

SUSTAINABLE COSMETICS: GREEN FORMULATIONS, ECO-FRIENDLY PACKAGING, AND CONSUMER TRENDS

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Abstract- Sustainable cosmetics have emerged as a significant trend in the global beauty and personal care industry, driven by growing environmental awareness, regulatory pressures, and evolving consumer preferences for safer and eco-friendly products. Green formulations emphasize the use of natural, biodegradable, and renewable ingredients while minimizing harmful chemicals and environmental impact. Advances in green chemistry, biotechnology-derived actives, and sustainable sourcing practices are supporting the development of effective yet environmentally responsible cosmetic products. Eco-friendly packaging innovations, including recyclable, biodegradable, refillable, and reduced-plastic materials, further contribute to sustainability goals by lowering waste generation and carbon footprint. Additionally, changing consumer trends such as clean beauty, ethical purchasing,

transparency, and environmentally conscious lifestyles are influencing product development and marketing strategies within the cosmetic sector. Despite notable progress, challenges remain related to ingredient standardization, regulatory compliance, cost implications, and verification of sustainability claims. Continued research, technological innovation, and collaborative industry efforts are essential to ensure that cosmetic products achieve both environmental sustainability and high performance while meeting consumer expectations.

Keywords: Sustainable cosmetics; Green formulations; Eco-friendly packaging; Cosmetic sustainability; Biotechnology-derived actives; Environmental impact; Sustainable skincare; Cosmetic innovation.

I. Introduction

Sustainable cosmetics have emerged as a major focus within the global personal-care

industry due to increasing environmental awareness, stricter regulatory expectations, and evolving consumer preferences for safer and more responsible products. Modern consumers are increasingly concerned about the ecological and health impacts of cosmetic products, including ingredient toxicity, environmental pollution, ethical sourcing, and packaging waste. As a result, cosmetic manufacturers are shifting toward sustainability-oriented practices that prioritize environmental protection, human safety, and social responsibility while maintaining product efficacy and quality. Sustainable cosmetics emphasize not only the use of environmentally friendly ingredients but also responsible manufacturing processes, ethical sourcing, reduced carbon emissions, and transparent communication with consumers.

The concept of sustainability in cosmetics extends beyond ingredient selection to encompass the entire product lifecycle. This includes raw material sourcing, formulation development, packaging design, distribution, product usage, and disposal. Lifecycle assessment approaches are increasingly used to evaluate environmental impacts such as greenhouse gas emissions, water consumption, resource depletion, and waste generation. These assessments help

manufacturers identify areas for improvement and adopt strategies that reduce ecological footprints. Sustainable cosmetic production also involves waste minimization, energy-efficient manufacturing, renewable resource utilization, and implementation of environmentally friendly processing technologies. Such integrated approaches contribute to the broader goal of achieving environmentally responsible and economically viable cosmetic innovation.

Regulatory agencies worldwide play a crucial role in promoting sustainability and safety in cosmetic products. Organizations such as the European Union have introduced stringent regulations governing cosmetic safety, chemical usage, labeling transparency, and environmental impact. Similarly, the U.S. Food and Drug Administration monitors cosmetic safety standards and encourages responsible manufacturing practices. International guidelines from the International Organization for Standardization further support sustainable production by establishing quality, environmental management, and safety standards applicable to the cosmetic industry. These regulatory frameworks not only protect consumer health but also encourage

companies to adopt greener technologies, safer ingredients, and sustainable sourcing practices.

Green chemistry has become a fundamental driver of sustainable cosmetic innovation. This approach focuses on designing chemical processes and formulations that minimize hazardous substances, reduce waste, and enhance environmental compatibility. Cosmetic scientists are increasingly replacing synthetic chemicals with naturally derived, biodegradable alternatives obtained from renewable plant, marine, or microbial sources. Biotechnology-derived ingredients, including biofermented actives and enzyme-based formulations, are gaining popularity because they offer high purity, consistency, and reduced environmental impact compared with conventional extraction methods. Additionally, sustainable ingredient sourcing emphasizes fair trade practices, biodiversity conservation, and ethical labor conditions, aligning cosmetic development with broader social responsibility goals.

