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Sustainable utilization of natural plant resources in eco-friendly cosmetic production

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ABSTRACT

In the context of mounting environmental awareness and the imperative to mitigate the adverse ecological impact of the cosmetics industry, plant-based raw materials are acquiring heightened significance. This article provides an overview of contemporary trends in the domain of natural cosmetics production. It placed particular emphasis on the utilization of plant-based raw materials and agricultural byproducts. The text provides a comprehensive overview of bioactive plant ingredients, their cosmetic properties, and their applications in cosmetology. The significance of sustainable technologies, including green chemistry, biocatalysis, and microbial fermentation, in the production of cosmetics derived from natural active ingredients was emphasized. The present study assesses the potential of rural areas as a source of plant-based raw materials for the cosmetics industry, with a focus on organically grown and wild plants. The challenges associated with the certification of natural cosmetics, and the importance of product life cycle assessment, were analyzed. The article highlights the importance of integrating agriculture and cosmetology within the context of the circular economy and sustainable development.

Keywords: plant raw materials, natural cosmetics, sustainable development.

INTRODUCTION

In the cosmetic industry, natural raw materials and products—sourced from ecosystems such as forests, meadows, orchards, or obtained directly from agricultural production—are gaining increasing importance. The dynamic development of this sector is reflected in cosmetology, an interdisciplinary field that combines physiology, biochemistry, dermatology, and agricultural sciences. Current trends are shaped by growing awareness of environmental pollution as well as its impact on health and skin condition. Consequently, research is directed toward multifunctional skincare products based on natural, low-impact raw materials. These formulations aim to protect the skin from environmental aggressors while supporting its regenerative processes, with particular emphasis on sustainable sourcing from organic farming, wild plant communities, or biotechnology. A related innovation is minimalist yet personalized skincare, where simplified formulations are tailored to the physiological needs of the skin while meeting ecological standards (Bîrsan et al., 2021; Potaś et al., 2024). Among natural bioactive substances, peptides are of particular interest due to their role in collagen and elastin synthesis, skin firmness, and wrinkle reduction. Neuropeptides further contribute to muscle relaxation without irritation. In addition, plant-based ingredients, such as *Centella asiatica* and *Chamomilla recutita*, are valued for their regenerative, anti-inflammatory, and soothing effects, especially for sensitive or acne-prone skin and in post-procedural care (Ferreira et al., 2021; Huynh et al., 2021). Modern production technologies increasingly rely on renewable raw materials from both natural ecosystems and sustainable farming systems designed to minimize environmental degradation. Beneficial microorganisms are also gaining importance in natural product development. At the same time, advances in digital technologies enable cosmetic personalization, allowing for precise adjustment of formulations to individual skin characteristics (Manea et al., 2023; Bîrsan et al., 2024). Sustainable agriculture plays a key role in this context. Intensive farming methods based on mineral fertilizers and synthetic pesticides are incompatible with eco-conscious cosmetic production. Instead, attention is turning to raw materials from organic systems and the valorization of agri-waste. By-products, such as fruit peels, seeds, and plant biomass, are processed with environmentally friendly technologies, supporting circular economy strategies and reducing the ecological footprint of industry (Lee and Hyun, 2023; Silvério et al., 2023; Manuful et al., 2024).

This article reviewed the literature on the use of natural raw materials from rural landscapes and agricultural systems in sustainable cosmetic production. It highlighted the technological and environmental potential of renewable resources, including agro-industrial by-products, as well as discussed the growing synergy between agriculture and cosmetology. This integration fosters environmentally responsible practices and technologies aligned with the goals of sustainable transformation in the European cosmetic and bioproduct industries.

THE IMPORTANCE OF NATURAL RAW MATERIALS IN COSMETOLOGY

The history of cosmetics dates to the beginning of civilization. Various ointments and creams obtained from natural components, therapeutic essences, or natural oils were already known in those times. The customs of Egyptian women who used light ochre powder, of Roman women who bathed in goat or donkey milk, and of Greek women who used different henna colors are also known. Special creams based on waxes, olive oil, and cypress were prepared. The inhabitants of Egypt attached great importance to the care of their bodies, and their cosmetics was a manifestation of a refined lifestyle. The Asian continent is thought to be the cradle of a civilization that used numerous plant species for cosmetic purposes (Chaudhri and Jain 2009). During the past centuries, cosmetics played a smaller or larger role, but only natural preparations were always used for beautification or basic hygiene. It was only in the 18th century, which saw the beginning of scientific chemistry, that the composition of cosmetics was enriched to include synthetic substitutes for nature, which was driven out slowly and systematically. Nowadays, cosmetics have since transformed into a highly advanced branch - cosmetology. It combines many sciences: physiology, biochemistry, cosmetic chemistry, aesthetic medicine, dermatology, oncology, and dietetics as well as agricultural science. The term “cosmetics” is probably derived from the Greek word “kosmeo” that means “to adorn” (Draelos 2000; Chauhan et al., 2014).

Despite the rise of synthetic ingredients, the interest in natural cosmetics has resurged significantly in recent years. Europe has positioned itself as the world’s leading importer of key natural cosmetic raw materials, especially vegetable and essential oils. In 2023, the EU accounted for 48 % of global import volume and 42% of global import value for these ingredients, with imports reaching approximately 470,560 t and €2.22 billion in value. This trend reflects a growing consumer preference for natural and organic

