



Biocosmetics: technological advances and future outlook

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Abstract

The paper provides an overview of biocosmetics, which has tremendous potential for growth and is attracting huge business opportunities. It emphasizes the immediate need to replace conventional fossil-based ingredients in cosmetics with natural, safe, and effective ingredients. It assembles recent technologies viable in the production/extraction of the bioactive ingredient, product development, and formulation processes, its rapid and smooth delivery to the target site, and fosters bio-based cosmetic packaging. It further explores industries that can be a trailblazer in supplying raw material for extraction of bio-based ingredients for cosmetics, creating biodegradable packaging, or weaving innovation in fashion clothing. Lastly, the paper discusses what it takes to become the first generation of a circular economy and supports the implementation of strict regulatory guidelines for any cosmetic sold globally.

Keywords Ingredients · COVID-19 · Bioactive · Adjuvants · Organoclay · Formulations · Microbiome

Introduction

Biocosmetics are cosmetic products made from 100% natural ingredients derived from plants, animals, microbes, enzymes, insects, and organic crops that are free of pesticides and chemical fertilizers and used for topical skin, hair, face, and oral care (Vandamme 2001; Novak et al. 2014). Most of the conventional skin-care cosmetic formulations use petroleum or mineral oil-derived ingredients, which are harmful and non-biodegradable. To achieve a circular economy while satisfying customer demand for green cosmetics and addressing environmental concerns, many cosmetic giants have diverted their attention from fossil-based ingredients to bio-based ingredients. The current market for sustainable, natural, and greener cosmetics is massive because such products garner trust and respect by fairly treating nature. Additionally, government support and faster product approval for biocosmetics are creating a favorable climate for big business players such as The Estée Lauder

Companies, Inc. (USA), L'Oréal SA (France), Bare Escentuals, Inc. (USA), Nature's Gate (USA), Aubrey Organics, Inc. (USA), and FANCL Corp. (Japan). This market has seen a sharp rise over the period 2018–2021 (Market Research Report 2019). As per market analysis reports related to skin-care products, the global organic and natural cosmetic market is expected to reach USD25.11 billion by 2024 (Market Research Report 2021). Biocosmetic products with standard organic certification labels such as Ecocert, Cosmébio, NaTrue, USDA Organic, BDIH, and Soil Association allow their commercialization worldwide. The distribution channel for such products includes drugstores, pharmacies, organic food shops, health food retailers, department stores, beauty retailers, and online shopping sites.

This review highlights the importance of key ingredients in a cosmetic formulation and assesses the environmental and health risks associated with conventional petroleum-based ingredients. Active ingredients extracted from renewable bio-based alternatives are preferred because they are nontoxic and biodegradable. The search for high-performing, safe, and sustainable ingredients led many cosmetic manufacturers worldwide to explore the processes for producing natural and greener cosmetics. This review unifies technological innovation and industry in sourcing/extracting bio-based ingredients using lab cultivation processes, green synthesis of nanoformulations for fast and effective delivery,

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and selecting the best bioactive ingredient during process formulation steps using computational modeling. These scientific achievements are highly promising in incorporating new generation safe ingredients into our cosmetic products and in achieving zero waste goals.

The chemistry of a cosmetic formulation

The chemical composition of the ingredients and their doses in the formulation decides the potential impact of the formulation on our health. A typical cosmetic contains about 15–20 ingredients and considering, the use of at least five cosmetic products per day; we are placing 75–100 chemicals on our skin through cosmetic use (Jones and Selinger 2017). While the formula of a product may differ, the key ingredients in a cosmetic formulation are water, emulsifier, preservatives, thickeners, color, emollient, and fragrances (Darling 1959). Ultra-pure distilled water is the basis of almost every formulation, including creams, lotions, makeup, deodorants, shampoos, and conditioner, and acts as a solvent to emulsify for consistency. Emulsifiers such as potassium cetyl sulfate and polysorbates are added to relieve the surface tension between oil and water and form a homogenous and uniform texture of the formulation. A water-soluble preservative such as paraben, formaldehyde, salicylic acid, and benzyl alcohol is added to extend the shelf life of the product and prevent the growth of microorganisms. The concentration of preservatives may range from 0.01 to 5% (Benson et al. 2019). Thickeners, as the name suggests, increase the viscosity of the formulation by absorbing water and oil. Thickeners can be synthetic, natural, mineral, or lipid-based. Coloring agents/pigments are added to appeal to the users and fulfill their demands. A huge range of substances is used in this category including, both organic and inorganic. Organic substances come from plants or animals, such as beet powder, cochineal extract, while inorganic substances include coal tar, chromium oxide, and manganese. Emollients such as beeswax, coconut oil, olive oil, petroleum jelly, mango butter, and glycerine are used to soften the skin by reducing water loss. Fragrances are added to add a pleasant smell, which is a key factor in consumer decisions and is considered a trade secret. The USA alone approved approx. 12,500 unique chemical ingredients for personal care products (Oh and Kim 2020; Wang et al. 2020).

The transition from fossil fuel-based to bio-based cosmetics

The use of chemicals in cosmetic formulations has raised several questions on its safety aspects. Several reports in social media or news websites relate to potentially toxic compounds viz. lead, aluminum, mercury, parabens, etc., present in a cosmetic formulation. Panico et al. 2019 (Panico

et al. 2019) conducted a detailed study to assess the presence of potentially toxic substances by examining product labels. A total of 283 products, collected from various shops in Italy, were divided into three categories: rinse-off (toothpaste, shower gel, liquid soap, shampoo, soap, and shaving foam), leave-on (moisturizer, face/hand cream, sunscreen, and aftershave deodorant), and make-up (lip balm, lipstick, nail polish, and foundation). A total of 26 compounds were identified in the fragrances category as skin sensitizers, skin irritants, and allergens. Benzophenone, a component of sunscreen, is carcinogenic to humans, and due to its good lipophilic properties, this substance is absorbed in high concentrations and can be detected in biological fluids including mother's milk (Author 2010). Toluene and dibutyl phthalate, used in several cosmetic products and nail polish, enter through both dermal and inhalation routes and cause reproductive toxicity and damage to the nervous system (Hyun and Byung 2004; Kopelovich et al. 2015). A review by Matwiejczuk et al. 2020 (Matwiejczuk et al. 2020) on the use of parabens and their derivatives as preservatives in cosmetic applications stated the presence of parabens in the body in a non-metabolized form which enters by absorption, transformation, and accumulation. Few studies on cultured skin cells proved the undesirable effect of paraben on keratinocytes, fibroblast, and collagen expression (Darbre and Harvey 2008). There are dozens of studies on the safety of parabens, and hence many countries banned the use of this chemical in personal care products for infants and children (Vinet and Zhedanov 2011). Prolonged exposure to triclosan, a cosmetic preservative, can cause liver fibrosis, disrupt hormonal balance, impair muscle contraction and reduce bacterial resistance and its recommendable concentrate is up to 0.3% (Dinwiddie et al. 2014; Dhillon et al. 2015; Lee et al. 2019). Above this triclosan concentration, the word “poison” has to be labeled. Trace presence of heavy metals such as lead (Pb), aluminum (Al), chromium (Cr), cadmium (Cd), zinc (Zn), titanium (Ti), manganese (Mn) in lip products have always been a concern and invites safety regulations (Al-Saleh et al. 2009; Brown 2013; R. Sahu, P. Saxena 2014; SCCS and Rousselle 2015; Kaličanin and Velimirović 2016). Limonene, widely used for fragrance in cosmetic products, is a potential allergen (Nardelli et al. 2011; Bråred Christensson et al. 2016). Given these estimates, we could potentially be exposing ourselves to a variety of unknown hazardous chemicals, and hence a systematic and intelligent move to replace chemical cosmetics with biological cosmetics or preferring alternative substances of natural origin is of considerable interest. Table 1 lists chemical ingredients of concern used in cosmetic formulations that need immediate replacement with ingredients of natural origin.