Packaging sustainability has also become a major area of focus in cosmetic innovation. Conventional cosmetic packaging often relies heavily on plastic materials, which

contribute significantly to environmental pollution and landfill accumulation. To address this challenge, manufacturers are adopting recyclable, biodegradable, refillable, and reduced-plastic packaging solutions. Advances in material science have enabled the development of bio-based plastics, compostable packaging materials, and lightweight designs that minimize resource consumption while maintaining product integrity. Refillable packaging systems and circular economy models are increasingly being implemented to reduce waste generation and encourage responsible consumer behavior. These initiatives not only support environmental sustainability but also enhance brand reputation and consumer trust.

Consumer awareness and behavior play a crucial role in driving the adoption of sustainable cosmetics. The growing popularity of “clean beauty,” eco-conscious lifestyles, and ethical consumption has influenced purchasing decisions worldwide. Consumers increasingly seek products that are cruelty-free, vegan, biodegradable, and produced using environmentally responsible methods. Transparency in ingredient disclosure, sustainability certifications, and ethical sourcing claims has become essential for building consumer confidence. Social

media, environmental activism, and increased access to scientific information have further heightened consumer expectations regarding product safety, sustainability, and corporate accountability.

Technological advancements continue to support the development of sustainable cosmetic solutions. Innovations in green formulation science, biotechnology, nanotechnology, and digital supply-chain management enable manufacturers to optimize resource utilization, improve ingredient stability, and reduce environmental impact. Artificial intelligence and data-driven approaches are also being explored to design efficient formulations, predict ingredient interactions, and optimize sustainability metrics. Such technological integration supports the development of high-performance cosmetic products that align with environmental and ethical considerations.

Despite significant progress, several challenges remain in achieving comprehensive sustainability in cosmetics. These include higher costs of sustainable raw materials, variability in natural ingredient quality, regulatory inconsistencies across regions, and difficulties in verifying environmental claims. Additionally,

balancing product performance with environmental responsibility requires continuous research, innovation, and interdisciplinary collaboration among cosmetic chemists, dermatologists, environmental scientists, and industry stakeholders.

II. Green Formulations in Cosmetics

2.1 Natural and Bio-Based Ingredients

Green formulations in cosmetics emphasize the use of renewable, naturally derived, and biodegradable ingredients as alternatives to conventional petrochemical-based components. This shift is largely driven by increasing environmental awareness, regulatory encouragement for safer chemicals, and consumer preference for sustainable and “clean label” products. Natural ingredients such as botanical extracts, plant oils, essential oils, herbal actives, and naturally derived emulsifiers are widely incorporated into cosmetic products due to their lower ecological impact and favorable safety profiles.

Plant-derived compounds often possess multifunctional biological properties that enhance both product efficacy and sustainability. For example, botanical extracts rich in polyphenols, flavonoids,

vitamins, and carotenoids provide antioxidant protection against oxidative stress and environmental damage to the skin. Natural oils such as jojoba, argan, coconut, and almond oil serve as emollients that improve skin hydration while maintaining compatibility with the skin barrier. Similarly, naturally derived surfactants from coconut or sugar-based sources offer mild cleansing action with reduced irritation potential compared to synthetic detergents.

Bio-based polymers such as cellulose derivatives, chitosan, and alginate are increasingly used as thickeners, film-forming agents, and stabilizers in cosmetic formulations. These materials are biodegradable and exhibit minimal environmental persistence. Moreover, advances in green extraction technologies, including supercritical fluid extraction, ultrasound-assisted extraction, and microwave-assisted extraction, allow efficient recovery of bioactive compounds with reduced solvent usage and energy consumption.

Despite their advantages, natural ingredients present certain challenges, including variability in composition, potential allergenicity, stability issues, and microbial contamination risks. Standardization, quality

control, and proper preservation strategies are therefore essential to ensure safety, consistency, and long-term product stability. Overall, the integration of natural and bio-based ingredients represents a critical component of sustainable cosmetic innovation while supporting both environmental responsibility and consumer demand for safer skincare products.

2.2 Green Chemistry Principles

The application of green chemistry principles in cosmetic formulation has become increasingly important as the industry seeks to reduce environmental impact and improve product safety. Green chemistry focuses on designing chemical processes and products that minimize hazardous substances, reduce waste generation, conserve energy, and utilize renewable resources. These principles are particularly relevant in cosmetic manufacturing, where large-scale production and extensive chemical processing can significantly affect environmental sustainability.

One important aspect of green chemistry in cosmetics is the reduction or elimination of toxic solvents and synthetic additives. Solvent-free formulations, water-based systems, and biodegradable solvents are

increasingly preferred over volatile organic compounds that contribute to environmental pollution. Low-energy manufacturing processes, including cold emulsification and low-temperature processing, help reduce energy consumption and carbon emissions while maintaining product quality.