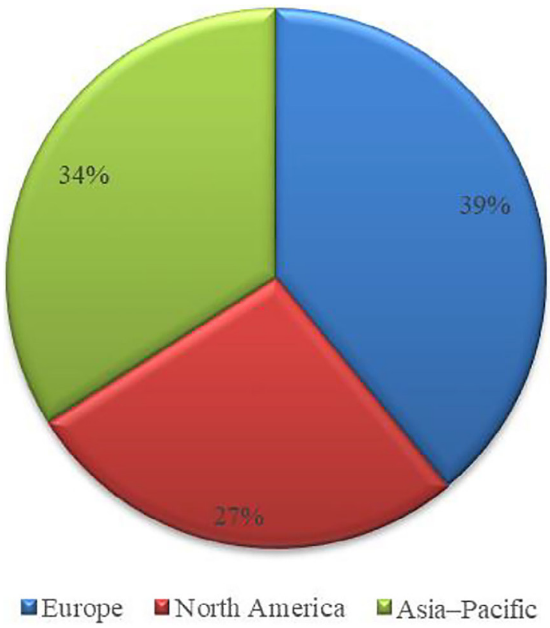

Figure 1. Market share by region – natural cosmetic market (2023) (CAS 2025)

products, supported by favorable regulations and a mature industry. As shown in Figure 1, Europe leads the global market for natural cosmetics with a 39% share, followed by Asia–Pacific (34%) and North America (27%). Although Europe currently dominates, the Asia–Pacific region is projected to experience the fastest growth in the coming years.

Despite the progress in cosmetic science, it cannot be stated unambiguously that raw materials used in them are entirely safe. A "new niche" is opened here for agriculture as a producer of raw materials for cosmetology. The group known as conscious consumers, having no problem with access to information and scientific publications, have started to look closer at what they use to care for their skin. There is no specific legal framework in Europe regulating organic cosmetics. Such products must meet all the requirements set for cosmetics by the EU directives. Natural cosmetics are products that are produced almost exclusively from natural substances. Natural raw materials are substances of plant, animal or mineral origin as well as mixtures and products of reactions between them. To obtain and process them, physical processes such as expeller pressing, extraction (with water, ethanol, glycerol or carbonic acid), filtration, distillation, drying, etc., can only be used. Apart from that, enzymatic and microbial processes that are used on naturally occurring, unmodified enzymes and microorganisms are permissible. The production of eco-cosmetics involves many requirements (EC 1223/2009, Scientific Committee 2022).

The plant extracts used in cosmetic formulations must originate from supervised plantations, whose supervision starts from soil preparation. Before an organic plantation is established, the chemical composition of the soil in which plants are to be grown is checked over a period of 3 years. Apart from the soil, rainwater and the water used to water crops are tested for the degree and type of contaminants occurring in it. It is also impermissible to apply conventional plant protection products and fertilizers. Only the products that are included in the lists of permitted and certified agents can be used. "Eco-" and "biocosmetics" must have a certificate confirming the authenticity of their organic composition (Regulation (EC) 2009, Commission Regulation (EU) 2023).

In the cosmetic industry, cosmeceuticals – as a synthesis of cosmetology and pharmacy – are gaining ever greater recognition. Cosmetic-pharmaceutical hybrids are cosmetic-pharmaceutical hybrids aimed at improving health and beauty through the ingredients that affect the biological functions of the skin and hair (Bisset, 2009). The most readily used natural products in cosmetics include milk and its processed products, honey, chocolate, coffee, tea, as well as beer and caviar. These products are a source of valuable vitamins, macro- and micronutrients, proteins and amino acids, carbohydrates, fatty acids, phospholipids, antioxidants, and cosmetically active alkaloids, such as caffeine or theobromine. These compounds show strengthening and protective effects on the skin and hair, are ingredients of moisturizing, peeling, as well as anti-cellulite preparations, have an anti-aging activity, and protect against UV radiation (Martin and Glaser, 2011).

Table 1. Plant components in the cosmetic industry and their cosmetic applications (Babich et al., 2025)

Plant component	Cosmetic effects	Application in cosmetics
Polyphenols	Antioxidant, antimicrobial, anti-inflammatory, UV protection	Anti-aging creams, products for sensitive/damaged skin
Phytosterols	Skin barrier enhancement, moisturizing, anti-aging	Lipsticks, deodorants, soaps, shampoos, eye makeup
Fatty acids	Moisturizing, anti-inflammatory, hair loss prevention	Hair care products, lip balms, oils, anti-acne cosmetics
Vitamins (C, E)	Skin brightening, antioxidant, UV protection, anti-aging	Serums, creams, whitening lotions, hair products
Carotenoids	UV protection, anti-aging, brightening, dandruff prevention	Sunscreens, anti-aging cosmetics, hair products, brightening creams
Peptides and Sugars	Skin defense activation, moisturizing, rejuvenating, anti-inflammatory	Moisturizers, anti-aging and anti-inflammatory cosmetics
Flavonoids	Free radical scavenging, skin protection	Antioxidant creams, sun care products
Tannins	Astringent, anti-inflammatory, antimicrobial	Intimate hygiene products, anti-acne treatments
Phenolic acids	Antimicrobial, anti-aging, anti-inflammatory	Acne creams, UV-protection products
Essential oils	Antibacterial, antifungal, fragrance	Perfumes, soaps, shampoos, creams
Saponins	Natural surfactant and cleansing effect	Natural detergents, shampoos

As the scientific understanding of plant-based actives in skincare improves, it becomes increasingly important to classify and highlight the most significant bioactive compounds found in plants, which are widely applied in cosmetic formulations. Table 1 presents a summary of the most common plant-derived components, their cosmetic effects, and applications in modern cosmetology.