Concerned with the toxicity of ingredients, the Australian Government's National Industrial Chemicals

Table 1 Fossil-based active ingredients used in cosmetic formulations associated with health risk

Active ingredient of concern (Fossil fuel-based)	Uses	Risk	Reference
Sodium lauryl sulfate (SLS)	Ability to foam, rinse off, or suspend certain types of ingredients, surfactants, emulsifying agents in household cleaners	Remove moisture from the skin, eyes, skin, and lungs irritant, the possible presence of human carcinogen 1,4 dioxane	(Black et al. 2001; Heefeld et al. 2020)
Synthetic colors—petroleum-based ingredients	Use in pharmaceuticals and cosmetics, artificial dyes	Contribute to cancer, allergies, hyperactivity in children, and other health issues	(Kim et al. 2021)
Phthalates: diethyl, dibutyl phthalate (DBP)	Give products a silky feel, allow the fragrance to last longer, aid lotions in penetrating and softening skin	DNA damage in sperm, which can contribute to infertility and miscarriage	(Konięcki et al. 2011)
Aluminum	Antiperspirants	Linked to breast cancer, Alzheimer's disease, and osteoporosis	(SCCS and Rousselle 2015; Kalogria et al. 2019)
Microbeads	Chewing gum, toothpaste, facial cleansers, and synthetic textiles	Contaminate our environment, water, and food supply	(Lochhead 2017; Hunt et al. 2020)
methyl-, butyl-, and propyl-paraben	Antimicrobial and preservative agents, cost-effective, and easy to use	Endocrine disruption, reduced fertility, and cancer risk	(Evans et al. 2016)
Paraffin wax	Easily spreadable, soothe achy joints, used in moisturizing products, skin hydration	Carcinogenic, inhalation of the particle leads to allergy and asthma	(Gomes et al. 2020a)
Mineral oil	Moisturize skin, keep skin hydrated, non-lergic	Skin irritant such as rash or burning, inhalation to lungs cause breath shortness/coughing	(Chuberre et al. 2019)
Toluene listed as methacide, methylbenzene, phenylmethane, and toluol	Used in nail polish and hair dyes	Most toxic ingredients, developmental damage to the fetus, and blood cancer	(Al-Hajri and Del Bigio 2010; Verma 2012)
Triclosan: high-concern ingredient	Antibacterial soaps, deodorants and toothpastes, anti-gingivitis and anti-plaque agent	Hinder muscle function, endocrine disruption, create drug-resistant germs, and colon tumorigenesis	(Dhillon et al. 2015; Lee et al. 2019)
Anything with PEG (polyethylene glycol)	Used as cosmetic cream bases, moisture-carriers, thickeners, softeners, penetration enhancers, and surfactants	Often contaminated with ethylene oxide or 1,4-dioxane which are carcinogenic, irritation, and system toxicity	(Fruijtier-Pölloth 2005)
Anything with DEA (diethanolamine) or TEA (triethanolamine)	DEA-emulsifier in shampoos, cleaners, and detergents TEA-fragrance, pH adjuster, and emulsifying agent	Accumulates in liver and kidney, reduce sperm ability to swim, impaired memory, and brain development in offsprings	(Panchal and Verma 2013)(Gamer et al. 2008)
EDTA (ethylenediaminetetraacetic acid)	Stabilizer, preservative, improve the foaming abilities of cleansers, soaps, and body washes	Reproductive toxicity and irritation, weakly mutagenic	(Lanigan et al. 2002a)
Any word with propyl—isopropyl alcohol, propylene glycol, propyl alcohol, and cocamidopropyl betaine	Surfactants, use rinse-off cosmetic products as a foam booster, antistatic agents, and hair-conditioning agents	Dermal irritants, allergies, rosacea, and eczema	(Burnett et al. 2012)
Formaldehyde-releasing preservatives	These preservatives are present in a wide range of cosmetics, as well as in cleaning products such as toilet bowl cleaners	Formaldehyde-releasing preservatives continuously release small amounts of formaldehyde, a known human carcinogen	(Moennich et al. 2009; Lv et al. 2015)

Table 1 (continued)

Active ingredient of concern (Fossil fuel-based)	Uses	Risk	Reference
Coal tar dyes: listed as p-phenylenediamine or colors titled "CI" and followed by a 5-digit number	Color additive in lipsticks, used in many hair dyes	These dyes are mixtures of petrochemicals and linked to cancer in humans, brain damage	(FDA 2019)
BHA (butylated hydroxyanisole) and BHT (butylated hydroxytoluene)	Synthetic antioxidants, preservatives, stabilizer, and most common in lipsticks and moisturizing creams	Disrupt the endocrine system	(Jayalakshmi and Sharma 1986; Lanigan et al. 2002b)

Notification and Assessment Scheme (NICNAS) set a regulatory control on the import, use, and manufacturing of cosmetic chemicals in Australia so that every ingredient contained in the product is scientifically assessed to ensure the safety of the user (Phua 2020). The European Union (EU) banned 1328 chemicals used in cosmetics that are responsible for a genetic disorder, birth defect, and reproductive harms, while the number of ingredients banned by the Food and Drug Administration, USA is a mere 12, possibly due to lack of updates in federal regulations since 1938 or strong favoritism toward cosmetic manufacturing companies (Alexa Riccolo 2021; Pistollato et al. 2021). Other countries such as Canada, Japan, China, Ethiopia, India, Cambodia, and Vietnam are also banning the chemical ingredients or amending the existing regulations to satisfy the public safety concerns and spreading awareness through warnings on cosmetic labels (Raj and Chandrul 2016; Pistollato et al. 2021).

In addition to the toxicity of fossil-based ingredients, several other factors such as environment, sustainability, cost, effectiveness, and long-term health push for the much-needed transition from conventional to bio-based cosmetics. Due to a rapid decline in nonrenewable sources and strict environmental regulation, the market demand for natural products derived from oils, agricultural plants, and bacteria has increased substantially over the past few years (De Mejia et al. 2020). Bio-based personal care products offer waste reduction, recycling, low-energy consumption, safety, and well-being (Secchi et al. 2016). Natural and oleochemical ingredients such as 2-ethyl hexyl stearate, cetyl stearyl, and polyhexanide render natural healing, increased effectiveness, and fewer allergic reactions (Kulka 2009). They are safer and cheaper to produce, source, and ship compared to their chemical alternatives. Their low cost is due to the abundance of raw materials in Southeast Asia with modern biorefinery technologies and safety owing to the bio-based processes such as fermentation that are not only safe but also less energy-intensive. An example is butylene glycol, a widely used emollient and humectant in cosmetics, produced by fermentation of plant-based sugars making it a more natural and sustainable alternative than catalytic dehydrogenation of carcinogenic acetaldehyde (Fulmer et al. 1933; Dwivedi 2020). Conscious consumers and manufacturers care for social and environmental responsibilities. However, a lack of knowledge and standardization for "eco-labels" allow manufacturers, suppliers, and advertisers to use this term voluntarily without any compulsion or consequences (Cervellon and Carey 2012). Selling natural ingredients in cosmetics is also a secret marketing strategy for industries to enhance their brand value and improve customer loyalty.

Active ingredients and adjuvants

The active ingredient is a term for a pharmaceutical drug that is biologically active. In cosmetics, the active ingredient is a marketing terminology and refers to substances claimed in skincare products to target skin concerns. The skin has three main layers i.e., epidermis, dermis, and subcutaneous tissue, and a few appendages such as hair, nail, sweat, and sebaceous gland. As shown in Fig. 1, the route of transport of a cosmetic ingredient through the skin can be transepidermal (intercellular or transcellular) and transappendageal. The delivery through the latter is of low importance because it constitutes a very small area (01–1%) of the skin surface. Skin influences penetration of active ingredients depending on physiological factors such as skin permeation and skin retention (dependent on age, ethnicity, gender, and skin disorder), drug physicochemical properties, and the properties of the vehicle (Soares et al. 2015).

Active ingredients are often supported with scientific studies to show the efficacy of the target and categorized into antioxidants, astringents, exfoliant, humectant, skin conditioner, and surfactant. Examples are, alpha/beta hydroxy acids (AHA/BHA), ceramides, hyaluronic acid (HA), niacinamide, peptides, retinol, vitamin C, E, etc. (Darling 1959). AHA/BHA works by exfoliating the dead skin by dissolving the bonds between skin cells. Ceramides are fat molecules that protect our skin from pollution and other environmental stressors and keep the skin hydrated and moisturized. HA, a moisture-binding ingredient, keep the skin soft and radiant and is mostly used in anti-aging skincare products. Niacinamide has anti-inflammatory properties and boosts the level of fatty acid in our skin. Peptides signal the body to produce more collagen, retinol is a derivative of vitamin A, which promotes skin renewal, boosts cell turnover, and is used for acne-fighting ability. Vitamin C is proven as an antioxidant scientifically to boost the synthesis of collagen, minimize

scars and wrinkles. Alpha-lipoic acid is an antioxidant and is soluble in both oil and water.

Adjuvants are ingredients that help in preparing the formulation with desired properties to ensure delivery of the active ingredients, for example, emulsifier, buffer, thickener, preservative, surfactant, fragrance, emollient, humectant, occlusive, and penetration enhancer. They determine the product form, such as gel, serum, cream, etc.; maintain the product texture, enhance the performance of active ingredients, prevent microbial growth and chemical decomposition, and help to make the product smell nice and look good. The label on a cosmetic product lists the ingredients used for its preparation as per International Nomenclature of Cosmetic Ingredients (INCI) names. The ingredients are listed in decreasing order of their content in the formulation. This information gives the customer an informed choice for choosing a product.

