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"Revolutionizing Powder Characterization: A Microfluidic Biomimetic Skin Model for Screening Sustainable Alternatives"

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1. Introduction

Talc, a naturally occurring hydrated magnesium silicate found in the Earth's crust, has long been a key ingredient in numerous cosmetic formulations, including facial powders, foundations, and baby care products. Valued for its excellent absorption properties, mattifying effect, and smooth sensory feel, talc plays a critical role in controlling excess sebum and enhancing skin comfort. However, despite its undeniable functional benefits, talc has come under increased scrutiny from health authorities and the public in recent years. Several studies have raised concerns about a potential association between long-term talc exposure and serious health issues, particularly ovarian cancer. These concerns are further exacerbated by the risk of natural contamination with asbestos, a carcinogenic fibrous mineral that often coexists with talc in geological deposits. **[1-4]**

In light of these health concerns and increasing regulatory pressure, the cosmetics industry is compelled to reconsider the use of talc and to develop safe, sustainable, and high-performance alternatives. These substitute ingredients must not only exhibit a favorable toxicological profile and align with environmentally responsible practices but also deliver equivalent performance, particularly in terms of sebum absorption, shine control, and formulation stability.

Nevertheless, the rational selection of such alternatives largely relies on traditional ingredient characterization methods, such as sebum saturation tests. These tests aim to quantify the maximum amount of sebum that a given quantity of powder can absorb. Although widely used, these methods present several limitations: they often fail to accurately reflect real physiological conditions, lack standardization, and therefore hinder the objective comparison of different powders.

These tests are typically supplemented by in-depth physicochemical analyses, such as specific surface area measurement using the Brunauer-Emmett-Teller (BET) method, scanning electron microscopy (SEM), and particle size analysis by laser diffraction. These complementary techniques are time-consuming and require specialized equipment. **[5]**

To overcome these limitations and accelerate the identification of viable talc alternatives, this study employs an innovative device: the Microfluidic Biomimetic Skin (MBS) model. This microfluidic system faithfully replicates the pulsed excretion of human sebum and enables physiologically relevant evaluation of the interactions between cosmetic powders and skin-like substrates. Notably, the MBS platform provides a standardized approach to assessing surface glossy dynamics through image analysis, as the excreted sebum directly affects the visual brightness of the applied ingredients due to their physicochemical interactions. This is particularly relevant for evaluating functional ingredients already recognized for their high sebum absorption capacity, where differences in gloss and light diffusion can serve as indirect indicators of absorption performance.

Within this framework, the performance of talc is compared to that of three natural-origin powders, rice starch, activated charcoal, and bamboo powder, selected for their naturality, sustainability, and promising potential as talc replacements in cosmetic formulations. This research contributes to a broader effort toward responsible innovation, aiming to reconcile cosmetic efficacy, safety, and environmental sustainability.

2. Materials and Methods

2.1. In vitro measurement on Microfluidic Biomimetic Skin (MBS) Device

The MBS device was developed to overcome the inherent limitations of conventional cosmetic powder evaluation techniques. Rooted in advanced microfluidic engineering, the system integrates a polymer-based chip specifically designed to replicate key surface characteristics of human skin, including roughness, hydrophobicity, and porosity.

Inspired by the work of Hou et al. 2013, with targeted modifications, the surface of the MBS chip features a microfabricated structure composed of a biocompatible polymer matrix containing a high-density array of pores. These artificial pores, 400 per cm² with a diameter of 60 µm, mimic the distribution and dimensions of human sebaceous gland ducts, enabling controlled excretion of artificial sebum. The sebum reservoir, located beneath the chip, is connected to a programmable microfluidic pump that delivers the fluid at a precisely regulated flow rate, adjustable between 10 nL/min and 10 µL/min.

This microfluidic device is coupled with a state-of-the-art imaging system capable of capturing high-resolution images under both polarized and standard lighting conditions. These visual data are analyzed in real time using dedicated image analysis software, allowing for continuous monitoring and quantitative assessment of surface dynamics throughout the experiment (Figure 1).