Today, edible food ingredients are increasingly found in modern cosmetic preparations. Some wines and beers as well as luxury products, e.g. caviar or truffles, are also characterized by high cosmetic activity. Ingredients such as vanilla, warming cinnamon and ginger, nuts, maple syrup, as well as some mushrooms also appear in cosmetic preparations and their offer is systematically expanded (Ballesteros et al., 2014; Pandey et al., 2023). Phytoestrogens derived from, e.g., red clover (*Trifolium pratense* L.), soybean (*Glycine max* (L.) *Meroll*.), parsley (*Petroselinum sativum Hoffm*.), and common hop (*Humulus lupulus* L.) play an important role in cosmetics with a rejuvenating effect. The preparations enriched with biologically active substances derived from couch grass (*Elymus repens* (L.) *Gould*) rhizomes as well as from borage (*Borago officinalis* L.) and common evening-primrose (*Oenothera biennis* L.) seed oils are dedicated for skin requiring moisturizing. The products containing extracts from common horse chestnut (*Aesculus hippocastanum* L.) and arnica (*Arnica sp.*) are recommended for couperose skin. Field horsetail (Equisetum arvense L.) is a frequent additive in nail and hair strengthening preparations, whereas chamomile (*Chamomilla recutita* (L.) *Rauschert*.), pot marigold (*Calendula officinalis* L.), and common nettle (*Urtica dioica* L.) are a source of antioxidants in cosmetics. Moreover, the medicinal plants containing saponins (e.g. common soapwort - *Saponaria officinalis* L.) provide natural detergents. Essential oils, which co-create perfumes, are used in the fragrance industry, but they also give an aroma to soaps, shampoos, conditioners, creams, and other cosmetic products (Teas et al., 2009; Lephart, 2021).

In the mid-20th century, the possibility of cosmetic application of coffee was discerned. Attention was drawn to the possibility of using ground coffee as a peeling substance, which perfectly complements the anti-cellulite effect of caffeine. After it was found that coffee contained a large content of polyphenol compounds, primarily in the form of the so-called phenolic acids, coffee started to be used as a substance neutralizing free radicals and eliminating skin aging signs (fatty tissue and cellulite reduction). Both pure caffeine, mainly of natural origin, and a coffee bean extract, particularly from unroasted green coffee, are used in the preparations with such application. Green coffee not subjected to the roasting process, richer in chlorogenic acid, is an excellent anti-free radical preparation, protecting the skin against the effects of environmental factors, being similar to green tea in this respect. Caffeine easily combines with the skin protective layer and penetrates through the epidermis; thus, its major part is absorbed in the dermis. It stimulates microcirculation and improves blood circulation in capillaries as well as causes excessive fat to be released from adipocytes and accelerates the breakdown of fat into free fatty acids. Furthermore, caffeine inhibits the activity of phosphodiesterase and increases the secretion of catecholamines, thus contributing to improved skin smoothness and elasticity (Wintgens, 2009, Herman and Herman, 2013). Together with phenolic acids, it creates a complex of substances protecting skin cells against the harmful effects of solar radiation, mainly UVB. Contained in hair care cosmetics, it has a protective effect on hair follicles, thereby reducing the rate of hair loss in men. When it is used internally at a high dose of above 300 mg/day, caffeine causes a slight rise in body temperature, which increases the number of calories burned during physical exercise and contributes to a reduction in fat reserves. Therefore, it can be utilized in the so-called slimming treatments, but always under the control of a physiologist. Apart from the slimming effect of caffeine, any types of face masks made of roasted coffee can also exhibit skin color and elasticity improving effects (Wu et al., 2022; Rodrigues et al., 2023).

Leaves of Chinese tea (*Camelina sinensis*) and Indian tea (*Camelina assamica*) are of great importance in cosmetics. Polyphenols are the largest group of compounds in all teas. They include flavanols (catechin, gallocatechin, and their epimeric forms), flavonols (quercetin, kaempferol, rutin), phenolic acids (gallic, caffeic, chlorogenic, ferulic), tannins, which are esters of phenolic acids with catechins, and glycosides, being combinations of the latter with sugars. The next groups comprise the following: xanthenes (caffeine, theophylline, theobromine), pectins, protein compounds (glutelins, albumins, enzymes, and the amino acid theanine), mineral salt components, vitamins (group B as well as A, K, and C), pigments (chlorophyll, xanthophyll, carotene, thearubigin, theaflavin), and essential oils (Koch et al., 2019). The richness of active substances determines the beneficial effect of tea on the human organism and also allows it to be used as a cosmetic raw material. Due to a high content of polyphenols, exceeding 10% and sometimes reaching even 30%, in leaf dry matter of green tea, it exhibits strong oxidant properties, scavenging different forms of free radicals, such as: singlet oxygen, hydrogen peroxide, hydroxyl radicals, and peroxide radicals (Arct and Pytkowska, 2008).

Among the tea antioxidants, epigallocatechin gallate shows the strongest activity. Its ability to neutralize free radicals and antioxidant activity are combined with the capacity to chelate metals. By complexing metal ions, which are catalysts of free radical oxidation processes and the components of important enzymes, it contributes to slowing down the processes of formation of highly oxidized forms of active biomolecules, dangerous for the organism, or to the deactivation of biocatalysts, e.g. during the blocking of urokinase, which is an enzyme secreted by cancer cells and responsible for the destruction of healthy cells (OyetakinWhite et al., 2012; Saric et al., 2017; Zahra et al., 2022).

Jerusalem artichoke (*Heliantus tuberosus* L.) and sweet potato (*Ipomoea batatas* L. [Lam.]) are new cosmetic raw materials, less known in the market. Owing to the content of valuable mineral and nutritional components in tubers of these species, they can become very valuable raw materials for the pharmaceutical and cosmetic industries. Due to their rich composition of polysaccharides, proteins, organic acids, vitamins, and other compounds, the aboveground parts of these species are also excellent herbal and cosmetic raw materials (Alam, 2021, Tapera et al., 2024). The infusions made from Jerusalem artichoke flowers can purify the body as well as strengthen its immune system and blood vessels. The preparations containing *Helianthus tuberosus* are recommended, among others, in the prevention and treatment of diabetes, as well as heart and blood vessel diseases, at increased physical and mental burden (chronic fatigue), to maintain the proper gut microflora, and also to supplement diet with components supporting slimming (Dias et al., 2016; Sawicka et al., 2018).