Ingredients used in biocosmetics, active, or adjuvants, can be categorized as animal or vegetable-derived fats, waxes and oils, essential oils and oleoresins, vegetable saps and extracts, raw plant materials, and coloring matter of animal, or vegetable origin. Europe, the largest cosmetic market in the world, provides enough opportunities to developing countries to export natural ingredients (Centre for the Promotion of Imports from developing countries 2020). Due to increasing consumer demand and the need for sustainable raw materials, companies are putting efforts to replace synthetic ingredients with their natural variants. Table 2 lists common feedstock imported by European countries for bio-based chemicals (Centre for the Promotion of Imports from developing countries 2020). The top six natural ingredients in the European cosmetic market are shea butter, coconut oil, mango butter, frankincense essential oil, patchouli essential oil, and licorice extract. Since 1992, Greentech group, a France-based biocosmetic firm and one of the importers in the list has been using plants, algae, micro-algae, and

Fig. 1 Various routes of ingredients delivery through the skin

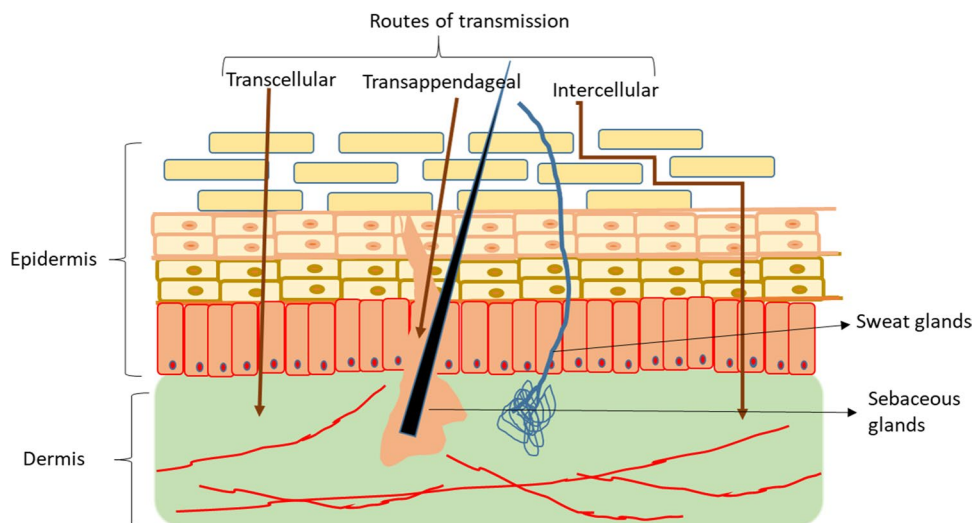


Table 2 List of commonly exported feedstock by developing countries to the European market

Class/category	Feedstock examples	Other remarks	References
Vegetable saps and extracts	Pomegranate extract, Aloe vera extracts, lavender, sea buckhorn and rosemary extracts, licorice, ginkgo extract, hops extract, marsh-mallow leaves, extract, etc	Protection from UV-A and -B rays, skin soothing and improving psoriasis, skin brightening, anti-aging and firming properties, medical or drug-like benefits, antioxidant, and antimicrobial	(Spekreijse et al. 2019; Centre for the Promotion of Imports from developing countries 2020)
Vegetable and animal-derived oil, fats, and waxes	Palm oil, olive oil, babassu oil, coconut oil, sunflower oil, rapeseed oil, hemp oil, avocado oil, shea butter, fat of cattle, fat of sheep, fat of buffalo, waxes of plant origin (commonly present as thin flakes), etc	Derived from plants, either from seeds or, less often, from other parts of fruits	(Centre for the Promotion of Imports from developing countries 2020; 2021)
Coloring matter of vegetable and animal origin	Alkanet (red/purple), annatto (orange/red), avocado (green/yellow), chamomile (blue), hibiscus (red/pink), nettle (green), etc	Derived from various parts of plants and other biological sources such as fungi and lichens	(Spekreijse et al. 2019; Centre for the Promotion of Imports from developing countries 2020)
Raw plant-based materials such as sugars, cellulose, and oils	Apple water, clover honey, comb honey, spring flower honey, green tea, lavender, nettle, rosemary, sandalwood water, etc	Surface-active agents as emulsifiers, solubilizing agents, etc. Humectants, thickening agents, film formers as well as polymers	(Spekreijse et al. 2019; Centre for the Promotion of Imports from developing countries 2020)
Essential oil and oleoresins (mixture of essential oil and a resin)	Peppermint, jasmine, lavender, basil oil sweet, cardamom seed, chamomile blue, caraway, lemongrass, lemon balm, lemon oregano, etc	Obtained by distillation and used in perfumery and personal care sector	(Barbieri and Borsotto 2018; Centre for the Promotion of Imports from developing countries 2020)

microbes to extract/develop active ingredients. URBALYS®, obtained from *Shisandra Chinensi*, EXPOZEN®, obtained from *Halymenia durvillei*, SOLIBERINE® obtained from *Buddleja* officials flowers, and HEBELYS®, obtained from optimized fermentation of *Sphingomonas sp.* are some of the newly launched products by Greentech group using new generation skincare active ingredients (Filaire 2019).

Technological advances favoring biocosmetics

Green synthesis of nanoparticles

Nanotechnology in cosmetics plays a big role in better performance, non-cytotoxicity, and bioavailability of active ingredients in personal care products. The active ingredients adsorb on the surface of nanoparticles and help in efficient absorption, increased color and finish quality, and enhanced penetration through the skin. Modifying the shape, chemical composition, size, solubility, and chemical reactivity of the nanoparticles used in the cosmetic formulation helps in further enhancement of cosmetic products such as shelf life, efficacy, and performance (Chaudhri et al. 2015). Different metal nanoparticles are used in cosmetic formulations, such as silver (Ag), gold (Au), titanium (Ti), zinc oxide (ZnO), Mica, platinum, alumina, copper, and fullerenes (Chiari-Andréo et al. 2019). TiO₂ and ZnO nanoparticles are non-oily and can be easily absorbed. TiO₂, ZnO, and ZrO₂ nanoparticles act as UV filters and are used in sunscreens, lip balms, and moisturizers (Wawrzynczak et al. 2016). Several research papers outline the pros and cons of nanotechnology in cosmetic formulations and describe their various types which impart different characteristics to cosmetic products (Mihriyan et al. 2012; Raj et al. 2012) (Ekpa Effiong et al. 2020). Nanoparticles used in cosmetics are liposomes, nanoemulsions, nanocapsules, solid lipid nanoparticles, nanocrystals, nanosilver, nanogold, dendrimer, hydrogel, etc. The synthesis and characterization procedure is also well described in the literature (Paiva-Santos et al. 2021) (Naveed Ul Haq et al. 2017) (Harishchandra et al. 2020). However, due to the small size of these nanoparticles, they can easily enter the bloodstream through skin or via inhalation to be transported to various organs. Malfunction of vital organs is also possible with higher doses and longer residence time of nanoparticles (Oberdörster et al. 2005; Subhashini et al. 2017). Environmental concerns have also been raised due to the release of nanoparticles into the air, water, and soil during their manufacture, use, and disposal. The ability of zinc oxide (ZnO), silver (Ag), titanium dioxide (TiO₂), cerium oxide (CeO₂), Cu, and Fe metal nanoparticles to induce oxidative stress has been reported (Manke et al. 2013). Fullerenes are known to kill water fleas besides

bacteriocidal properties and the potential of biomagnification (Brunet et al. 2009). The toxicity and regulatory aspect of nanotechnology-based products need careful consideration before implementing them in direct contact with our skins.

Due to drawbacks associated with conventional methods of synthesizing metal-based nanoparticles, green synthesis of nanoparticles is receiving attention due to nontoxic, clean, and eco-friendly methods which protect the ecology and restore the quality of the environment (Paiva-Santos et al. 2021) (Arroyo et al. 2020) (Keijok et al. 2019). Green synthesis of silver nanoparticles hybrid from the natural extract by Arroyo et al. 2019 (Arroyo et al. 2020) was found to be highly effective and an affordable alternative for the market. Abdullah et al. 2021 (Tan Sian Hui Abdullah et al. 2021) reported the synthesis, characterization, and application of Ag-nanoparticles from the extract of red-onion peel and display higher antioxidant properties as compared to ascorbic acid. These studies suggest the development of nonhazardous and biocompatible green catalysts for organic transformations. Biocompatibility and safety aspects of Phyto-metal nanoparticles (Phyto-MNPs), plant-mediated green synthesis of nanoparticles, synthesized for dermo-pharmaceutical, and cosmetic applications is detailed in a review by Paiva-Santos et al. 2021 and suggests the high potential of green synthesis toward clinical translation.

