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An Approach towards Ecological Sustainability in the Beauty Industry

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Abstract

The beauty industry is one of the most profitable and influential sectors globally, which means it has social, environmental, and moral responsibilities. Identifying and implementing strategies to meet these obligations is a significant challenge for the beauty industry. This study provides an overview of the leading technologies currently being investigated as alternatives for sustainability in the beauty industry. Discusses the industry's environmental impact and identifies the critical drivers for change. The literature review classifies the approaches to ecological sustainability in the beauty industry into four categories: biotech beauty, bioremediation, bioeconomy/circular bioeconomy, and biomimicry. The essential characteristics considered in each approach were deduced biocompatibility, biodegradability, biomass-based materials, and expression biology. It will be a sustainable long-term solution to ensure that the beauty industry, with its extensive resource consumption and expansive supply chain, does not negatively impact the ecosystem.

Keywords

beauty industry, sustainability, ecological

1. Introduction

Presently, sustainability is usually defined as the processes and actions through which humankind avoids the depletion of natural resources to maintain an ecological balance that does not decrease the quality of life of modern societies (Rawof, 2021). With the rise in demand for natural and greener products in the beauty industry, concerns arise about sustainability (Almendinger et al., 2020). Natural plant-based active ingredients are typically positioned as safer and more environmentally friendly. However, many plant- and animal-based ingredients require large amounts of farmland, water, and

energy, leaving a large carbon footprint (https://impag.ch). Natural fragrances are perceived as more environmentally friendly, healthier, and renewable, but they might pose sustainability problems, exemplified by the massive deforestation they cause (Martins et al., 2023). VOCs in fragrances and sprays cause smog and air pollution (Steinemann et al., 2021).

Furthermore, the beauty industry significantly impacts the planet's water quality. Synthetic antioxidants used as cosmetic preservatives enter aquatic species and cause genetic alteration (Goyal et al., 2023). In addition, the environmental impact of conventional cosmetics made of microbeads, microplastic, and triclosan is vast and calls for serious attention (Anagnosti et al., 2021). Cleansing products are the primary concern in this phase because water is used to apply and rinse off the product, alongside water heating in some cases, which consumes energy (Cosmetics Europe, 2019). Furthermore, the water that goes down the drain affects the aquatic environment due to non-sustainable ingredients, such as the microplastics mentioned previously. Another aspect of sustainability is how the beauty products are packaged and delivered. Cosmetic packaging combines different materials, complicating recycling (Goyal et al., 2023). It represents one of the most significant environmental challenges facing the beauty industry. The present study discusses sustainable approaches to mitigating the environmental impact of the beauty industry.

2. Method

In this study, we provided a comprehensive literature review that addressed the primary research regarding the ecological sustainability of the beauty industry. The literature review drew upon various sources, including online databases such as Google Scholar and Google platforms and scientific and non-scientific websites, articles, and periodicals. Additionally, we incorporated new information throughout the research and manuscript writing process.

We used the following keywords, alone or in combination: "beauty industry", "biotechnology", "sustainability", "cosmetics", "beauty", "microbes", and other words. To obtain the most relevant articles to the primary goal of this review, namely ecological sustainability in the beauty industry, we considered full-text English-language articles, preferably published in the last ten years. Consequently, the literature analyzed was limited to those published between 2009 and 2024.

3. An Approach to Ecological Sustainability in the Beauty Industry

3.1 Biotech Beauty

Biotech beauty is a technology that employs microorganisms (bacteria, yeast, and algae) to generate active ingredients in actives for effective results sustainably. The components that come out of the process are a mix of microorganisms (bio) and microbe-engineered DNA (tech) due to this manufacturing process, hence the word biotech (https://explorebiotech.com). Microorganisms are

favorable resources since producing metabolites from microbes is feasible, and scale-up can be achieved in large quantities at a reasonable cost (Gupta et al., 2019). Moreover, they are a rich source of new bioactive chemicals because they give rise to high yields and productivity (Wang et al., 2018). One of the significant advantages of microbial metabolites is their suitability in high demand for "natural", "biodegradable", and "eco-friendly", for instance (Barreto et al., 2023).