RURAL AREAS AS A "TREASURY" OF SPECIES OF WILD GROWING PLANTS, CROP PLANTS, AND TREES USED IN COSMETOLOGY – ON THE EXAMPLE OF POLAND

Many studies show that raw materials of natural origin used in cosmetics are safe for the human body. Selected plant raw materials, rich in active components: vitamins, micro- and macronutrients, proteins, amino acids, carbohydrates, phospholipids as well as natural antioxidants and preservatives, are predominantly used to produce natural cosmetics (Liu, 2022; Faria-Silva et al.; 2022).

Many known plants that are commonly used in cosmetics and in the perfume industry grow in natural stands in Poland. These plants are found in almost all habitat types, from very wet to extremely dry. They represent nearly all life forms, i.e. trees, shrubs, hemicryptophytes, therophytes, lianas, and semi-parasites. Among them, there are also noxious weeds such as cornflower (*Cyanus segetum Hill*), common fumitory (*Fumaria officinalis* L.), and field horsetail (*Equisetum arvense* L.). Numerous species from this group are grown in Poland, for example: elderberry (*Sambucus nigra* L.), common hop (*Humulus lupulus* L.), heartsease (*Viola tricolor* L.), oregano (*Origanum vulgare* L.), chamomile (*Matricaria chamomilla* L.), and rugose rose (*Rosa rugosa Thunb*.). The diversity and abundance of cosmetic plants in Poland offer great possibilities to select plant raw materials used to produce different cosmetic preparations. Selected examples of plant species occurring in Poland and their active compounds used in cosmetology are presented in Table 2.

Among cosmetic plant species, more than 110 exhibit a multi-directional effect on the skin. Their active substances are applied as ingredients in creams, balms, soaps, as well as skin and face care products. About 30 flora species in Poland provide raw materials for the production of hair shampoos and balms, among others silver birch (*Betula pendula Roth*), field horsetail (*Equisetum arvense* L.), common hop (*Humulus lupulus* L.), chamomile (*Matricaria chamomilla* L.), wild thyme (*Thymus serpyllum* L.), and common nettle (*Urtica dioica* L.). About 16 species contain fragrant essential oils used to perfume different cosmetic preparations. In Poland 70% of plant species with cosmetic properties grow in natural stands in meadow communities. Other ones come

Table 2. Selected plant species occurring in Poland along with their main active compounds and typical applications in cosmetology

Plant name	Main active compounds	Cosmetic application
Betula pendula / Silver birch	Flavonoids, saponins, essential oils	Anti-dandruff shampoos, tonics for oily skin
Equisetum arvense / Field horsetail	Silica, flavonoids, saponins	Hair strengthening, anti-aging products
Humulus lupulus / Common hop	Xanthohumol, essential oils, phytosterols	Soothing creams, seborrhea products, shampoos
Matricaria chamomilla / Chamomile	Azulene, chamazulene, flavonoids, essential oils	Soothing creams, sensitive skin products
Thymus serpyllum / Wild thyme	Thymol, carvacrol, flavonoids	Antiseptic soaps, tonics for acne-prone skin
Urtica dioica / Common nettle	Pantothenic acid, silica, flavonoids	Hair strengthening, cleansing tonics
Rosa rugosa / Rugose rose	Vitamin C, anthocyanins, flavonoids, essential oils	Anti-aging creams, regenerating products
Origanum vulgare / Oregano	Carvacrol, thymol, flavonoids	Anti-inflammatory and antibacterial cosmetics
Sambucus nigra / Elderberry	Anthocyanins, flavonoids, vitamin C	Brightening creams, products for capillaries
Viola tricolor / Heartsease	Salicylates, flavonoids, saponins	Products for acne-prone and sensitive skin

from forest and thicket communities as well as from anthropogenic crop field communities and ruderal areas.

The results of a detailed analysis of cosmetic plants in Polish flora can be evaluated more closely by comparing them with the floras with a similar floristic composition from other regions. The percentage of cosmetic species in the native flora is 5% and is relatively comparable to the flora of central, western and northern Europe (Tutin et al., 2010).

The percentage of cosmetic plants in the warmer regions of the temperate zone as well as in the tropical and subtropical zones is much higher compared to Polish flora. This is due to a richer species composition and the degree of plant resources utilization (Wyk and Wink, 2004; Bärtels, 2009).

Due to their aromatic properties, herbal plants (herbs) have very versatile applications. They are used in pharmacy (as human and animal drugs), cuisines, and cosmetology. About 130 herbal plant species are grown in Europe, predominantly in the Mediterranean Sea region, though most of them can also be grown successfully in Poland. It is estimated that more than 50 herb species are grown in Poland, including over 20 local varieties (European Food Safety Authority, 2012).

According to Jambor (2018), the herbal plantations in Poland occupy an area of about 30,000 ha and they are run by 20,000 farms with an average farm area of 0.5–2.5 ha. About 70 herbal plant species are currently cropped. Kozłowski et al. (2008) report that the Polish herbal industry utilizes about 130 plant species harvested from nature and about 60 cropped species, which gives about 10.000 t of naturally harvested raw material and about 50,000 t from field crops. These are products with a high biological value, finding enormous application in cosmetics and pharmacy.