Enzymatic synthesis has also gained attention as a sustainable alternative to traditional chemical synthesis. Enzymes operate under mild conditions, generate fewer by-products, and exhibit high specificity, leading to improved efficiency and reduced environmental burden. For example, enzymatic esterification is used to produce emollients and surfactants with enhanced biodegradability.

Waste minimization is another critical component of green cosmetic production. Recycling of raw materials, optimization of manufacturing processes, and implementation of closed-loop systems help reduce industrial waste. Additionally, life-cycle assessment (LCA) tools are increasingly applied to evaluate the environmental impact of cosmetic products from raw material sourcing to disposal.

Green chemistry also encourages safer product design, including the use of non-toxic preservatives, biodegradable colorants,

and environmentally friendly fragrance components. These approaches not only reduce ecological toxicity but also improve consumer safety. Although implementing green chemistry can involve initial costs and technical challenges, long-term benefits include regulatory compliance, improved brand reputation, and sustainable business growth.

2.3 Biotechnology-Derived Actives

Biotechnology has emerged as a transformative approach in sustainable cosmetic formulation by enabling the production of high-quality active ingredients through environmentally responsible methods. Techniques such as microbial fermentation, plant cell culture, enzyme biotechnology, and bioengineering allow the controlled production of cosmetic actives with reduced dependence on agricultural resources and minimal environmental impact.

Microbial fermentation is widely used for producing bioactive compounds such as hyaluronic acid, peptides, amino acids, vitamins, and antioxidants. These ingredients are valued for their moisturizing, anti-aging, and skin-repair properties. Fermentation processes are highly efficient, scalable, and capable of producing

consistent, high-purity ingredients with reduced batch-to-batch variability.

Plant cell culture technology offers another sustainable alternative to traditional crop harvesting. Through controlled laboratory cultivation of plant cells, valuable phytochemicals can be produced without extensive land use, pesticides, or seasonal variability. This approach supports biodiversity conservation while ensuring reliable ingredient supply.

Advances in synthetic biology and genetic engineering have further enhanced the potential of biotechnology-derived cosmetic actives. Tailored peptides, growth factors, and bioengineered antioxidants can be developed to target specific skin concerns such as aging, hyperpigmentation, inflammation, and barrier dysfunction. These precision-designed ingredients contribute to the growing field of personalized skincare.

Biotechnology also supports sustainability by reducing water consumption, energy requirements, and carbon emissions associated with conventional agricultural production. Additionally, bio-based manufacturing often generates fewer hazardous by-products, aligning with environmental regulations and sustainable development goals.

However, the adoption of biotechnology in cosmetics requires careful safety evaluation, regulatory approval, and consumer acceptance. Transparent labeling, ethical sourcing, and clear communication about biotechnology processes are essential to build consumer trust. Despite these considerations, biotechnology-derived actives represent a promising pathway for sustainable cosmetic innovation, offering both environmental benefits and enhanced product performance.