Biotechnological ingredients: safe and effective

The contribution of biotechnological processes toward the cosmetic market is huge owing to the production of safe and effective active ingredients via low-cost and contamination-free methods. Gomes et al. 2020 (Gomes et al. 2020) discuss some of these biotechnological processes and products used for developing cosmetic formulations. Some of the active ingredients resulting from biotechnological processes are kojic acid (Lajis et al. 2013), hyaluronic acid (Pan et al. 2015; Cheng et al. 2017), resveratrol (Donnez et al. 2009), human epidermal growth factors (Ferrer-Tasies et al. 2021), superoxide dismutase (Carroll et al. 2007), and photolyases (Marizcurrena et al. 2020). Traditional biotechnology exploits the potential of microbes via fermentation, while modern biotechnology manipulates the genetic material and inserts it in a suitable host for the desired application. During fermentation, microbes/enzymes are used as biocatalysts in bioreactors for large-scale production of proteins, secondary metabolites, and cosmetic ingredients, and the process is further optimized for enhanced productivity and yield (Sajna et al. 2015). Fermented food items viz. sauerkraut, kimchi, cheese, tempeh, beer or wine, etc. are well-accepted and possess multiple benefits. Similarly, fermented ingredients for cosmetics such as fermented coconut

(*Lactobacillus/Cocos nucifera* fruit extract) (HANDAY-ANI et al. 2008), fermented chili (*Lactobacillus* and *Cap-sicum frutescens* fruit ferment extract) (Xu et al. 2021), fermented pumpkin (*Lactobacillus/pumpkin* fruit ferment filtrate) (Park et al. 2019) offer the ability to replace conventional synthetic preserving agents, stimulate blood circulation for strengthening of hair and scalp, and exfoliating properties, respectively. Organic acids viz. citric acid, lactic acid, glycolic acid, etc. produced by microbial fermentation processes are the most versatile ingredients and used in pharmaceutical and cosmetic industries (Vandenbergh et al. 2018). Hemisqualane, made via fermentation of sugarcane, is a sustainable and naturally derived alternative to cyclomethicone, a type of liquid silicones used as an emollient, stabilizer, etc. in cosmetics products and associated with bioaccumulation and toxicity (McPhee et al. 2014). Fermented ingredients are considered new-generation active ingredients in cosmetic startups (Ecovia Intelligence 2020a) “Hands on veggies” in Austria is one such start-up working on organic ferments and encouraging pure plant-based products and recyclable packaging made of organic plastic.

Recombinant DNA (rDNA) technology is a process for the production of a wide range of pharmaceutical compounds from genetically manipulated microbe/plant/animal cells. Examples of rDNA technology are lipids/oil from algae, proteins derived from stem cell lines, stabilized enzymes for topical application, etc. (Rinaldi 2008). Microalgae is a rich source of fatty acids, lipids, proteins, amino acids, and algal extract from *Spirulina* that has been used as an antioxidant, and anti-aging agent (Miranda et al. 1998; Bermejo et al. 2008; Koh et al. 2017). The ability of stem cells to regenerate old damaged cells is remarkable and various plant stem cells showed a great effect in the treatment of wrinkles, improved skin elasticity and smoothness, and improved activity collagen production (Bazylak and Gryn 2015; Miastkowska and Sikora 2018). Different peptides, produced via biotechnological processes, are shown to trigger fibroblast for collagen synthesis, stabilize trace elements needed for wound repair, and inhibit neurotransmitters at the neuromuscular junctions (Weidmann and Craik 2016; Bae et al. 2020). The use of marine biotechnology in fighting against aging, inflammation, generation of free radicals, and degradation of skin cells is gaining momentum (S. Babitha 2011; Wu and Lu 2011). A product Homeo-Sea from Atrium Biotechnologies combines ingredients from four different parts of algae as Homeo-Shield, Homeo-Age, Homeoxy, and Homeo-Soothe and is used as a “marine solution for skin homeostasis.” Biotechnology also has an important role in the development of bio-based polymers for replacing plastic with bioplastic for recyclable and biodegradable

cosmetic packaging and contributes toward sustainable global growth (Degli Esposti et al. 2021).

Bio-based cosmeceuticals

When a pharmacy meets cosmetics, it is known as cosmetic pharmaceuticals or cosmeceuticals. Cosmeceuticals have both cosmetic and therapeutic value, but this term is a marketing term and does not have a legal meaning. Common ingredients present in cosmeceuticals are listed in Table 3. Some ingredients are permitted in cosmetics at low concentrations while are classified as drugs at higher concentrations. As a consumer, we want to have multiple benefits from a cosmetic product. Imagine you apply lipstick or lip balm, and in addition to great color and smell, it rejuvenates or regenerates your cracked lips. Developing such skin-care formulations along with consumer therapeutics benefits is the need of today’s cosmetic industry. However, cosmeceuticals are low-risk products that have defined skin benefits as per cosmetic indications. They are categorized based on the etiology of the target conditions such as skin lightening, sunscreens, scar reducing, antioxidants, anti-aging, etc. Rice bran, one of the most abundant agricultural by-products, when fermented with mixed cultures of *Aspergillus oryzae* and *Rhizopus oryzae* was confirmed as an anti-pigmentation and anti-aging agent for cosmeceutical potential (Abd Razak et al. 2017). Jerusalem artichoke extract or powder fermented with *P. rhodozyma* for astaxanthin synthesis was studied because of its anti-inflammatory, sun proofing, anti-aging, antioxidative, and immune-boosting functions (Jiang et al. 2017). *Aronia melanocarpa* leaf and fruit extract are used in cosmetic products for skin conditioning, skin whitening, anti-inflammatory, and collagen-boosting properties (Cujic et al. 2017; Lee and Ryu 2018). Novel cosmeceutical delivery systems that act as smart carriers for encapsulation or attachment of therapeutic ingredients need to be explored. Arora et al. 2012 (Arora et al. 2012) listed some novel cosmetic delivery systems viz. vesicular delivery system, particulate systems, emulsion delivery systems, and delivery devices such as iontophoresis and cosmetic patches which can help to modulate the skin barrier or administer active ingredients in the skin while minimizing systemic involvement. Some of the commercially available smart delivery systems are microsponge, unispheres, natipide II, Orgasol, Elespher, etc. (Arora et al. 2012). Herbal extracts or ingredients used to cure diseases are explored in the literature to usher in a new era of cosmeceuticals (Patil et al. 2017).

Microbiomics: targeting skin microbiome with biocosmetic

Our skin microbiota is comprised of millions of microbial species including, bacteria, yeast, fungi, and viruses, and

Table 3 Commonly used ingredients in cosmeceuticals

Class	Examples	Function	Reference
Sunscreens	Zinc oxide and titanium dioxide, ecamsule, avobenzone, octocrylene, p-aminobenzoic acid, dioxybenzone, etc	Protect against skin tumors and increase reactive oxygen species	(Shanbhag et al. 2019)(Wawrzynczak et al. 2016)
Antioxidants	A-lipoic acid, vitamin C, B3, E, N-Acetyl-glucosamine (NAG), and ubiquinone (CoQ10)	Antioxidants generate free radicals, which “mop up” and reduce inflammation and pigmentation. Protect skin against sun damage due to collagen breakdown or skin cancers	(Simo et al. 2014; Van Tran et al. 2019)
Hydroxy acids	α -hydroxy acids (AHAs), polyhydroxy acids (PHAs), and β -hydroxy acids (BHAs)	Known as “fruit acids,” they provide hydration to skin and promote shedding of dead skin, improve skin texture and signs of aging	
Retinoid	Tretinoin or retinoic acid, retinol, and retinaldehyde	BHAs promote pores penetration and fats solubility Acts as skin repair from photodamaged skin and reduce fine line, excessive pigmentation, and wrinkles	(Sorg et al. 2006; Babamiri and Nassab 2010; Alamgir 2017)
Skin lightening agents	Hydroquinone, vitamin C, kojic acid, azelaic acid, licorine extract (glabridin)	Inhibit melanin production, act as a skin lightening agent and prevent skin discoloration	(Badreshia-Bansal and Draelos 2007)(Sarkar et al. 2013)
Botanicals	Plant extracts from leaves, roots, fruits, berries, stems, bark, and flowers. For example, soy, curcumin, silymarin, pycnogenol, ginkgo biloba, green tea extract, grape seed extract, aloe vera, witch hazel, allantoin, and ferulic acid	Antioxidants, anti-inflammatory, and skin soothing agents	(Kumar 2017)(Campa and Baron 2018)
Peptides and proteins	Pentapeptide pal-KTTKS	Short-chain amino acids that imitate biological signals and accelerate/inhibit skin aging	(Husein el Hadmed and Castillo 2016)(Alamgir 2017)
Growth factors	Heparin-binding endothelial growth factor, Fibroblast growth factor, types 1, 2, and 4, Platelet-derived growth factor, Type-1 insulin-like growth factor	Important in wound healing and damage repair by stimulating collagen/elastin production	(Husein el Hadmed and Castillo 2016)(Alamgir 2017)

maintaining the right balance between them is required for healthy skin (Byrd et al. 2018). Several skin disorders have been associated with alteration in microbial communities, such as atopic dermatitis with *Staphylococcus aureus* species (Kim et al. 2019), acne with *Cutibacterium acnes*, and *Staphylococcus epidermidis* (Fournière et al. 2020), dandruff with *Malassezia* species (Saxena et al. 2018), psoriasis with an increase in Firmicutes (Koper et al. 2020), etc. Some microbes modulate the body odor in particular auxiliary odor by decomposition of apocrine sweat and foot odors from eccrine sweat (James 2020). A range of cosmetic products has been developed to improve or alter our skin microbiota. The first cosmetics developed to study the effect of the microbiome on auxiliary odor were deodorants. Since then, new approaches were exploited to treat acne, dermatitis, or even dandruff. Dr. Chris Callewaert created “Dr. Armpit,” a communication platform to discuss research on the microbiology of body odors. The majority of the skin microbiota are still not studied due to difficulty in their isolation. Very specific symbiotic living conditions make them almost impossible to grow in lab conditions. Bacterial species with high impact on dry, oily, and normal skin types are *Cutibacterium acnes*, *Staphylococcus Epidermidis*, and *Corynebacterium Kroppenstedtii*, respectively (DSM 2018). Today, diversity among skin-related bacterial communities is widely explored in forensic studies as well.