CHALLENGES RELATED TO NATURAL COSMETICS

A key tool in assessing the environmental impact of cosmetics "from cradle to grave" is life cycle assessment (LCA). This approach allows for the identification of stages in need of improvement, such as raw material sourcing, manufacturing processes, packaging, and end-of-life disposal. Implementing LCA enables companies to make informed decisions that reduce the environmental footprint of their products. Sustainable cosmetic production involves not only ethical sourcing and biodiversity preservation, but also the use of environmentally friendly chemical processes and the reduction of hazardous substances. Furthermore, it requires investments in energy-efficient technologies and the use of renewable energy sources (Hopewell et al., 2009). The holistic nature of this approach is illustrated in Figure 2, which presents the closed-loop flow of plant-derived raw materials. It highlights the successive stages of the life cycle: sourcing of eco crops, wild plants, and agricultural by-products, their processing through green chemistry methods, such as extraction, fermentation, and biocatalysis, followed by the formulation of natural cosmetics, and finally the application of biodegradable packaging and recycling strategies. Such a model emphasizes the interconnections between production and waste management,

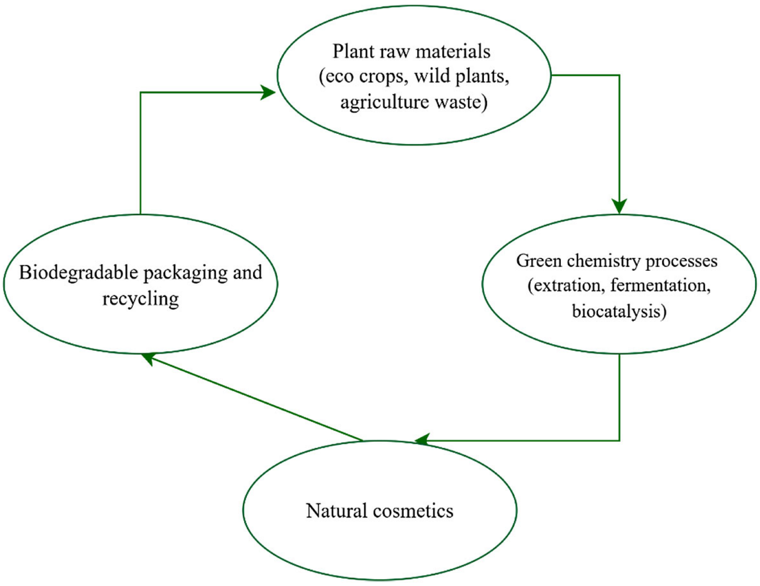

Figure 2. Life cycle of natural cosmetics

pointing to the possibility of continuous reuse of resources and the minimization of environmental burdens. In the context of natural cosmetics, LCA plays a particularly important role, as it allows for the comprehensive evaluation of the impact of raw material cultivation on biodiversity, the benefits of reducing greenhouse gas emissions, the implementation of renewable energy in production processes, and the substitution of conventional packaging with biodegradable alternatives. Moreover, comparative LCA studies enable the quantification of environmental advantages of natural cosmetics over conventional ones, providing measurable evidence of the effectiveness of sustainable practices in this sector (Martins and Marto, 2023).

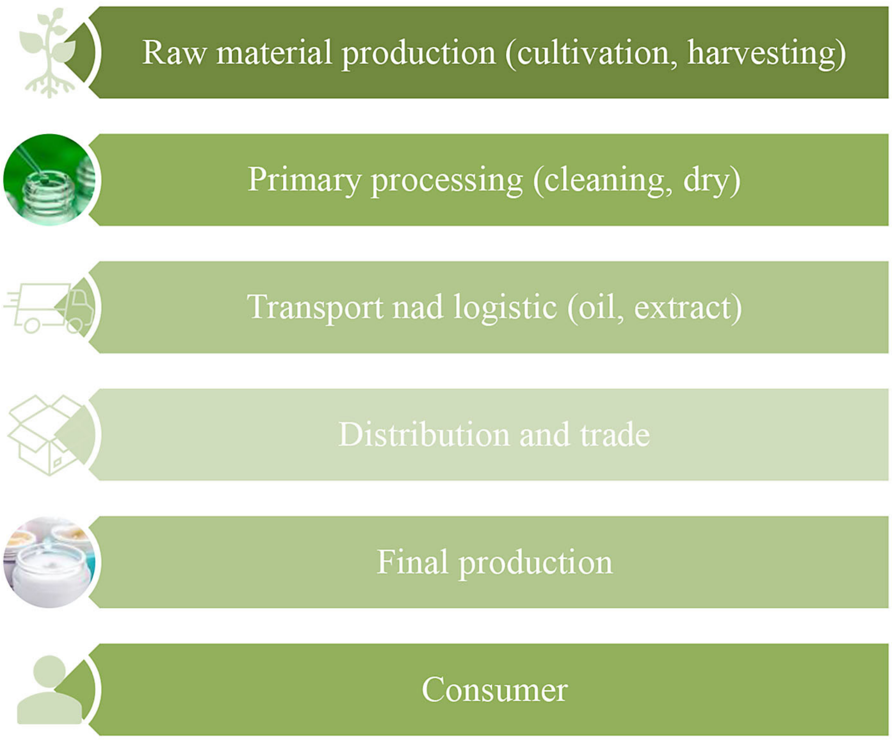

Figure 3. Plant-based raw material supply chain (Rogers et al., 2024)

The complexity of the life cycle of plant-based cosmetics can be best understood by analyzing all stages – from cultivation and raw material sourcing, through processing and distribution, to use and disposal. Figure 3 illustrates these stages in a concise way, emphasizing the importance of a sustainable approach at each of them.

Despite their potential, natural cosmetics face numerous challenges. As noted by Juliano and Magrini (2018), integrating plant-derived active ingredients into functional cosmetic formulations is complex. Technical difficulties include limited solubility, low stability of certain compounds, issues with skin permeability, and the risk of skin irritation. The lack of comprehensive research in these areas hampers the wider adoption of natural cosmetics, despite their environmental and potential health benefits.