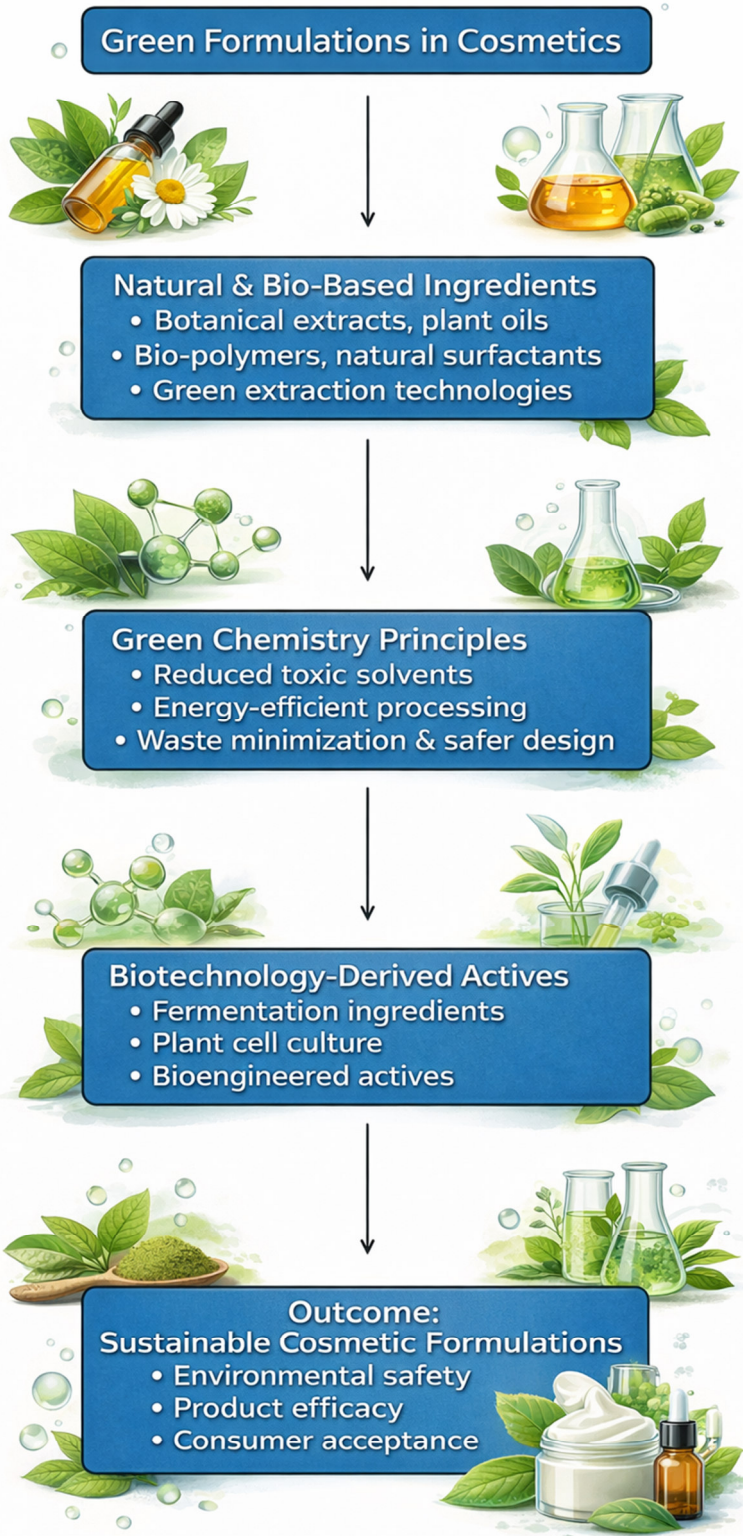


Figure 1. Formulation flow chart in cosmetics

III. Eco-Friendly Packaging Solutions

3.1 Biodegradable and Recyclable Materials

Packaging plays a crucial role in the environmental footprint of cosmetic products, often contributing significantly to plastic waste, carbon emissions, and resource depletion. In response, the cosmetic industry is increasingly shifting toward biodegradable, recyclable, and renewable packaging materials. Biodegradable plastics derived from plant sources such as polylactic acid (PLA), starch blends, and cellulose-based materials are gaining popularity because they break down more easily under environmental conditions compared with conventional petroleum-based plastics. These materials help reduce long-term environmental pollution and landfill accumulation.

Recycled polymers, including post-consumer recycled (PCR) plastics, are also widely used in cosmetic packaging. Utilizing recycled materials conserves natural resources, reduces energy consumption during production, and supports circular economy initiatives. Traditional materials such as glass, aluminum, and paper-based packaging

remain highly sustainable due to their recyclability and lower environmental persistence. Glass and aluminum, in particular, can be recycled multiple times without significant loss of quality, making them attractive choices for premium cosmetic products.

However, challenges such as cost, material durability, and compatibility with cosmetic formulations must be addressed. Ensuring that sustainable materials maintain product stability, safety, and aesthetic appeal remains a key consideration for manufacturers seeking environmentally responsible packaging solutions.

3.2 Minimalist and Refillable Packaging

Another important trend in sustainable cosmetic packaging is the adoption of minimalist design strategies and refillable packaging systems. Minimalist packaging focuses on reducing unnecessary layers, excessive decorative elements, and bulky containers. By optimizing packaging size and eliminating redundant materials, companies can significantly reduce waste generation, transportation costs, and carbon emissions.

Refillable packaging systems are gaining widespread acceptance among

environmentally conscious consumers. These systems typically involve durable outer containers designed for repeated use, while refill cartridges or pouches supply the cosmetic product. This approach reduces single-use plastic consumption and promotes responsible consumption behavior. Many cosmetic brands now offer refill stations in retail stores or subscription-based refill services to encourage sustainable purchasing habits.