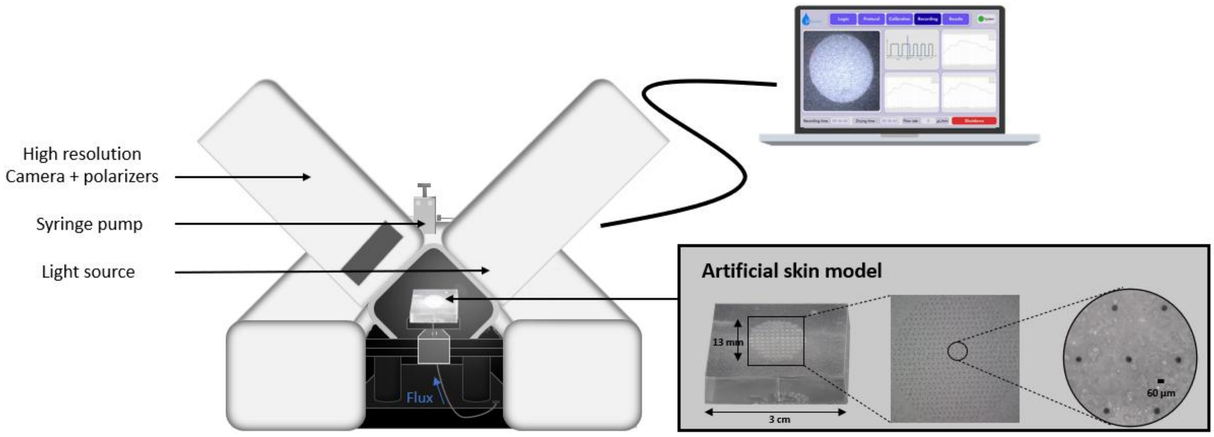

***Figure 1**. Microfluidic Biomimetic Skin (MBS) Device and artificial skin model.*

2.2. Experimental protocol on MBS Device

The powders assessed in this study included talc, used as the reference material, as well as rice starch, activated charcoal, and bamboo powder. These ingredients were selected for their natural origin, environmental sustainability, and promising potential as functional alternatives to talc. Each powder was uniformly applied to the surface of the synthetic skin model at a standardized dosage of 0.9 ±0,05 mg/cm² using a cosmetic-grade sponge to ensure consistent coverage across all samples. (Figure 2.1)

The experimental protocol uses a microfluidic system to simulate pulsed sebum excretion. Each cycle consists of a 2-minute excretion phase, during which 1.3 µL of sebum is excreted at a rate of 0.65 µL/min, followed by a 20-minute rest phase. This cycle is repeated 10 times to observe the interaction between the sebum and the applied ingredients. (Figure 2.2).

During the experiment, polarized and standard images were captured and analyzed in real-time. The analysis was performed on a Region of Interest (ROI) with a diameter of 650 pixels to ensure standardization across all measurements.

These images were then processed to quantify several key parameters, including the immediate gloss reduction following powder application, gloss variation analysis, the mean gloss, and the overall capacity for sebum absorption. (Figure 2.3). All measurements were performed in triplicate, and data are expressed as mean with standard deviation.

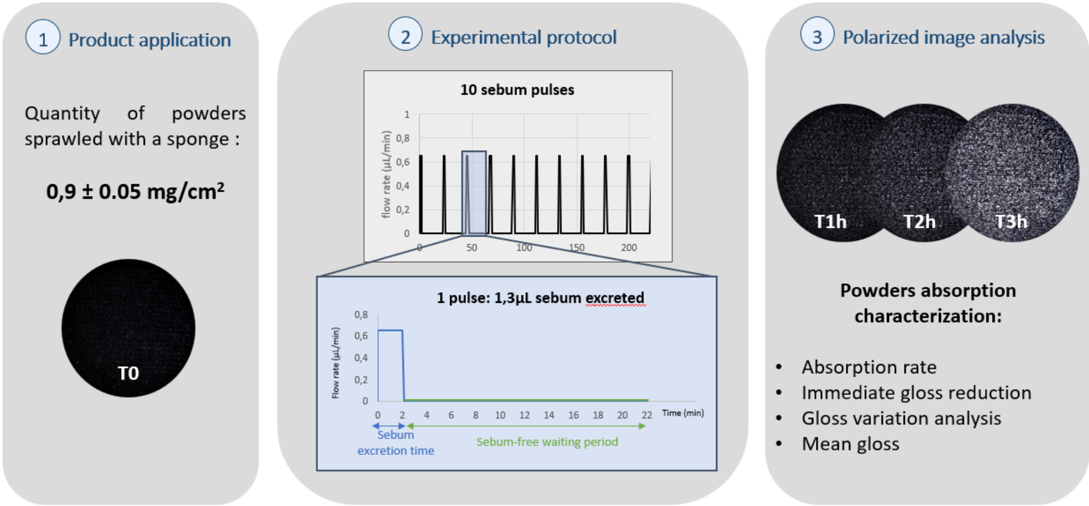

Figure 2*. Overview of the experimental protocol on MBS.*

(2.1. Initial application of the product followed by acquisition of a polarized image at T0.2.2. Execution of the experimental protocol consisting of 10 sebum excretion cycles. 2.3. Polarized image acquisition and analysis: one image is captured per minute and processed to assess brightness variation over time.)