Nhani et al. (2024) highlight the promising role of nanocarriers in the delivery of bioactive compounds derived from plant-based waste in cosmetics. Nanotechnology can enhance the effectiveness of natural ingredients and respond to the increasing consumer demand for eco-friendly products. However, this also introduces challenges, such as regulatory complexities, the necessity of full product life cycle evaluations, as well as high research and development costs. The nanocarriers derived from plant and animal by-products offer significant advantages, including improved bioavailability as well as efficacy through enhanced skin penetration and controlled release of active substances. Their use supports sustainable development by reducing waste and promoting a circular economy. Compared to synthetic materials, natural by-products are also more cost-effective. Importantly, the nanocarriers from natural sources tend to be more biocompatible and safer for skin applications, with a lower risk of allergic reactions (Zhou et al., 2021; Sharma et al., 2022).

The 12 principles of green chemistry, illustrated in Figure 4, provide a holistic framework for reducing waste, improving energy efficiency, and designing safer chemicals and processes. The adoption of "green chemistry" principles in the extraction and processing of natural raw materials is another essential step toward sustainability. Their implementation not only minimizes the environmental footprint of cosmetic production, but also aligns with the growing consumer demand for sustainable and health-conscious products. However, there is an urgent need to develop standardized procedures to assess the quality and consistency of by-product-derived ingredients. A promising trend is the development of personalized skincare solutions tailored to individual skin types, enabled by nanotechnology. Additionally,

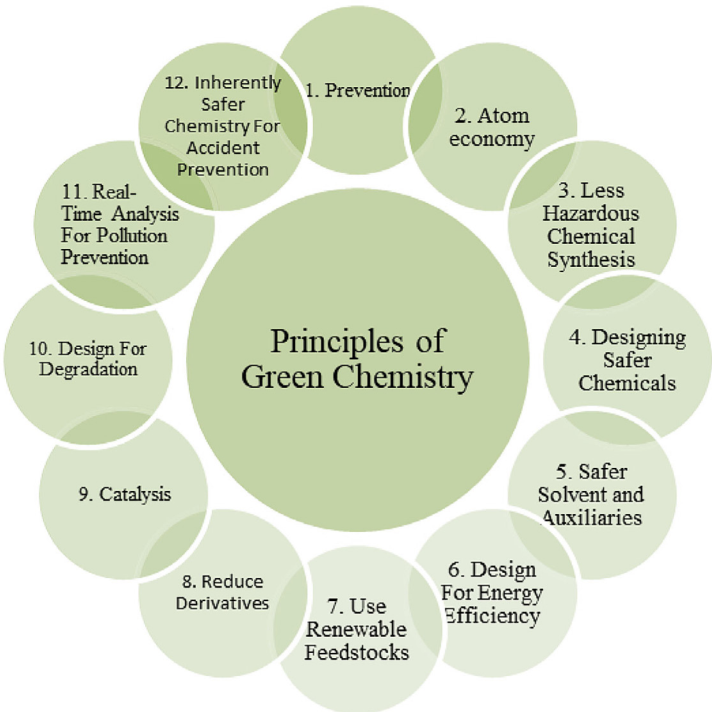

Figure 4. The 12 principles of green chemistry (Krasnodębski, 2024)

innovations such as artificial intelligence (AI) are being explored for smart ingredient delivery systems that respond to specific skin conditions or environmental factors (Fonseca-Santos et al., 2015, Hameed et al., 2019, Chang et al., 2023).

Another critical area is the transparency of supply chains and the standardization of nano-product characterization methods. Addressing these issues can enhance the sustainable development of natural cosmetics and increase consumer trust.

A notable example of a brand meeting the challenges of natural cosmetics is Lancôme. The company implements a strategic approach that includes sustainable cultivation and sourcing, fair trade practices, and carbon footprint reduction. It also applies green chemistry and biotechnology to minimize the use of natural resources and incorporates recyclable materials in its packaging. Moreover, Lancôme supports biodiversity preservation initiatives and institutions, reflecting its commitment to sustainable innovation in cosmetology (Nikolova, 2022).

PLANT PROCESSING TECHNOLOGIES FOR FRAGRANCE PRODUCTION

Michailidou (2023) notes that an ever-greater importance is attached to the concept of sustainable fragrances as high value every day and everywhere chemicals. The widely understood biotechnology, including fermentation, biocatalysts, and genetic engineering, has the potential to reduce the environmental footprint of fragrance production, while maintaining the quality and consistency. The possibilities to augment sustainable fragrance production should be sought in, among others, computational (in silico) methods, including machine learning (ML). Besides, the author claims that the continued innovation and collaboration of cosmetic industry businesses will be of crucial importance to the future of sustainable fragrances. This particularly applies to the incorporation and development of novel sustainable ingredients as well as ethical sourcing practices.

Agosto-Maldonado et al. (2024) noted that enzymatic syntheses are a promising "green route" to produce cosmetics. Nonetheless, the broad application of such technology requires engineering advancements for expanded diversity, improved selectivity, and enhanced stability so that the cosmetics produced with the current methods can be cost-competitive. The advances and outlooks for enzyme engineering in the area of cosmetology will focus on carboxylic acid reductases (CARs) and unspecific peroxygenases (UPOs). They enable the selective production of complex flavors and fragrance molecules for cosmetics. Another example can be the application of protein engineering methods, including rational design and directed evolution combined with computational modeling (designed to unleash the full potential of enzymes in the biosynthesis of chemicals as an added value of this technology).

Eichhorn et al. (2023) claim that there is a constant demand for the development of new odorant molecules of cosmetics and of novel processes for their production to create unique and instantly recognizable perfumes. The example of Givaudan's activities demonstrates that the use of renewable carbon has high potential due to its efficiency in synthesis and in the production of powerful as well as biodegradable odorant molecules, using upcycled carbon available from waste and natural raw materials.

Manina and Forlani (2023) noticed that in recent years biotechnology has played an ever-greater role in the fragrance industry. It enables the production of sustainable and high-quality fragrance ingredients, such as e.g. terpenoids. This also allows the development of new biotechnological pathways to produce compounds extracted from natural sources. Metabolic engineering enables the introduction of specific synthase genes and the modulation of the mevalonate pathway, which has been successful in altering terpene metabolism. Using plants as platforms to produce terpene compounds exploited in the fragrance sector seems to be cost effective.