Additionally, concentrated formulations requiring smaller packaging volumes are becoming more common. Products such as solid shampoos, concentrated serums, and waterless cosmetics reduce packaging requirements while also lowering transportation emissions due to decreased product weight. These innovations align with broader sustainability goals and reflect changing consumer expectations toward environmentally responsible products.

3.3 Life-Cycle Assessment (LCA)

Life-cycle assessment (LCA) has emerged as an essential tool for evaluating the environmental impact of cosmetic packaging from raw material extraction to manufacturing, distribution, use, and final disposal. This comprehensive analytical approach allows manufacturers to identify

environmental hotspots and implement strategies for reducing ecological impact throughout the product lifecycle.

LCA helps companies make informed decisions regarding material selection, manufacturing processes, transportation methods, and waste management practices. For example, it can reveal whether recyclable materials, biodegradable options, or reusable packaging provide the most sustainable outcomes under specific conditions. Such insights guide eco-design strategies and encourage more responsible resource utilization.

Furthermore, lifecycle assessment enhances transparency and credibility in sustainability claims. Consumers are increasingly interested in environmentally responsible products, and LCA-supported data provide scientific validation for green marketing claims. Regulatory agencies and industry standards also encourage lifecycle-based evaluations to ensure accurate environmental reporting and prevent misleading sustainability assertions.

IV. Consumer Trends Driving Sustainable Cosmetics

4.1 Ethical Consumerism

Ethical consumerism has become a powerful force shaping the cosmetic industry, with consumers increasingly prioritizing products that align with their environmental and social values. Many buyers now prefer cruelty-free, vegan, and ethically sourced cosmetics that avoid animal testing, animal-derived ingredients, and exploitative labor practices. Transparency regarding ingredient sourcing, supply-chain ethics, and manufacturing practices plays a significant role in purchasing decisions. Consumers expect brands to disclose information about sustainability initiatives, environmental impact, and corporate responsibility. This shift toward conscious consumption has encouraged companies to adopt ethical sourcing policies, environmentally responsible manufacturing, and clear labeling practices to build consumer trust and loyalty.

4.2 Clean Beauty Movement

The clean beauty movement has gained considerable momentum as consumers seek safer, non-toxic, and environmentally friendly cosmetic products. This trend emphasizes formulations free from controversial ingredients such as parabens, sulfates, phthalates, synthetic fragrances, and certain preservatives that are perceived

to pose potential health or environmental risks. Although definitions of “clean beauty” vary across brands and regulatory bodies, the underlying goal is to provide products that are both safe for consumers and environmentally responsible. Increased scientific awareness, media influence, and health-conscious lifestyles have contributed to growing demand for cleaner formulations. As a result, cosmetic manufacturers are investing in alternative preservatives, naturally derived actives, and safer formulation strategies to meet evolving consumer expectations.

4.3 Digital Awareness and Transparency

Digital platforms have significantly influenced consumer awareness regarding sustainability in cosmetics. Social media, online reviews, sustainability reports, and environmental campaigns have empowered consumers to access detailed information about product ingredients, environmental impact, and brand ethics. Certification labels and eco-labeling programs also help consumers make informed decisions by providing standardized indicators of sustainability performance. Certifications related to organic production, fair trade practices, cruelty-free status, and environmentally friendly packaging enhance

credibility and influence brand perception. Digital transparency has increased accountability among cosmetic companies, encouraging them to adopt more responsible practices while communicating sustainability initiatives clearly to their target audience.

4.4 Sustainability as Brand Value

Sustainability has increasingly become a central element of brand identity within the cosmetic industry. Companies are integrating environmental responsibility into their corporate strategies, marketing communication, and product development processes. Sustainable branding includes

responsible sourcing, eco-friendly packaging, reduced carbon emissions, ethical labor practices, and community engagement initiatives. Such strategies not only appeal to environmentally conscious consumers but also strengthen long-term competitiveness and brand reputation. Corporate social responsibility initiatives, sustainability reporting, and transparent communication further reinforce consumer trust. As sustainability continues to influence purchasing behavior, companies that prioritize environmental stewardship and social responsibility are likely to gain a competitive advantage in the evolving cosmetic market.