The current skincare market analyses four approaches i.e., removing bacteria, feeding good bacteria (prebiotic), adding good bacteria (probiotics), and adding by-products of bacteria (postbiotic). Often there are hurdles while developing a cosmetic formulation on probiotics, i.e., living bacteria due to the maintenance of their integrity and survival, their lifetime, and impact on skin microbiota and hence “probiotic”-containing products are either lysate or fermentation extracts. Elle Magazine, 2015 named probiotics as “bacteria which make us beautiful.” Vogue, 2016 claimed probiotics as an “invisible anti-aging shield.” Elle Magazine, Madame, Figaro, Shape, and Vanity Fair, 2017 claimed probiotics as a “solution for beauty.” Some pre, pro, and postbiotic beauty products occupying the cosmetic market are The One Restorative Cream, Symbiome, Bio Barrier Nourishing Oil, Biophile, Vitamin C Probiotic Polish, Osea, Moisturizer, Mother Dirt, Pre + Probiotic Daily Mist, Marie Veronique, Revitalise and Glow Serum, Aurelia Probiotic Skincare, etc. There are plenty of opportunities to create, redefine or reposition the established products. Major players who turned their attention toward developing microbiome-based cosmetics are Unilever, Johnson and Johnson, Amore Pacific, L’Oreal, Bebe & Bella, Esse, and Mother Dirt. Some of the key challenges associated with a flourishing market are lack of standards and regulations, lack of clinical evidence, and the limit on microorganisms in cosmetic products (Dreher-Lesnick 2018; Boxberger et al. 2021).

Cosmetic use of organofilization technology

Organoclay is defined as the combination of clay minerals (phyllosilicates) and organic surfactants (quaternary alkylammonium salts and others). Organoclays are formed when the hydrophilic surface is modified by introducing long-chain organic compounds (organofilization) for high sorption of organic pollutants and reduced volatile organic compounds (VOCs) (de Paiva et al. 2008). In cosmetic use of organofilization technology, organically modified clays and active agents are used to develop biocomposites/nanocomposites with better quality and shelf life. Salmiņa et al. 2021 (A. Salmiņa, R. Ozola-Davidane 2021) proposed anthocyanin-based composites in biocosmetics by intercalating anthocyanin into montmorillonite. Anthocyanins are water-soluble natural pigments with antioxidant activity and play a vital role in many health disorders such as diabetes, cardiovascular diseases, cancer, etc. But these molecules are unstable with changes in pH, temperature, and light and limiting their usage (Georgiev et al. 2014; Santos-Buelga and González-Paramás 2018). Once combined with clay minerals, these pigments can be stabilized and used for a wide range of applications such as food, biocosmetics, and biomedicine (Ribeiro et al. 2018; Rose et al. 2018). A recent study investigated the use of polylactide (PLA)-organoclay nanocomposite for cosmetic packaging, a biodegradable solution for conventional petroleum-based plastic (Connolly et al. 2019). PLA is produced industrially (NatureWorks® LLC, USA) through fermentation of sugars (starch, sugarbeet, and corn) however factors such as brittleness, cost, and poor gas barrier properties limit the use of these polymers. Depending on the structure of clay material and its dispersive nature, these composites may confer more strength and enhanced barrier properties due to the compatibility of hydrophilic organoclay with polymeric matrix (Prakalathan et al. 2012; Darie et al. 2014; Murariu and Dubois 2016). The use of nanoclay and organoclay-based composites in cosmetic packaging and migration studies related to the release of these materials into cosmetics is still limited and needs further investigations.

Hydrotalcite (HT) or layered double hydroxide (LDH) is an anionic clay, a versatile substance and “darling of the science world.” Its name is derived from its resemblance with talc and high water content. HT hybrids offer drug encapsulation with high loading capacity, non-toxicity, controlled and targeted delivery, biocompatibility, and desired superficial accumulation of active ingredients through the skin (Ryu et al. 2010; Jin et al. 2020; Kesavan Pillai et al. 2020). It helps to enhance rheological properties as well as stabilization of the cosmetic formulation. Encapsulating the actives in HT extends their release time and, in turn, increases the effectiveness and tolerance. HT is an anion exchange material and its guest–host type structure offers

exceptional intercalation chemistry for a wide range of applications (Kesavan Pillai et al. 2020). In sunscreens, HT hybrids/LDH are used as carriers for controlled delivery of chemicals (UV absorbers/filters), which on direct contact with skin may cause skin allergies or irritation (Perioli et al. 2006, 2008; Costantino et al. 2008; Li et al. 2017; Egambaram et al. 2019). Due to its versatility, HT hybrids can also be used as a smart carrier delivery system for the transfer of natural pigments, which are essential for skin but suffer from disadvantages such as low stability, skin irritations, pH and temperature limitations, and light irradiations (Bernardos et al. 2019).

Identify, predict, and screen bioactives with artificial intelligence (AI)/machine learning (ML)-based approaches

AI/ML-based tools like SkinBug (Jaiswal et al. 2021) help predict the reaction between active molecules and skin microbes and determine whether it will be bio-transformed or metabolized to other products to ensure product safety. AI is not only used for the selection of bioactive ingredients, but it also has a bigger role in the selection of formulation process and in offering customized cosmetic formulations. An Irish biotech company “Nutritas” uses genomic technology and AI to identify and extract unique bio-peptides or bioactive peptides for health benefits. Their focus is to identify them first using AI and then extract these ingredients to unlock health potential. Beiersdorf, a company behind Nivea and La Prairie, announced a partnership with a biotech firm “*Insilico Medicine*” for discovering new active ingredients for cosmetics using AI. AI-powered skin analysis uses face-mapping technology and looks for signs of aging, pigmentation, skin tone, elasticity, skin texture, moisture, brightness, etc., and allows shoppers to suggest the right cosmetic product for specific skin and health requirements. An MIT-founded AI-driven start-up “Atolla” (Deanna Utroske 2021) uses AI to develop skin-specific customized serum and claims its ingredients to be vegan, cruelty-free, without added fragrance, allergy-friendly, and responsibly farmed. Some of the principal, supporting actives and base ingredients in such formulations are coconut extract, ginger root extracts, cactus extract, prickly pear extracts, rumex occidentalis extract, alpha arbutin, betaine, diacetyl boldine, willow bark, apricot kernel, oil, safflower seed oil, etc. All top beauty brands MAC, Estée Lauder, Clinique, L’Oréal, and Neutrogena dedicate their resources to AI to compete in the global market and anticipate emerging trends. Using big data and machine-learning algorithms, beauty apps such as ModiFace, CareOS Technologies’ Smart Mirror, FOREO For You provide customized skincare products as per skin concerns and goals.

Personalized cosmetic with 3D bioprinting

3D bioprinting or additive manufacturing is a process where tissue-like structures are built in record time to mimic the natural tissues of our body. It enables the production of the patient’s cells, which are perfectly compatible during skin grafting or even during organ replacement (Velasquillo et al. 2013; Yan et al. 2018). Bioinks used in bioprinters are biocompatible materials such as polysaccharides, protein, synthetic polymers, etc., and depending on the application personalized treatment can be developed, e.g., depigmented surface for treating vitiligo can be treated with growth factors, stem cells, and cytokines (Czajkowski 2011). Skin scars, often hyperpigmented, can be treated with bioprinting by incorporating a specific amount of melanocytes. Inducing hair follicle regeneration using stem cells has also been demonstrated in the literature (Weinberg et al. 1993).