Compared to conventional methods, microbial biosynthesis of cosmetic ingredients also seems to be promising. Biotransformation can occur in water and at reduced temperatures with high enantioselectivity. This is a more sustainable and energy-efficient method in comparison with chemical synthesis or the extraction from natural resources. In this case, it is essential to select an appropriate microbial strain (Guan et al., 2015; Wang et al., 2018; Aguilar et al., 2020).

Eichhorn and Schroeder (2023) describe ambergris and the investigation into the source of its distinctive scent, which identified (–)-ambrox as its key olfactory compound. Today, (–)-ambrox is recognized as the principal fragrance component of ambergris and is among the most widely used biodegradable aroma ingredients in cosmetics.

Traditionally, it has been synthesized from the diterpene sclareol through a series of classical chemical modifications and cyclization steps. However, the emergence of a new fermentation-derived feedstock, (E)-β-farnesene, has provided an alternative pathway via (E,E)-homofarnesol as a precursor to (–)-ambrox. The combination of chemical conversion of (E)-β-farnesene into (E,E)-homofarnesol and its subsequent enzymatic cyclization at an industrial scale highlights the role of biotechnology in enabling more sustainable fragrance production. At the same time, this approach responds to growing consumer demand for sustainably manufactured, high-quality perfumes and personal care products.

THE POWER OF PLANTS IN COSMETICS: GREEN CHEMISTRY AND NEW TECHNOLOGIES

In the cosmetic industry, a constantly developing market for natural ingredients and hence the shift of parties towards sustainable development are observed. This is distinctly illustrated by the following data – according to the projections, the market for natural ingredients is to rise from $642 million in 2022 to $1095 million in 2030. The trend reflects a significant change in consumer behavior (more than 40% of customers buying cosmetics prioritize natural ingredients in their beauty and personal care products) (CAS 2025).

On average, a cosmetic product contains between 15 and 50 different components, including solvents, pigments, surfactants, emollients, and preservatives. Unfortunately, many of these ingredients contribute to environmental, health, and social issues. Advances in green chemistry and biotechnology, however, offer sustainable alternatives—for instance, replacing petrochemical-based emollients (such as petroleum jelly, dimethicone, or phenoxyethanol) with plant-derived oils or squalene from renewable sources. Moreover, progress in biocatalysis, microbial cell factories, and solvent-free extraction techniques makes it possible to produce natural ingredients (such as esters and fatty alcohols) in an eco-friendly way and to obtain the materials that are otherwise difficult to source. These environmentally friendly solutions influence the entire value chain of cosmetic products and support sustainable development efforts both at the level of individual companies and across the cosmetics industry as a whole (Bom et al., 2019).

The modern cosmetic industry is increasingly adopting strategies aimed at reducing environmental impact while maintaining product quality and safety. Natural ingredients derived from vegetable oils, microbial fermentation, and biocatalytic processes are emerging as viable alternatives to conventional petrochemical components. These innovations reflect a broader commitment to sustainability and the development of eco-friendly cosmetic formulations. Table 3 summarizes the main categories of emollient ingredients, their sources, and their relevance to sustainable cosmetology.

Natural emollients currently represent the cornerstone of sustainable development strategies in the cosmetic sector. However, the next crucial step lies in the development and implementation of natural preservatives, which will ensure both the longevity and effectiveness of cosmetic products. This direction highlights a holistic approach to cosmetic formulation, integrating safety, efficacy, and environmental responsibility.−(Kaliyadan et al., 2021; CAS, 2025).

THE POTENTIAL OF NATURAL RAW MATERIALS IN COSMETICS

Sasounian et al. (2024) emphasized that every category of cosmetic ingredients carries both advantages and limitations. Plant-based components

Table 3. Key groups of sustainable cosmetic ingredients

Category	Example	Source / Process	Relevance to cosmetology
Hydrocarbon-based emollients	Conventional emollients	Petroleum-derived (traditionally) → shifting to vegetable oils	Occlusive and moisturizing properties; transition to eco-friendly plant-based alternatives
Squalane	Squalane	Vegetable sources (e.g., olives) or microbial fermentation	High stability, renewable origin, consumer safety
Fatty alcohols	e.g., cetyl alcohol	Sustainable agriculture, bioengineering	Replacement for synthetics; evidence of industry-wide shift toward renewable resources
Esters	e.g., Tegosoft OER (Evonik)	Biocatalytic processes	Reduced environmental footprint, innovation, and improved efficiency

are commonly applied and relatively easy to source, while those produced through in vitro culture demand specific conditions to ensure high quality. Ingredients of animal origin remain controversial and often only partially aligned with consumer expectations. Recycled or upcycled raw materials are noteworthy, as they hold considerable potential for environmental benefits and align well with circular economy principles. However, when incorporating plant-derived substances into cosmetics, it is essential to address the concerns regarding sustainable agriculture practices and the protection of biodiversity. In addition, many consumers are wary of genetic, chemical, or biological modifications in plant materials prior to their industrial use in cosmetic products. There is a lot of discussion concerning plant bioprospecting, which is the selection of wild plants with potential industrial use, as well as concerning increasing yields and accessing biological molecules ethically (Manjari et al., 2021).

Thus far, plant extracts have been used in cosmetics quite cautiously due to their peculiar odors, some color-changing profiles, and chemical instability. Nevertheless, the benefits derived from the use of plant extracts are undoubted and appreciated by consumers. Antioxidant phytocompounds in cosmetics are an example of that; apart from their effects on different skin degradation processes, they also help stabilize cosmetic formulations (Pintathong et al., 2021). Currently, cosmetic emulsions and foams are synthetic or semi-synthetic compounds (e.g. tweens, spans or sucrose esters). However, they can be of plant origin. Along with the trend to increase sustainable industrial production, renewable biosurfactants have been created. These are biocompatible and biodegradable derivatives, the advantage of which is their gradual absorption (Xu et al., 2020).