Microbes are used in cosmetics for various purposes. They can enhance product attributes, substitute chemical compounds, and provide beneficial properties such as biosurfactants, vitamins, antioxidants, pigments, enzymes, and peptides (Bhat et al., 2021). Marine microbial-derived bioactive compounds and enzymes are also attractive for cosmetic applications (Zhang et al., 2023). The marine environment selects for species of microorganisms with metabolic pathways and adaptation mechanisms different from terrestrial organisms, resulting in their natural products exhibiting unique structures, high diversity, and significant biological activities (Ding et al., 2022). These molecules can exhibit potent pharmacological and cosmetic properties, such as anti-inflammatory, antioxidant, and antimicrobial activities. The significant advantage of using microbial ingredients is their biocompatibility; additionally, they have other benefits like simplified processes, improved and consistent product quality, no seasonal growth constraints, and an environmental footprint (Gupta et al., 2019). With the growing demand for cosmetic and skin care products, cosmetic scientists are turning to microorganisms for stabler, more sustainable ways of manufacturing biologically derived molecules (https://medium.com). Microbial biosurfactants comprise lipids, carbohydrates, or proteins, making them more biocompatible and biodegradable than their synthetic and bio-based counterparts.

Additionally, they should not be cytotoxic, making them suitable ingredients for cosmetic formulations (Moldes et al., 2021). Studies have shown that microbial biosurfactants have various advantageous features that can improve the quality of cosmetics and personalized care products (Karnwal et al., 2023). Production of bio pigments from plants could be better because it has drawbacks such as non-availability, scalability, stability, content, and impurities. In contrast, microbial pigments are devoid of limitations and serve as a readily available source of critical natural biomolecules (Kumar et al., 2017). In addition, microbial pigments can be used as antimicrobial metabolites. This property can benefit cosmetics formulations, increasing their safety and products' shelf life, especially the most perishable ones (Barreto et al., 2023). It has several applications in cosmetics due to its melanogenesis inhibition, photoprotective, antioxidant, and anti-aging properties (https://personalcareinsights.com). Microbes are also used to produce natural fragrances for cosmetics. Bacteria and yeast can ferment, creating a variety of compounds. In addition, genetically modified yeast and bacteria produce fragrances that mimic natural resources. On the one hand, the natural volatile aromas of some marine microbes could be used as a new source of perfume; on the other hand, known perfume ingredients can be produced through biological transformation. These methods are greener and more environmentally

friendly than those used in the traditional chemical industry. Additional aromas from marine microbes will likely be discovered (Ding et al., 2022).

As illustrated in the preceding section, Biotech Beauty provides sustainable alternatives by reducing reliance on finite resources and minimizing environmental impact.

3.2 Bioremediation

Bioremediation uses living organisms, primarily microorganisms, to degrade environmental contaminants into less toxic forms (Kensa, 2011). Bioremediation is an eco-friendly and sustainable approach to addressing environmental pollution compared to conventional techniques like chemical treatments or physical removal (Saravanan et al., 2024). The increased use of numerous cosmetics and personal care products in modern society has raised concerns about their potential adverse environmental effects. These products contain various chemical compounds that can persist in water bodies, leading to water pollution and ecological disturbances. Contrary to pharmaceuticals, which are made for internal use, are made for external application to the human body and are unaffected by metabolic processes. As a result, significant amounts of various chemical compounds enter the environment unchanged through daily use (Okoye et al., 2022). In addition, when salon waste enters neighborhood water bodies, a large amount of dye can have opposing effects on water assets, soil fertility, aquatic organisms, and human health using metal chains. The discharge of these dyes has a negative aesthetic effect, and their chemical constituents are toxic (Maiti et al., 2017). Creating eco-friendly and sustainable bioremediation technologies is vital to successfully reducing these contaminants' ecological impact. The remarkable ability of living organisms to break down and change contaminants has rendered bioremediation a promising method for addressing the environmental risks these products constitute (Narayanan et al., 2023). It has been validated that bioremediation is an apt remediation method due to its massive scope (Sanjana et al., 2024). Additionally, understanding the strengths and limitations of these bioremediation techniques regarding ecological implications and long-term sustainability is essential for developing effective and environmentally friendly solutions to mitigate the impact on ecosystems (Saravanan et al., 2024).