The first living organ to be introduced in the market is a human skin made of all three layers. The key to success i.e., how to mix the individual bio components is patented by CIEMAT (Center for Energy, Environmental and Technological Research) (Cubo et al. 2017). Printed skin was successfully used to treat burns and surgical wounds. This technology is revolutionizing the beauty industry as a game-changer by attracting interest from cosmetic giants such as L’Oréal, BASF, and Procter & Gamble from the skincare industry. Unlike the current facemask, where valuable serum leaks everywhere, facial recognition technology like MaskiD helps us to scan and print 3D sheet masks for applying on your face perfectly without any leakage. “Mink,” the first 3D printer for wearable make-up, allows users to choose image color either from the web or in the real world and print that color into blush, eye shadow, lip-gloss, etc. A new development in 3D cosmetics is “human hair” that makes the lives of cancer patients easier. L’Oreal and French biotech company Poietis signed an agreement to bioprint hair follicles capable of growing to attack baldness. Another application is cosmetic packaging such as Collcap Packaging with Objet 3D Pro 3D printing system for cosmetics and perfumes.

Role of industries in offering natural ingredients

Food and marine industry

Cosmetic ingredients are categorized into active ingredients, excipients, or additives. The marine industry opened up many possibilities for the isolation of active ingredients, and nearly 25,000 new bioactive compounds have been identified (Alves et al. 2020). Some of them are high commercial value market products used in pharmaceuticals and cosmetics (Martins et al. 2014a). Marine bacteria, micro-algae,

macro-algae, and halophytes are the major source of compound isolation (Lopes et al. 2016). As listed in Table 4, the bioactive compounds extracted from marine organisms are used for treating skin-related issues. A few marine ingredients are used as excipients and additives in cosmetic formulations for preservatives, essential oil, antioxidants, and dyes (Guillerme et al. 2017; Thiyagarasaiyar et al. 2020).

Dietary ingredients when used in cosmetics are referred to as food-based cosmetics or healthier cosmetics or nutraceuticals. Detoxifying effects and safety of food ingredients are the major motivations behind this industry. Nutrients present in food such as minerals, vitamins, lipids, proteins, carbohydrates, polyphenols, etc. either provide energy or repair the body for proper functioning. Some dietary ingredients such as vitamins, and carotenoids act as antioxidants, neutralize the free radicals generated during irradiation with UV or during oxidative stress, and prevent skin aging (Akbar et al. 2020). Bioactive peptides, derived from food proteins, offer antioxidant, antimicrobial, immunomodulatory, cytomodulatory properties, and other metabolic effects. Once absorbed, they modulate the physiology of systems and improve skin permeability, solubility, stability, and interaction with cell surface receptors. A bioactive peptide can be a signal peptide, carrier peptide, or a neurotransmitter inhibiting peptide. Their development through enzymatic hydrolysis and microbial fermentation has challenges such as stability, susceptibility to further hydrolysis, and reproducibility due to the uncontrollable nature of metabolic activities in microbes respectively. Several companies e.g., PharmaSpecial®, Galena®, Biotec®, Lipotec®, and Silab® are investing their efforts and money developing innovative bioactive peptides. Despite many cosmetic ingredients from marine or food sources, only a few are commercialized because of the need to optimize the process for its production and purification. Furthermore, cost analysis and scalability of the process to ensure the feasibility and performance test to study the effectiveness and safety of cosmetic formulations are needed for large-scale applications.

Textile industry

With the growing trend toward a greener and sustainable market, the textile industry is also looking for innovative ways to create fabric, which can transfer active substances on contact with the skin. The idea is to impart natural ingredients to the fabric so that the wearer's skin can be moisturized, slimmed, energized, or protected against UV radiations (G and S 2018). To achieve this, microencapsulation technology appears to be a suitable method because of its versatile and flexible nature. In this technology, active ingredients are encapsulated in microcapsules, which are tiny particles of liquid/solid material (core) surrounded by a continuous film of polymeric materials (coating), and act as a barrier for the controllable release of core content (Cheng et al. 2008; Martins et al. 2014b; Carvalho et al. 2016; Nandy et al. 2020). The natural movement of the body, pH, temperature, humidity triggers microcapsules in cosmetotextiles and breaks up to liberate cosmetic ingredients to the skin. Cosmetotextile is associated with toxicity due to polymeric coatings and hence fabric with natural/bio-based microparticles known as dermatextile replace cosmetotextile. Dermatextile offers deep penetration of active ingredients into tissues and protects/preserves skin and hair. Developing odor-resistant textiles, incorporation of fabric with vitamins and minerals are some of the innovative ideas of the future textile industry. The hydrophobic odor molecules entrap in the cavities of cyclodextrins and wash up during laundering (Andreaus et al. 2010). Natural materials used for impregnation of textile are plant derivatives such as aloe vera, padina povonica, flowers, fruits, essential oils, animal derivatives such as chitosan, squalene, and sericin, and synthetic materials such as iron oxide, ethanediol, zinc oxide, and zinc nanoparticles (G and S 2018). The cosmetic finish is not just for the wearable fabric but also applicable for interior textile products such as curtains, bedsheets, pillow covers, carpets, etc. A neck warmer, debuted in 2015 by L'Oréal and Roxy, claimed for skin nourishing is made of microcapsules that contain anti-inflammatory ingredients such as apricot oil,

Table 4 Bioactive ingredients isolated from marine organisms and their use in cosmetic products

Marine organisms	Compounds extracted	Use in cosmetics	References
Bacteria	Mycosporine-like amino acids, carotenoids, polyphenolics, peptides and proteins, lipids, fatty acids, glycosides, and isoprenoids	Antioxidants, antibacterial, photoprotection, anti-aging, skin hydration and skin moisturizing, anti-melanogenesis	(Poli et al. 2010)
Microalgae	Carotenoids, canthaxanthin, astaxanthin, lutein, and phycobiliproteins	Source of pigments and vitamins. Antioxidants, UV protectors, thickening agents, skin sensitizers, moisturizing agents, tanning, etc	(Mourelle et al. 2017)
Macroalgae	Phycocolloids, minerals, polysaccharides, proteins, lipids, and secondary metabolites	Anti-aging, antioxidants, moisturizing and hydrating lotion, collagen-boosting effect, anti-inflammatory, antiviral effect, etc	(Pimentel et al. 2018)
Marine halophytes	Phenolic compounds and tyrosinase inhibitors	Antioxidant and anti-inflammatory activities, skin hyperpigmentation	(Lopes et al. 2016)

shea butter, marine-christe extract, and antioxidant vitamin E (Mellage 2016). Beiersdorf launched Nivea Q10 plus firming and shaping shorty said to encapsulate Q10 ingredients (Knott et al. 2015). The global market for cosmetotextile is expanding with products in the market that prevent the skin from aging, wrinkles, brown age spots, and UV radiations.

Biopolymer industry

The diverse range of synthetic and natural polymeric materials are used in cosmetics for applications such as film former in hair fixatives, rheology modifier in gel, emulsifier and waterproofer in sunscreens lotions and makeup, hair and skin conditioner, emollient in lotions, pigment disperser, emulsion stabilizer, thickener, and as micropore sponge for controlled release of ingredients (Lochhead 2007, 2017). Synthetic polymers are classified into homopolymers viz. polystyrene, polyisobutene, etc., copolymers viz. acrylamide, acrylate, simple vinyl polymers, etc., and cross polymers viz. adipic acid/diethylene glycol/glycerin, etc. Natural polymers can be homopolymers i.e., mono, di, and polysaccharides, heteropolymers composed of different monosaccharides and their derivatives, large groups of complex polysaccharides attached to proteins, protein type polymers, and nucleic acid. Other subcategories are silanes or siloxane-based polymers. Natural polymers are used as thickeners, structuring agents that give rigidity, hair products are starch, gelatin, agar, alginates, polysaccharides, pectin, xanthan, or guar gum, hydrolyzed proteins, cellulose derivatives, natural waxes, long-chain fatty alcohols, and triglycerides (Aggarwal et al. 2020). Biopolymers serve as a delivery system for natural antioxidants, antimicrobial and anti-acne ingredients such as hydrogel based on collagen chitosan, gellan gum (Lochhead 2017; Das and Giri 2020; Mitura et al. 2020) micro, nano, and carboxymethylcellulose with crosslinking agent alginate encapsulating bioactive compound from *Chlorella vulgaris*, etc. (Morais et al. 2020).

Rubber industry

Natural rubber latex obtained from *Hevea brasiliensis* is a milky fluid with polymer cis-1,4-polyisoprene and various plant proteins and is known to possess antibacterial and antiviral properties for plant protection. Natural rubber latex has high strength, tensile strength, easy film-forming, and the capability to stretch without breaking. Compounds from natural rubber are exceptionally flexible, corrosion-resistant, and electric insulators. Natural rubber is positioned as a cleaning sponge in the cosmetic industry. The Thailand Center for Excellence and Life Sciences (TCELS) claimed to transfer innovation and technology to companies for several skincare products with rubber latex extract in collaboration with other leading universities (Andrew McDougall 2014).