Taofiq et al. (2017) reported that numerous fruits and vegetables contain hydroxycinnamic acids and their derivatives, which contribute to skin protection against UV radiation. These compounds also exhibit antioxidant, anti-collagenase, anti-inflammatory, and antimicrobial properties. As a result, they represent valuable ingredients in formulations aimed at skin rejuvenation.

Essential oils represent another example of natural, eco-friendly substances used in cosmetology. They are most often obtained through hydrodistillation of various plant species. Due to their pleasant aroma, essential oils are widely applied in cosmetic formulations, but their antifungal and antimicrobial activities are equally important, allowing them to act as natural preservatives. Their composition is complex, typically including terpenes, alcohols, esters, and ketones, each with distinct physicochemical and biological properties (Miranda et al., 2019; Aćimović et al., 2020). In addition, essential oils are employed to combat body odor. In many cultures, excessive sweating is linked to poor hygiene, as bacteria in the underarm area can generate unpleasant smells. Conventional synthetic deodorizing agents, however, often pose risks due to uncertain toxicity or environmental impact (e.g., triclosan or aluminum salts). Consequently, the cosmetic industry has increasingly turned to natural, biologically sourced compounds as safer alternatives (Antoniotti et al., 2014).

In the cosmetic industry, microorganisms deserve special attention. Many specialists even use the term "microbial cultivation", which can offer alternative benefits associated with reduced demand for space and water compared to conventional cultivation (Hussain et al., 2022). Microbial-based biosynthesis has advantages, since it facilitates molecule purification and is an efficient and low-cost method for producing contaminant-free cosmetic ingredients (Goyal and Jerold, 2021). Another interesting technique is biocatalysis, in which microorganisms or enzymes are used to obtain cosmetic ingredients through fermentation (Heath et al., 2022). For example, *Saccharomyces cerevisiae* can use plant-extracted xylose to produce fatty alcohols. They act as emulsifiers and lubricants in the cosmetic industry (Mellou et al., 2019). In the gene co-expression method, this microorganism can also be used to biosynthetize sinapic, caffeic, ferulic and coumaric acids (Correddu et al., 2019; Rocca et al., 2022).

Synthetic polymers used in cosmetics can be replaced by bacterial nanocellulose in sustainable technologies. It is a polysaccharide produced by acetic bacteria. Therefore, it is a renewable and biodegradable product. Nanocellulose is utilized in cosmetic formulations to improve the texture of a product and enhance its action in the body. Nanometric cellulose can be obtained from different bacterial strains, e.g. *Komagataeibacter*, *Achromobacter*, *Aerobacter*, and *Agrobacterium*. Nanocellulose has a porous structure, which is a desired characteristic in the production of – among others – face masks, since it maintains an elastic structure, improves skin adhesion, and increases the penetration of active substances present in the skin pores. Owing to its viscosity, bacterial nanocellulose is particularly recommended for cosmetic gel formulations, providing the desired organoleptic properties. It can also be a microplastic substitute (Sharma et al., 2019; Almeida et al., 2021).

CONCLUSIONS

Plants are gaining increasing importance and recognition in cosmetology. With the development of civilization and technology, the use of plants in cosmetics has undergone significant transformations. Today, owing to advanced analytical methods, it is possible to precisely determine the composition of plant-based raw materials and accurately dose ingredients of proven quality. Innovative methods are also being developed for preparing plant-based intermediates for cosmetic and pharmaceutical use. Plant extracts, as well as vegetable fats and oils, remain popular ingredients in cosmetic formulations, primarily because they are well tolerated and rarely cause allergic reactions. Medicinal plants are being increasingly valued in cosmetology, and moreover, they are used in both traditional and modern methods of treatment.

Countryside regions, together with agriculture and horticulture, are an important source of natural raw materials for the cosmetics field. The fast-expanding demand for natural cosmetics and pharmaceuticals creates new prospects for the farms engaged in ecological and sustainable practices, positioning them as dependable providers of key resources. Increasing consumer interest in healthy living further strengthens the role of agriculture by linking local production with global developments in the cosmetic industry. A review of the literature confirms that the foundation of "green cosmetics production" is the responsible sourcing of sustainable raw materials. The cosmetics industry increasingly relies on organic and renewable resources, which helps reduce environmental damage, lower the carbon footprint, and align production with consumer expectations. At the same time, this approach supports biodiversity preservation and reduces the use of harmful chemicals. Ethical sourcing practices are of key importance, with companies collaborating with suppliers who adhere to strict environmental and social standards, thereby ensuring transparency and accountability throughout the supply chain. It is also necessary to implement circular economy principles, including the use of agricultural and food processing by-products as cosmetic raw materials. Certification, supply chain transparency, and full life-cycle assessments of products are essential tools for supporting responsible environmental decisions in the cosmetics sector.

In the future, the cosmetics industry should prioritize accelerating the implementation of circular economy strategies and eco-innovations, such as nanocarriers or biotechnological processes, which can enhance product effectiveness while reducing environmental impact. For policymakers, it is crucial to develop more coherent regulatory frameworks and simplified certification procedures that provide stronger support for sustainable production and fair trade. For the scientific community, future research should focus on the stability, bioavailability, and skin permeability of plant compounds, as well as on assessing their safety and long-term effects in cosmetic applications. Particularly promising are further studies on microbial fermentation, biosurfactants, and biodegradable nanomaterials, which may provide breakthrough solutions for sustainable cosmetics production.

The integration of science, industry, and policy is essential to ensure that plant-based cosmetics not only meet consumer needs but also genuinely contribute to biodiversity conservation, efficient resource management, and the achievement of sustainable development goals.

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