Table.1. Consumer Trends Driving Sustainable Cosmetics

Trend Area	Key Focus	Main Consumer Expectations	Industry Response / Impact
Ethical Consumerism	Environmentally and socially responsible cosmetic choices	Preference for cruelty-free, vegan, ethically sourced products; transparency in sourcing, labor practices, and sustainability initiatives	Adoption of ethical sourcing, responsible manufacturing, transparent labeling, and corporate social responsibility programs to build consumer trust
Clean Beauty Movement	Safer and environmentally friendly	Demand for products free from parabens, sulfates, phthalates, synthetic	Development of alternative preservatives, naturally derived actives,

	formulations	fragrances, and other controversial chemicals; emphasis on non-toxic ingredients	safer formulations, and increased research on ingredient safety
Digital Awareness & Transparency	Information accessibility through digital platforms	Expectation of ingredient transparency, sustainability reporting, eco-certifications, and authentic brand communication	Increased sustainability disclosures, eco-labels, online education, and greater brand accountability through social media and reporting
Sustainability as Brand Value	Integration of sustainability into brand identity	Preference for brands demonstrating environmental responsibility, ethical practices, and social commitment	Sustainable branding strategies, eco-friendly packaging, reduced carbon footprint initiatives, and stronger sustainability marketing

V. Challenges in Sustainable Cosmetic Development

Sustainable cosmetic development has advanced considerably, yet several important challenges remain. Natural and bio-based ingredients often show variability in composition, quality, and shelf stability compared with synthetic counterparts, which can affect product consistency. Ensuring long-term stability without synthetic preservatives is another technical difficulty.

Sustainable packaging materials, although environmentally beneficial, may face higher costs, limited durability, and scalability constraints in large-scale production. Supply-chain sustainability also presents challenges, particularly regarding ethical sourcing and resource availability. Greenwashing, or misleading environmental claims, continues to create confusion among consumers and calls for stricter regulatory oversight. Achieving transparency in labeling and certification remains essential

to build consumer trust. Additionally, balancing product efficacy, safety, affordability, and environmental impact requires careful formulation strategies. Regulatory differences across regions can further complicate global product development. Research into alternative preservatives, biodegradable materials, and sustainable processing technologies is still evolving. Consumer expectations for both performance and sustainability place additional pressure on manufacturers. Overall, continued scientific innovation and regulatory clarity are necessary to overcome these challenges and ensure genuinely sustainable cosmetic products.

VI. Future Perspectives

Future developments in sustainable cosmetics are expected to emphasize biodegradable and environmentally compatible formulations that reduce ecological impact. Carbon-neutral manufacturing processes, including renewable energy use and efficient resource management, are likely to become industry standards. Advances in biotechnology will support sustainable production of high-purity cosmetic ingredients through fermentation and bioengineering techniques. Artificial intelligence and predictive

modeling may assist in designing eco-friendly formulations while maintaining product efficacy and safety. Circular economy approaches, such as refillable packaging, recycling initiatives, and waste valorization, are expected to expand significantly. Greater transparency in supply chains will enhance consumer confidence and regulatory compliance. Sustainable sourcing of raw materials will remain a priority for manufacturers. Increasing global regulatory harmonization may help standardize sustainability guidelines across markets. Consumer awareness and education about environmental impact will continue to drive demand for green products. Collaboration among scientists, industry, and policymakers will support innovation. Continued research into biodegradable materials and green chemistry is essential. Overall, sustainability will remain a central pillar of future cosmetic development.

VII. Conclusion

Sustainable cosmetics represent a significant shift toward environmentally responsible and ethically conscious beauty products. These formulations aim to balance product efficacy, consumer safety, and ecological sustainability. The adoption of green chemistry principles and biotechnology-

derived ingredients has improved both performance and environmental compatibility. Eco-friendly packaging solutions, including recyclable and biodegradable materials, further support sustainability goals. Growing consumer awareness has accelerated demand for transparency, ethical sourcing, and clean formulations. Despite these advances, challenges such as higher costs, ingredient variability, and regulatory inconsistencies still persist. Ensuring product stability and scalability while maintaining sustainability remains a key research focus. Collaboration among scientists, manufacturers, regulators, and consumers is essential for progress. Clear labeling and responsible marketing practices can reduce misinformation and build trust. Continued innovation in sustainable design and manufacturing will strengthen industry resilience. Environmental stewardship must remain central to cosmetic development. Overall, sustainable cosmetics are poised to play a vital role in shaping the future of responsible beauty.

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