2.3. Evaluation of Powder Physicochemical Performance

The goal of this study is to establish a correlation between the physicochemical characteristics of the powders and their performance observed in a biomimetic model. To achieve this, each powder was first analyzed using various laboratory techniques: laser diffraction to measure particle size and distribution, the BET method to assess the specific surface area, which influences absorption, and Scanning Electron Microscopy (SEM) to examine particle texture, porosity, and structure. These physical properties were then compared with the results obtained from the biomimetic model, where the powders were tested under conditions simulating sebum excretion on skin. By correlating these data, the aim is to better understand how the physical characteristics of the powders, such as size, porosity, or surface area, affect their ability to interact with sebum and perform effectively under realistic conditions.

3. Results

3.1. Powder physicochemical evaluation

The physicochemical properties of four powders, talcum powder (used as a reference), activated charcoal, bamboo powder, and rice starch, were characterized to assess their potential for sebum absorption. Scanning electron microscopy (SEM) images (Figure 3) reveal distinct morphologies among the ingredients.

Talcum powder exhibits relatively smooth and rounded particles, activated charcoal shows a porous and fragmented structure, bamboo powder presents fibrous aggregates, and rice starch is composed of smooth and compact granule. These morphological differences are consistent with the quantitative data.

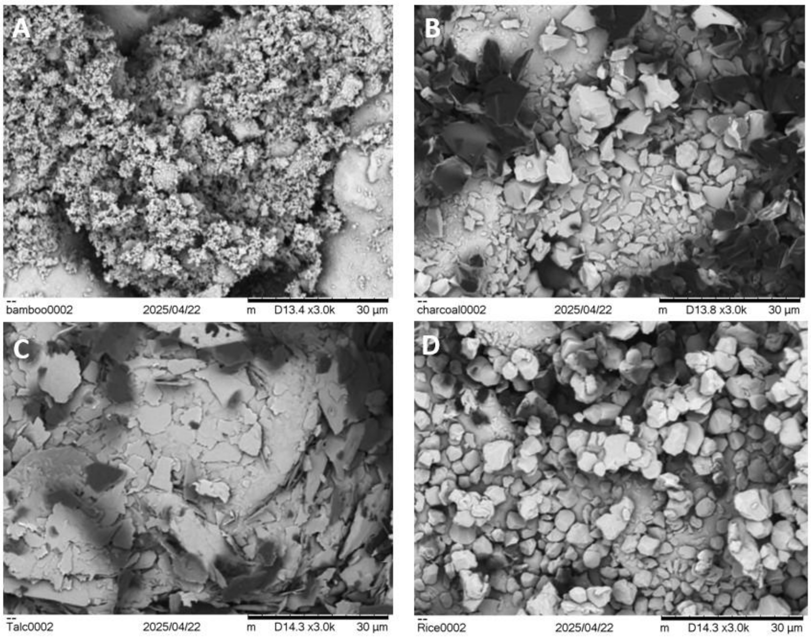

Figure 3. *Scanning electron microscopy image of the four ingredients.*
(A: Bamboo powder; B: Activated charcoal; C: Talcum powder; D: Rice starch)

If we regarding the physicochemical characteristics of the ingredients, and particularly their surface polarity, the powders range from very lipophilic (activated charcoal) to hydrophilic (rice starch), with talcum powder being moderately lipophilic and bamboo powder moderately hydrophilic. Sebum affinity follows a similar trend: low for rice starch, high for activated charcoal, and intermediate for talcum powder (good) and bamboo (medium).

Specific surface area values vary significantly, from extremely high for activated charcoal (265.5 m^2/g) to low for rice starch (0.23 m^2/g), with bamboo (1.87 m^2/g) and talcum powder (2–12 m^2/g) falling in between. In terms of porosity, activated charcoal displays the highest total pore volume (0.1637 cm^3/g), whereas talcum powder is the least porous. Bamboo and rice starch powders exhibit medium porosity. Particle size and shape also differ: bamboo powder particles are the largest (7–14 µm), followed by talcum powder (5–10 µm), rice starch (6 µm), and activated charcoal (2.5–5 µm). Finally, sebum saturation capacity (mL/g) ranges from 0.6 for talcum powder and rice starch to 1.3 for bamboo powder, with activated charcoal showing intermediate values (0.8–1).