In a study by Oya et al. 2000 (Oya et al. 2000), natural rubber latex is used for making a cosmetic Eye Putti® for treating blepharoptosis and showed satisfactory results. In another study by Pichayakorn et al. 2013, a peel-off mask was prepared from natural rubber latex (Pichayakorn et al. 2013). However, several latex-derived products such as face and body paints, eyelash adhesives, hair bonding adhesives, eyeliner, etc., are associated with allergic reactions and need FDA approval before commercialization (Zaza et al. 1994; Smith et al. 1998; Farnham et al. 2002).

Waste industry

Recycling waste is an excellent approach in the new sustainable cosmetic product development to address consumer needs. Different categories of agro-industrial residues e.g., food by-products, vegetable peels, groundnut oil cake, soybean oil cake, coconut oil cake, ashes, clays, seeds, stalk, leaves, roots, husk, bagasse, molasses, etc., are explored for extraction of natural ingredients. Such wastes are rich in healthy compounds and produced in heavy volumes due to consumption by a large population. Ingredients extracted from food waste such as orange peels, coffee grounds, broccoli leaves/stems have been used for developing cosmetics groundnut scrub, face cream, and peel-off masks (Pacífico et al.). The food processing industry generates an enormous amount of non-edible waste, which has safe and effective ingredients to create biocosmetics. Sugarcane ash, the byproduct of the sugar industry produced after burning sugarcane bagasse, has become a source for a new ingredient “silica,” widely used in the personal care industry. Aprinova, a leading manufacturer of natural and sustainable emollients and silicone replacements, claims that “Biosilica” can be used as a sustainable alternative to silica used in foundation, creams, lotions, etc. Research studies demonstrated the mesoporous structure of biosilica for high adsorption capacity (Rovani et al. 2018), sebum control, and as a photochromic pigment filler (Chindaprasirt and Rattanasak 2020). Oil palm leaves and leftover residue contain antimicrobials such as alkaloids, tannins, and flavonoids and are used in producing soap bars (Febriani et al. 2020). Sugar beet pulp, waste during extraction of sugar from sugar beet and is usually sent for animal feed, is used to produce 2G-lactic acid via continuous fermentation by *Bacillus coagulans* used in a variety of applications such as plastic replacement, medical sutures, controlled release of drugs, etc. (Febriani et al. 2020). Table 5 lists some of the waste residues widely used for the extraction of bioactive. The Biowaste program funded by European Commissions Department of Agriculture aims to explore agricultural products with high protein and oil-containing residues under a project “Apopros,” and products derived from fruits and vegetables under another project called “Transbio” (Giorgio Dell’Acqua, Ph.D. 2017).

Table 5 Agricultural and Industrial wastes utilized for the extraction of bioactive ingredients in cosmetics

Waste	Active ingredients	Benefits	References
Coffee waste: unused coffee beans, spent coffee grounds, and silver skin/husks	Phenols and polyphenols (Caffeoylquinic acids, caffeic acid, and ferulic acid), linoleic acid, phytosterols	Antioxidants, protect against accelerated aging, protect against UVB, limit photo-aging and/or stimulate skin repair, increased skin hydration	(Toschi et al. 2014; Abdeltaif et al. 2018)
Tomato waste: unused pulp, skin, and seeds	Caffeic acid, ferulic acid, chlorogenic acids, quercetin-3- β -O-glycoside, quercetin, lycopen, naringenin-chalcone	Antioxidant and anti-inflammatory activities, modulate cell growth, and impart anti-mutagenic properties	(Stajčić et al. 2015; Nour et al. 2018)
Olive waste: olive oil mill wastewater (OMWW), olive pomace, and filter cake	Polyphenols (hydroxytyrosol, tyrosol, caffeic acid, vanillic acid, verbascoside, oleuropein, ferulic acid, and p-coumaric acid), ammonium, and phosphorus	Strong antioxidants, inhibit cancer cell proliferation and protect DNA from oxidative damage, antimicrobial potency, anti-aging, inhibition of melanogenesis	(Rodrigues et al. 2015)
Mango fruit waste: leaves, stems, bagasse, seeds and kernels, peels, and barks	Dietary fiber (pectin/cellulose), carotenoids, flavonoids, polyphenols, and phytosterols as campesterol, sitosterol and tocopherols, and hydrolysable tannins	Antioxidants, anti-inflammatory, and antibiotic potential	(Wall-Medrano et al. 2020)(Tesfaye 2017)
Chestnut waste: leaves, burs, and husks	Minerals (Fe, Zn, Cu, K, and Ca), CsL ellagic acid, and gallic acid Derivatives, phenolics, and flavonoids, such as chlorogenic acid, rutin, hyperoside, and isoquercitrin	Antioxidants, anti-wrinkle properties, protection from UVB, and activation of proteolytic enzymes	(Flórez-Fernández et al. 2020; Hu et al. 2021)
Citrus waste: peel, molasses, seeds, and leaves	Flavonoids, carotenoids, phenolic compounds, vitamin E, phytosterols and essential oils, terpene d-Limonene, and perillyl alcohol	Antioxidant, anti-inflammatory, immune-stimulatory, antimicrobial, preservatives, protect from UV-induced inflammation	
Peel waste: potato and red beet	Minerals (Fe, Zn, K, and Ca), vitamins (B and C), polyphenols, and phenolic acids such as gallic acid, protocatechuic acid, vanillic acid, caffeic acid, chlorogenic acid, p-hydroxybenzoic acid, and p-coumaric acid, fatty acids, alkaloids, tannins, flavonoids, and lipids. Betaine	Antioxidants, antibacterial properties, skin lightener, skin conditioning, humectant, emollient, color pigments, and hepatoprotective actions	(Samarin et al. 2012; Costa et al. 2017; Pathak et al. 2018; Samotyjia 2019)
Onion skin, leftover roots of sansing green onions, and garlic husk	Fiber and phenolic compounds, such as quercetin and other flavonoids, Di-ferulic acid, hydroxybenzoic acid, p-coumaric acid, caffeic acid-O-glucoside, coumaric acid-O-glucoside, caffeoylputrescine, bactericidal alliin, mallic acid, phosphate sugar, prosta-glandin	Antimicrobial and antioxidant properties, melanin synthesis inhibition, anti-aging, skin whitening, and moisture retention	(Kallel et al. 2014)(Chen et al. 2019)

The challenging part is to extract and purify the ingredients without compromising the stability of ingredients in an environmentally friendly manner with a high yield. In some studies, the toxic nature of these wastes has also been demonstrated, e.g., coffee silverskins, the main waste of the coffee-roasting industry, have undesirable compounds such as phytosterol-oxidized products (POP) and ochratoxin A (OTA). OTA has been classified as a possible carcinogen by the International Agency for Research on Cancer (IARC) and is known to induce nephropathy, renal toxicity, and immunosuppression (Ferraz et al. 2010; Kumar et al. 2012). Its content is three times higher than permissible limits in coffee silverskin and is a risk to human safety (Toschi et al. 2014). Agro-waste can also be contaminated with fungal toxins, pesticides, and industrial chemicals and hence they need careful neutralization before putting it for human use (Abou Fayssal et al. 2020).

Beauty and personal care: post-COVID-19 outbreak

The coronavirus pandemic has affected every facet of the economy and redirected our minds to create a better and healthier world. During the pandemic, the cosmetics industry was severely affected due to the disrupted supply of raw materials, production processes, marketing, and distribution of finished products. The impact of COVID-19 on the cosmetic industry was discussed in European and North American editions of the Sustainable Cosmetic Summit 2020 and emphasized the need for a circular economy in the beauty and personal care industry (Deanna Utroske 2020). During this summit, industry experts and executives discussed several approaches, such as a change in existing cosmetic formulations, ingredients, growing consumer sentiments toward natural products, and sustainable packaging. The key issues of the summit were (1) cosmetic products are directed to interact with human virome to maintain good skin health, (2) the growing consumer trend is toward natural ingredients to boost skin immunity and hence the beauty industry must leverage the products with anti-inflammatory and skin immune-boosting ingredients, (3) changing sustainability agenda in the cosmetic industry, implementing good sustainability practices in the cosmetic industry, and choosing the product sustainable “inside and out,” (4) disruption of supply for raw material due to higher freight costs, longer transportation times, and quarantine measures at ports during the pandemic is encouraging the operators to go regional for natural ingredients, (5) upcycling food ingredients e.g., a French firm developed a product for eye puffiness and dark circles from discarded avocados, Givaudan Active Beauty launched Koffee’ Up™, an alternative to argan oil, from spent coffee grounds, Rahn AG and Cargill beauty is upcycling pumpkin

seeds and leftover lemon peel for skin care products (Ecovia Intelligence 2020b; Deanna Utroske 2020), (6) sustainable palm oil and rainforest ingredients, which are environmentally and socially acceptable, (7) the social value of cosmetics by promoting social inclusivity and multiculturalism, (8) retailing implications due to the ongoing shift to digital, and (9) marketing to the post-COVID consumer by focusing on health-related product development.

