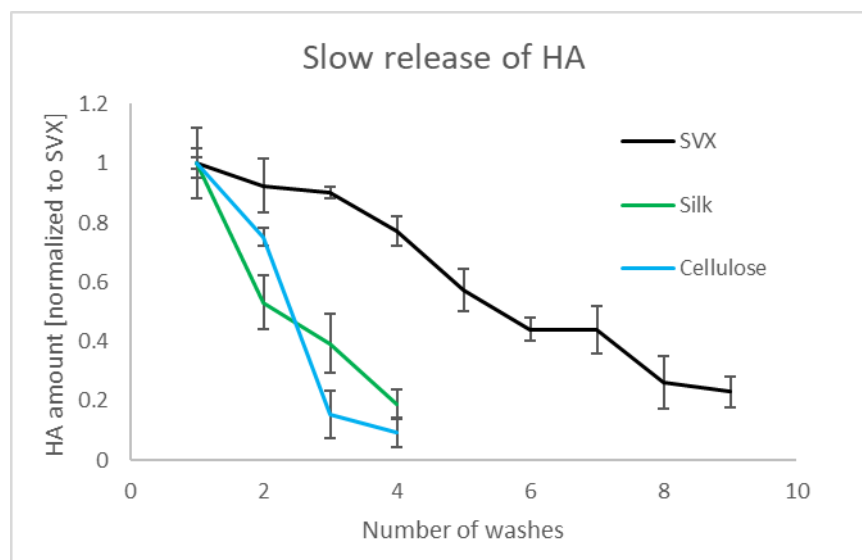


Figure 7. Slower release of hyaluronic acid (HA) measured by FTIR in comparison to non-porous silk and cellulose fibers.

This slow-release mechanism is crucial for reducing irritation while maintaining effective moisturization, addressing an unmet need in the cosmetic industry. High concentrations of HA provide prolonged hydration, but the SVX complex allows for a gentler, sustained moisturizing process.

Unlike traditional encapsulation systems, which are often sensitive to high temperatures and mechanical damage, SVX offers an alternative, making it a promising innovation for the encapsulation and delivery of sensitive cosmetic ingredients. In summary, the smart delivery capabilities of SVX enhance the stability and effectiveness of active ingredients like retinol and hyaluronic acid, offering advantages in cosmetic formulations. The dual role of protection and controlled release positions SVX as a potentially valuable addition to the field of cosmetic science.

4. Discussion

The development and application of SVX as a multifunctional biopolymer in skin and hair care formulations represent an advancement in the field. This study has demonstrated the benefits of SVX through various experiments, emphasizing its potential to enhance product performance and safety.

SVX's ability to form a skin barrier and protective layer has been substantiated through experiments using a polyurethane skin model. The application of SVX significantly enhanced the removal of PM_{2.5–10} pollution particles compared to control samples, illustrating its capacity to protect the skin from environmental pollutants. This protective barrier was also effective for hair, where SVX-treated hair maintained its color integrity better than untreated hair when exposed to seawater and pool water, highlighting its antioxidant properties that prevent color fading and structural damage.

The antioxidant capabilities of SVX were rigorously compared to vitamin C, the gold standard in skincare antioxidants. While vitamin C is known for its potency, its instability in the presence of air and water limits its efficacy. In contrast, SVX exhibited robust antioxidant

activity, maintaining its effectiveness over time and under various conditions. This stability is crucial for protecting skin and hair from oxidative stress and environmental damage.

Safety tests conducted by Bio-EC labs, including patch tests, HRIPT, phototoxicity, and ocular irritation potential, confirmed that SVX is non-irritant and non-sensitizing, making it suitable for cosmetic use. Additionally, SVX was shown to be readily biodegradable, addressing environmental concerns associated with many synthetic polymers used in cosmetics.

The smart delivery system of SVX further underscores its innovative potential. Through encapsulation experiments, SVX demonstrated superior protection and controlled release of sensitive ingredients like retinol and hyaluronic acid. Retinol, known for its skin rejuvenation benefits but prone to oxidation and irritation, was stabilized effectively within the SVX matrix. The SVX:retinol complex maintained its integrity under oxidative stress and free radical exposure, outperforming both pure retinol and commercial retinol complexes. Similarly, the SVX:HA complex provided a gradual release of HA, enabling prolonged moisturization.

These findings collectively indicate that SVX offers a multifaceted potential solution for enhancing the stability, efficacy, and safety of cosmetic formulations. Its ability to form a protective barrier, act as a potent antioxidant, and function as a smart delivery system could make it a valuable addition to the cosmetic industry's toolkit. The stability of active ingredients like retinol and HA within the SVX matrix not only improves their performance but also extends their shelf life, offering practical benefits for product development and consumer use.

The incorporation of SVX into skin and hair care products presents a promising approach to addressing common challenges in cosmetic formulations. Its multifunctional properties—ranging from environmental protection and antioxidation to smart delivery and biocompatibility—position SVX as a material with the potential to drive innovation and improve the overall effectiveness of cosmetic products. Future research should explore the long-term benefits of SVX in various formulations and its performance in broader environmental conditions to fully harness its potential in the cosmetics industry.

5. Conclusions

In conclusion, SVX emerges as a multifaceted potential solution addressing critical needs in the cosmetics industry. Through its unique properties, sustainable production process, and antioxidant activity, SVX offers a promising avenue for the development of eco-friendly, effective, and safe cosmetic formulations. By encapsulating and delivering sensitive ingredients while fortifying the skin's barrier and protecting against environmental stressors, SVX represents an advancement in cosmetic innovation, paving the way for a more sustainable and conscientious approach to skin and hair care without compromising its performance, positively changing consumers' experience.

6. Patents

This work has led to the filing of two patents that describe the cosmetic applications of the SVX biopolymer and its modifications, highlighting its multifunctional benefits in skincare and haircare formulations [12,13].

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