	Rice starch	Activated charcoal	Talcum powder	Bamboo
Contact angle	Hydrophilic	Very lipophilic	Moderately lipophilic	Moderately hydrophilic
Affinity with sebum	Low	High	Good	Medium
Specific surface (m^2/g)	0,23	265,5	2-12	1,87
Porosity (total pore volume in cm^3/g)	Medium	High: 0,1637	Low	Medium
Grain shape and size (µm)	6	2,5-5	5-10	7-14
Sebum saturation (mL/g)	0,6	0,8-1	0,6	1,3

Figure 4*. Table summarizing the various physicochemical characteristics of the four ingredients.*

3.2. In vitro results: Sebum absorption capacity of the ingredients (MBS)

3.2.1. Immediate gloss reduction

The Microfluidic Biomimetic Skin (MBS) model was employed to quantify the immediate reduction in surface shine following the application of cosmetic powders. This evaluation was based on the real-time analysis of polarized images, where brightness was expressed in gray-scale values measured within a standardized region of interest (ROI) with a diameter of 650 pixels. Lower grayscale values reflect a more effective reduction in light reflection caused by the presence of sebum on the surface. These results highlight notable differences between the tested ingredients in terms of their immediate sebum-absorbing capacity.

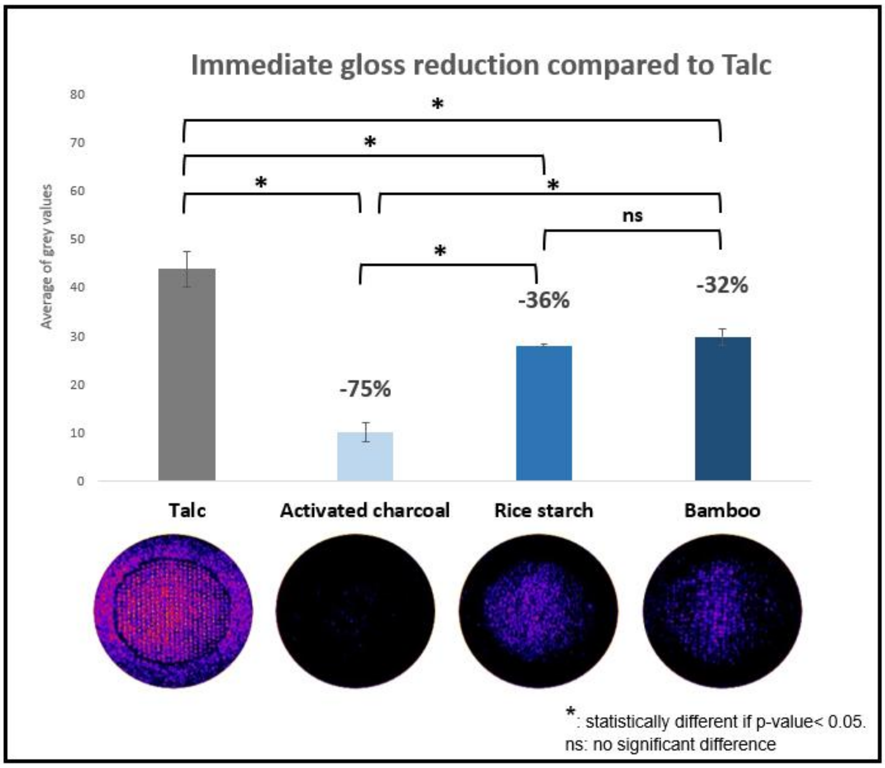

Figure 5*. Immediate gloss reduction compared to Talc.*

Talc, used as the reference material, exhibited an average brightness value of 43. In comparison, activated charcoal displayed a value of 10, corresponding to a 75% reduction relative to talc. Rice starch showed a value of 28 (−36% compared to Talc), and bamboo powder recorded a value of 29.8 (−32% compared to Talc), also indicating a significant reduction in surface gloss compared to talc.