Considering the growing threat of environmental pollution and climate change, the impact of these factors on the skin has become a significant concern. The neutralization of contaminants and their effects represents a crucial strategy for reducing their detrimental impact. This approach, when applied to the field of cosmetics, has led to the recognition of the beneficial role microbes play. Consequently, innovative and multifaceted strategies that prioritize the microbiome, microorganisms, and other related elements through the utilization of bioremediation concepts and the natural capabilities of microorganisms offer promising avenues for addressing these challenges.

3.3 Bioeconomy/Circular Bioeconomy

The bioeconomy is "the production, utilization, and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide information, products, processes, and services across all economic sectors aiming toward a sustainable economy" (Calicioglu et al., 2021). It is already making substantial contributions to sustainable development, making industrial processing cleaner and more efficient, and significantly contributing to the effort to mitigate climate change. For maximum benefit, the various sectors of the bioeconomy must be linked appropriately since they are all interdependent (Lokko et al., 2018).

Bioeconomy is a new and essential paradigm for reducing our dependence on natural resources and responding to Earth's environmental threats (Fernández et al., 2021). Therefore, utilizing renewable biological resources from living organisms is a significant driver of bioeconomies (Jeevanandam et al., 2020). Key industrial sectors that derive their raw material and critical components along the value chain from natural resources and biological processes constitute the bio-based economy or bioeconomy (Lokko et al., 2018). In this regard, during the pandemic, the beauty industry was severely affected by the disruption in the supply of raw materials, production processes, marketing, and distribution of finished products. The impact of COVID-19 has emphasized the need for a circular economy in the beauty industry (Goyal et al., 2023). An innovative technology that uses the circular economy model is the circular bioeconomy. In the beauty industry, the circular bioeconomy joins the aspects of sustainability, which are connected to production on the one hand and the necessary ingredients in cosmetics on the other. It can be said that the circular economy is only truly complete if it contemplates the foundations of the bioeconomy (https://nonsoloambiente.it). Therefore, the beauty industry must identify alternative sustainable business models to deliver environmental and economic benefits.

3.4 Biomimicry

Biomimetics is 'the study of the formation, structure or function of biologically produced substances and materials and biological mechanisms and processes especially to synthesize similar products by artificial mechanisms which mimic natural ones' (Das et al., 2017). Biomimicry is an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies at macro and nanoscale (https://medium.com). The approach is a practical framework that allows the designer to evaluate problems by asking nature to "model, measure, and mentor, and then mimic form, process, and ecosystems at all levels of design" to find solutions to complex problems (Rossin, 2010). However, imitating or being inspired by forms, textures, and colors alone is not biomimetics; it must have some biology. This means that to be genuinely biomimetic, a design should in some way be informed by nature's science, not just its look (El-Zeiny, 2012). Bringing nature aboard to help solve sustainability by employing biomimicry is now recognized as a viable approach. Rather than exploiting nature for man's purposes, the focus here is on identifying and

integrating ideas that are fundamentally sustainable and adaptable to the earth's capacity (Goss, 2009). To create a new generation of cosmetics, L'Oréal researchers observed natural structures to emulate them. They were inspired by the intense color effects found on the Morpho butterfly wing, the iridescence of peacock feathers, and the metallic sheen—all of these seem to have color even though the materials that make them up have little or none (Braun, 2011). In addition, Infinite ColorTM was developed by the Japanese cosmetics company Shiseido after comprehensive research on nacreous paints for cosmetics. Infinite ColorTM is a photochromic titanium dioxide formulation whose color changes with the viewing angle (Dushkina et al., 2009). These structural colors are due to regular and irregular scattering element arrays. Rich hues of structural colors are usually produced collaboratively by several physical mechanisms. Understanding these mechanisms and their interplays will help us formulate artificial structural colors for cosmetics and other applications (Sun et al., 2013). Structural colors resist photobleaching and avoid toxic dyes compared to pigmentary colors. Thus, they can be eco-friendly and fade-resistant, which makes them promising candidates for future color applications (LI et al., 2021). The examples above demonstrate that biomimicry provides a rich source of inspiration for innovations in the beauty industry and can significantly diminish the environmental impact.