3.2.2. Gloss variation over the sebum pulse

The results of the MBS experiment highlight distinct kinetic behaviours in terms of gloss reduction and sebum absorption for each ingredient. The sebum pulses, represented by the black curve, illustrate the periodic excretion of artificial sebum, allowing the observation of the interactions between the powders and the sebum throughout the experiment (Figure 6).

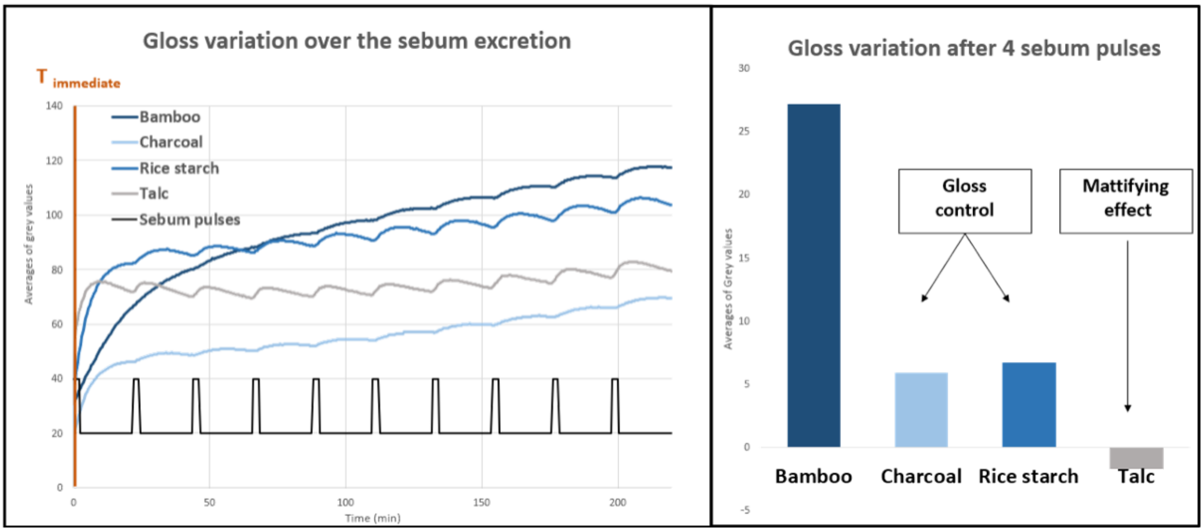

Figure 6. *Gloss variation over the sebum excretion and Gloss variation after 4 sebum pulses.*

Activated charcoal shows an immediate and stable gloss reduction for about 100 minutes, followed by a slight increase, while consistently maintaining the lowest grayscale values, indicating strong sebum absorption. Talc displays a similar initial behavior, with gloss stabilizing around 150 minutes and slightly increasing thereafter, reflecting moderate performance. Bamboo powder starts with very low gloss, rising rapidly from 30 to 80 within 50 minutes and continuing to increase up to 120, suggesting fast and sustained interaction with sebum. Rice starch remains stable for the first 120 minutes, then gradually increases in gloss, ending below bamboo, talc, and charcoal.

An analysis was conducted over the first four sebum pulses, which together represent an excreted volume exceeding 5.2 µL, comparable to the average sebum production observed over a 24-hour period on oily human skin. This analysis shows that bamboo powder undergoes a significant increase in gloss (Figure 6), indicating poor gloss control. In contrast, activated charcoal and rice starch maintain stable gloss levels, demonstrating effective gloss regulation. Talc shows a gradual gloss reduction, reflecting a slight mattifying effect.

4. Discussion

The kinetic profile of gloss variation, measured with the Microfluidic Biomimetic Skin (MBS) model in response to periodic sebum excretion, provides valuable insights into the functional performance of absorbent powders under biomimetic conditions. The results show that activated charcoal and rice starch maintain low and stable gloss levels during the initial sebum pulses, indicating an efficient and rapid absorption of surface lipids. In contrast, bamboo powder exhibits a marked increase in gloss early in the process, reflecting rapid surface saturation and a limited ability to control gloss dynamically. Talc shows intermediate behaviour, with a gradual and moderate gloss reduction, suggesting a mild mattifying effect that is more stable than that of bamboo powder. These results allow a clear distinction between the powders in terms of their ability to regulate surface shine in a context simulating oily human skin over time.

These functional observations can be directly correlated with each powder's intrinsic physicochemical properties. Activated charcoal, characterized by its highly porous, lipophilic structure and very large specific surface area, demonstrates the strongest sebum absorption performance, maintaining a stable gloss reduction for up to 100 minutes. Talc, with moderate porosity, shows consistent absorption for approximately 150 minutes, after which gloss levels begin to rise again due to its lower saturation capacity. Although bamboo powder has a high saturation potential, it proves less effective overall, likely because of its large particle size, which impairs sebum retention. Rice starch maintains stable gloss levels thanks to its hydrophilic nature and compact morphology, although its overall absorption capacity remains constrained by its low saturation threshold.

These physicochemical characteristics, such as structure, polarity, and surface area, emerge as decisive factors in the powders' real-time performance on the MBS model. To deepen this analysis, we applied a predictive model based on a weighted scoring system that incorporates seven physicochemical parameters: contact angle (A), sebum affinity (C), specific surface area (S), porosity (P), particle size (T), surface roughness (R), and density (D). **[6-10]** Each parameter contributes to the global absorption score according to the following equation:

$$S_{absorption} = 5A + 4C + 4S + 3P + 2T + 1R + 1D$$

Criteria (From 1 to 5)	Weighted scoring	Definition	Rice starch	Talc	Activated charcoal	Bamboo
Contact angle	5	Wettability of powder surface by sebum (lower is better)	3	3	3	2
Affinity	4	Surface chemistry compatibility with lipids	3	3	4	2
Specific surface	4	Total surface area available for absorption (BET method)	3	4	5	3
Porosity	3	Volume and connectivity of pores influencing capillarity	3	4	5	3
Grain size	2	Influences surface area and sebum retention	4	3	3	5
Rugosity	1	Microscale texture affecting mechanical trapping of sebum	2	2	2	1
Density	1	Inverse of powder packing; affects space for liquid penetration	2	2	3	2
TOTAL	100		60	65	77	52

***Figure 7**. Table summarizing the parameters used for the simplified equation of the absorbent capacities of ingredients.*

The multi-parametric scoring system allows for a quantitative and rational comparison of powders based on their physicochemical characteristics. In the table above, each ingredient was assessed across seven criteria, each weighted according to its relative impact on sebum absorption efficiency. The resulting scores, expressed on a scale of 100, provide a clear and intuitive ranking. Activated charcoal emerges as the top-performing ingredient, with a score of 77, reflecting its high surface area, porosity, and lipophilic affinity. Talc, used as the benchmark, scores 65, showing solid all-around properties but lacking the porosity and surface area of charcoal. Rice starch obtains 60, supported by fine particle size and good wettability, but limited by its low affinity with lipids. Finally, bamboo powder scores 52, penalized by its larger particle size and lower affinity, despite a decent porous structure.

This ranking is highly consistent with the functional behavior observed on the MBS (Microfluidic Biomimetic Skin) model, confirming the robustness of the scoring approach. By aligning theoretical scoring with real-world absorption dynamics, this model proves to be a powerful tool for pre-screening ingredients and guiding formulation choices in the search for effective talc alternatives.

5. Conclusion

In a context of increasing scrutiny over talc use, this study aims to identify safe and sustainable alternatives by applying a dual evaluation strategy. This approach combines a predictive scoring model, grounded in physicochemical parameters, with a dynamic in vitro assessment using the Microfluidic Biomimetic Skin (MBS) model. The scoring model provides a structured and rational framework for estimating ingredient performance based on measurable properties.

However, it also illustrates the inherent complexity of sebum absorption, arising from the interplay of multiple factors such as surface affinity, porosity, particle morphology, and capillarity. Even well-constructed models may fall short in predicting subtle real-world behaviors.

Despite these limitations, the scoring approach enabled the theoretical ranking of powders, with activated charcoal emerging as a particularly promising alternative to talc. This ranking showed excellent alignment with the dynamic gloss reduction profiles observed via the MBS model, reinforcing the correlation between static physical characteristics and functional performance under biomimetic conditions.

One of the key advantages of the MBS platform is its independence from prior physicochemical data. By mimicking human sebum secretion and capturing real-time image data, it offers a direct and kinetic insight into ingredient behavior, including the stability of absorption over time, an aspect often overlooked in conventional test protocols.

Together, these complementary methodologies form a robust and integrated strategy for screening and validating talc alternatives by directly comparing talc with natural-origin powders such as rice starch, activated charcoal, and bamboo, thereby supporting the development of cosmetic formulations that not only replicate talc's performance in sebum absorption and shine control, but also advance broader goals of safety, sustainability, and health-conscious innovation.

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