4. Essential Characteristics of the Approach

4.1 Biocompatibility

Biocompatible is a term that originates from the medical field. It refers to how a material—a biomaterial—interacts with a living organism, a host. In short, it means a material will not produce an immune response within the body (https://naturium.comility). In other words, its usual biological processes can easily absorb and use it. If the chemicals are biocompatible, they will have higher absorption and more efficient effects with lower amounts of product. Translating this to personal care, a product is biocompatible if it works without interfering with the physiology of the skin, causing irritation, creating an allergic reaction, or causing congestion. The materials in biocompatible skin care do not produce a toxic or immunological response when exposed to the body or bodily fluids. The most excellent thing about biocompatible skin care products is that they are gentle on all skin types, even on sensitive skin, because they are made with safe and biocompatible components. It means delivering the active to the site of action with minimal disruption and in harmony with the skin (http://timesofindia.indiatimes.com). The biocompatibility of materials for cosmetic use with the skin is an essential aspect of their production and marketing and mainly concerns the mechanisms of the innate immune response; the biological mediators of innate immunity are cytokines, which are multifunctional molecules implicated in various biological activities and endowed with pro- and anti-inflammatory activities (Coltelli et al., 2020). Therefore, when substances are biocompatible, our systems recognize the molecular structure of those ingredients, allowing them to operate in our body's

natural biological processes. If a component is not biocompatible, our bodies will not recognize it, and it may become an irritant, causing chemical build-up and cellular toxicity. Microbial biosurfactants, for example, are considered the most biocompatible and eco-friendly, as they are produced by living cells, primarily bacteria and yeasts, without the intermediation of organic synthesis (Moldes et al., 2021). That is why bacterial biosurfactants (BS) are becoming increasingly popular in industrial production as biocompatible, low-toxic alternative surfactants (Karnwal et al., 2023).

Since cosmetics are applied directly to the skin, they must comply with the human system. Consequently, the fundamental principle of biocompatibility in cosmetics is the selection of ingredients that exhibit a high affinity for the skin and that the skin can recognize and process, thereby minimizing the potential for irritation and adverse reactions. Furthermore, it positively impacts the environment and ecosystem, as it can have higher absorption and efficient effects with lower amounts.

4.2 Biodegradability

Biodegradation mechanisms and factors influencing degradation rates of biodegradable materials are essential considerations in assessing their environmental impact and effectiveness. Biodegradable materials are substances or products that can naturally decompose and disintegrate into harmless byproducts when exposed to environmental conditions like moisture, heat, and microbial activity. These materials are essential in ecological sustainability, as they mitigate environmental pollution and waste. The production and pervasive use of non-biodegradable and raw materials impact terrestrial and aquatic ecosystems (Rajesh, 2023).

Most conventional skin-care cosmetic formulations use petroleum or mineral oil-derived ingredients, which are harmful and non-biodegradable. In addition, with low or no biodegradability, synthetic pigments contribute to the planet's unsustainable production chains (Barreto et al., 2023). Many inorganic pigments become environmental pollutants since they are poorly biodegradable and bioaccumulated. Some makeup ingredients do not easily break down in landfills and can persist for many years, accumulating waste and pollution in landfills (Zhong et al., 2020). Nail polish can also include glitter, typically made of non-biodegradable microplastics. Gel and acrylic nails are not biodegradable and can remain in landfills for centuries. Another case is that silicones are very stable chemically. Although this is a desired property for cosmetics ingredients, it harms the environment due to bioaccumulation, especially in aquatic ecosystems. (Martins et al., 2023). The majority of surfactants are either only partly or slowly biodegradable, which results in environmental damage and toxicological problems. On the other hand, biosurfactants are beneficial substances that break down quickly into simpler metabolites than chemical surfactants (Nagtode et al., 2023). Compared to synthetic surfactants, they are also easily degraded by microorganisms and suitable for environmental applications such as bioremediation/biosorption (Bhattacharya et al., 2017). Similarly, although flavors are used in low concentrations, they can cause air pollution and have low biodegradability due to their

volatility (Martins et al., 2023). However, white biotechnology has emerged in biochemical manufacturing processes that use living cells and enzymes to synthesize readily biodegradable products (https://bio.news). Therefore, various biological molecules have intriguing capabilities, such as biosurfactants, vitamins, antioxidants, pigments, enzymes, and peptides. These are safer, biodegradable, and environmentally friendly than chemical options (Karnwal et al., 2023).

4.3 Biomass-based Materials

Biomass is any organic material derived from plants or animals. Plants, algae, fungi, and even waste items can all be used to generate biomass. Bioactive compounds extracted from biomass play a role in various biological processes and are intended for cosmetic formulations. These compounds derived from biomass possess desirable qualities such as anti-inflammatory, antioxidant, immunomodulatory, antibacterial, and antifungal properties, which make them suitable for cosmetic production (Juliadmi et al., 2024). Many biomass materials contain natural vitamins, minerals, and antioxidants with significant skin advantages. Biomass has emerged as a promising renewable resource for bio-based cosmetics (Sasounian et al., 2024). Because it is a renewable resource that can regenerate over time, it is a suitable ingredient for environmentally friendly cosmetics.

Additionally, it does not contribute to carbon emissions, can minimize environmental issues throughout the product's life cycle, and is biodegradable in aquatic environments. Substances taken from plants and other types of biomasses can extend shelf life and provide UV protection (Arung et al., 2024). These bioactive compounds are frequently derived from natural biomass. As a result, it is critical to discover effective ingredients with ecologically friendly properties, such as natural polyphenols, tannins, and lignin (Restu et al., 2024). Biomass-based cosmetic packaging is also attracting the attention of researchers who want to create effective and environmentally friendly cosmetic packaging (Kusumaningru et al., 2024).

Biomass converts into bioplastics, biodegradable materials, and bio-based chemicals in the beauty industry. Furthermore, biomass generation offers several additional benefits, including the production of various compounds, the creation of large amounts of biomass, and the capacity for easy environmental adaptation. It is a renewable and recyclable resource and is essential for the bioeconomy. The impact of biomass in the beauty industry on the bioeconomy is significant, as it promotes sustainability, resource efficiency, and waste reduction. Additionally, it reduces the beauty industry's environmental impact by encouraging a shift towards responsible production and consumption practices, focusing on the circular economy.

4.4 Expressive Biology

Biology is the most sophisticated technology on the planet. It has unparalleled precision and scale that modern means have never been able to replicate. The radical advances in modern biology are evolving and developing in various fields. The field of biology has also applied to the arts, with the emergence of

a novel trend known as biological arts. This approach uses biological materials, including animals, plants, microorganisms, and cellular tissues, as a medium in artistic creations. With this background, expressive biology is a term used to describe the study of biological processes, phenomena, and concepts through creative expression. Various art forms are used to communicate biological concepts, raise awareness of scientific issues, or showcase the beauty of the natural world, including exploration. Expressive biology combines past and present technologies with biology and is a creative tool for self-expression by combining biology's creativity with technology expertise (https://www.arcaea.com).

The broader application of biology in the beauty industry has the potential to develop innovative solutions to hitherto unsolved problems. Therefore, the application of expressive biology as a creative tool enables the conceptualization of a future in which the ecosystem on the skin can be harnessed or create hairstyles that can work off the hair's protein structure. Taking expression biology as a foundation for beauty design also permits consideration of environmental impact. It could change the way we look at the future of beauty. Consequently, it facilitates the delivery of solutions for beauty design, where personal style and expression play a significant role. Scientific and beauty industry experts predict that broadened research in biology has the potential for the beauty industry.

4. Conclusion and Outlook

Consumer demand drives the beauty industry, and contemporary consumers and beauty companies are concerned about the industry's environmental impact. The beauty industry significantly impacts sustainability, including excessive packaging waste and use of natural resources. Furthermore, one of the most significant challenges is mitigating the effects of climate change. Notably, with its extensive resource consumption and expansive supply chain, the beauty industry must reduce its reliance on finite resources and decrease its environmental impact. Consequently, industry must adopt more sustainable practices that minimize negative consequences and positively contribute to society and the planet. Many beauty companies are already implementing sustainability strategies concerning the environment, and the industry's future depends on a more sustainable approach.

This paper categorizes the approaches to ecological sustainability in the beauty industry into four categories: biotech beauty, bioremediation, bioeconomy/circular bioeconomy, and biomimicry. It deduces that biocompatibility, biodegradability, biomass-based materials, and expression biology should be considered characteristics in each approach. This entails adopting practices that replenish and restore the environment, ensuring the sustainability and improvement of the ecosystems. Therefore, ecological sustainability has become a fundamental value in the beauty industry, influencing consumer demands and guiding companies toward more environmentally friendly practices. In conclusion, the beauty industry is transitioning from industrial chemistry to a regenerative era driven by biology. Fits

into this context demonstrates that the beauty industry should aim for innovative approaches that respect the environment and ecosystems.

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