Factors fueling the growth of the cosmetic industry before COVID-19 were modern lifestyle coupled with aesthetic appeal plus highlighting/promoting the brand on various media platforms. However, with the coronavirus outbreak, the cosmetic market segment experienced a severe downfall due to lockdown and the worldwide closing of offline stores (Wood 2020). Several factories shifted to making hand sanitizers and cleaning agents to ensure their survival (Miller 2020). Although the COVID-19 outbreak forced the world to close borders, it kickstarted the idea to build back better with increasing demand for natural and healthier products. As per a recent survey, consumers perceive healthy skin as one of the resistant factors against environmental stress, and hence natural and organic ingredients are gaining more popularity after the pandemic (Intelligence. 2020). Suppliers of aloe vera, grapeseed oil, tea tree oil, CBD oil, palm oil reported a spike in demand for natural ingredients (Imogen Matthews 2019; Intelligence. 2020), and research studies in the past also demonstrated the importance of natural ingredients in personal care products and showing how nature can heal, smoothen, restore and support us to cope with life’s demands. For example, aloe vera, termed as the plant of immortality by ancient Egyptians, has both antibacterial and antiviral properties and is used in a variety of cosmetic products (Long 2016). Eucalyptus oil has virus-fighting properties, and essential oil-based ingredients such as balm, inhalers, and diffusers reduce virus transmission (Sienkiewicz et al. 2011). Grapeseed oil strengthens connective tissues along with its anti-inflammatory, antioxidant, and healing properties (Sumaiyah and Leisyah 2019). Green tea and black tea molecules were found to inhibit virus entry (Carneiro et al. 2016; Mahmood et al. 2016; Ohgitani et al. 2021). Palm oil, palm kernel oil, and its derivatives, present in almost 50% of the cosmetic products, are a rich source of vitamin E, carotenoids, squalene, lauric acid, etc., and are used as antibacterial liquid soap (Nainggolan and Sinaga 2021). Tea tree oil is a popular natural ingredient used in shampoos, skin and nail creams, massage oils, and laundry detergents. It is a known antiseptic agent used against bacteria, fungi, viruses, and mites (Larson and Jacob 2012). Tea extract and lemongrass, rich with phenolic compounds and antioxidants, are used for producing hand sanitizers with enhanced antimicrobial efficacy (Rana 2021). Post-Covid, Australian companies observed high demand for lemon oil, and 180,000 new lemon myrtle (*Backhousia citriodora*) and

anise myrtle (*Syzygium anisatum*) trees were grown to ramp up the production (Intelligence. 2020). Consumer sentiments toward hygiene, wellness, and safety are going to cause a longer shift in their spending priorities and trade down to value-for-money products. From the current scenario, it is predictable that sanitation and immunity-booster products will continue to occupy the high demand with a focus on family and self-care.

Future outlook

Zero waste cosmetic

Adopting a “zero waste” policy is an important step to stop cosmetic waste from entering the human body through a polluted environment. Implementing zero waste and zero CO₂ emission policies in the sourcing, extraction, production, and packaging processes of cosmetics will push the idea of “Green Growth.” Recycling industrial waste should not be an option rather an obligation to achieve a circular economy. Several make-up beauty brands such as Alima Pure, Axiology, The lip bar, Aether beauty, RMS beauty are adopting this policy and prioritizing cruelty-free, vegan, non-GMO ingredients and recyclable glass or fiber, paper-based packaging. The environmental impact of conventional cosmetics made of microbeads, microplastic, and triclosan is huge and calls for serious attention (Anagnosti et al. 2021). These smaller size particles are impossible to clear out of the ocean, become a part of the natural cycle, and enter the food chain. VOCs in fragrances and sprays cause smog and air pollution (Steinemann et al. 2021). The UV filters avobenzene, octocrylene, and oxybenzone in sunscreens are known to enter systemic circulation, contaminate the environment and crop productivity (Matta et al. 2019) (Zhong et al. 2020). Pesticides and chemicals sprayed on crops, which are used for the extraction of ingredients pose severe damage to human health (Kuang et al. 2020). Ultrafine crystalline silica (SiO₂) nanoparticles used in cosmetics alter genes and cause severe mutations. There is strong evidence that nanoparticles reach our brain through inhalation and cross the blood–brain barrier (Oberdörster et al. 2002). Wet wipes, used for cleaning our face, removing make-up, and cleaning baby bum are flushable and eventually reach oceans. Sea creatures such as turtles die when they consume these wipes (Ó Briain et al. 2020). BHA and BHT, synthetic antioxidants used as cosmetic preservatives, enter aquatic species and cause genetic alteration (Lundebyea et al. 2010). Although the above-mentioned environmental offenders raise serious concerns and cosmetic brands are committed to recycling cosmetic waste, progress is still very slow because recycling is not an easy one-step solution. Recycling waste is more complicated than it may seem and is associated with several

challenges (1) manual sorting and segregation of hazardous and non-hazardous waste where technology does not replace the decision-making ability of humans, (2) exposure of occupational workers to dust and airborne contaminants, (3) safety of workers toward potentially toxic substances and educating them about recycling equipment, and (4) cosmetic packaging is a mixture of different materials, making hard to recycle. A long-term sustainable solution is to switch from conventional to waste-free natural cosmetics.

Transformation to beauty and wellness with new generation natural ingredients

Moving away from illness, treatment, quick fix, reactivity, and obligation of current cosmetics toward the vitality, prevention, long-term effectiveness, proactivity, and experience offered by biocosmetics is the current consumer mindset. The cosmetics sector offers tremendous future opportunities for startups involved in the formulation and customization of products as per individual skin characteristics, replacing fossil-based ingredients with natural, clean, vegan, sustainable, and high efficacy ingredients, encouraging social inclusivity, and niche-focusing products based on gender, age group, price, etc. The technological advancements, as discussed, offer ways to produce natural, and effective ingredients with controlled and targeted delivery formulations. Industries, which offer bio-based raw materials such as agricultural, food, marine, waste industry, biopolymers, bioplastics, natural rubber, are helping to reduce carbon footprints and creating a recyclable and biodegradable regime for cosmetic products. Today’s ingredient-savvy consumer is demanding a combo of beauty and wellness and prioritizing quality over quantity. A new concept “beauty inside out” requires proactively looking into new-generation natural ingredients such as green surfactants and green materials with the aid of technological advancement. For example, natural deep eutectic solvents (NADES), the “natural” solution, is a new and exciting technology for the production of eutectic natural solvents where metabolites are solubilized inside the plant (Jeliński et al. 2019; Osowska and Ruzik 2019). Protective and defensive compounds extracted from marine algae (Stiger-Pouvreau and Guerard 2018), anti-aging, antioxidant, anti-wrinkle, skin-firming ingredients using plant-cell culture (Georgiev et al. 2018), novel cosmetic delivery systems (Patravale and Mandawgade 2008), stem cell-derived cosmetic products (Zarei and Abbaszadeh 2018), and novel anti-infective short antimicrobial peptides, as cosmetic ingredients (Rahnamaeian and Vilcinskas 2015) are some of the recent research addressing this area. Many natural ingredients with cosmetic potential are difficult to penetrate the skin barriers, showing poor bioavailability, low solubility, and uncontrolled release (Dini and Laneri 2021); therefore, novel methods of encapsulating these natural

bioactive substances with immediate and tangible results need further exploration. Cosmetic use of organoclay is also limited, with good color retention for nail paints, eye shadows, and lipstick, and offers a tremendous future opportunity to explore other applications.

Commitment to sustainability

With the rise in demand for natural and greener products, concerns arise toward sustainability. The production of grains (oat, barley, and wheat) based extracts used in face creams and foundations have concerns with water pollution (Almendinger et al. 2020; Hwang et al. 2020). Palm kernel oil-based products such as lipstick, soap, shampoo, etc., have concerns about massive deforestation and plant and animal diversity, and hence cosmetic companies are keen to search for an alternative such as coconut oil and babassu oil (Kaupper et al. 2020; Whiffin et al. 2016; Martinez et al. 2017). Sustainability is multidimensional and must address all economic, environmental, and social aspects. Company sustainability should have a “think green” holistic approach i.e., right from sourcing the raw material to the extraction of bioactive ingredients, formulation processes and finish, product testing, final packaging, and ultimately the marketing strategies. The “eco-conception approach” reviews all processing steps in terms of resource management, energy utilization, global impact, waste management, waste consumption, quality control, and lowering carbon footprints. Today, many cosmetic products do not deliver what they claim, which is a big disappointment for the customer. To address this problem, transparency on the sourcing of raw material, processing the ingredients as per regulatory guidelines on the use/concentration of ingredients in cosmetic formulations must be achieved that will ensure quality, integrity, and safety of the product. Eco-compatible cosmetic packaging is receiving much attention due to its reuse, recycle, and biodegradable nature; however, it poses a challenge due to packaging often contaminated with cosmetic residues difficult to remove by washing. Compostable packaging replaces plastic packaging with bio-based polymers and bioplastic, but the degradation is affected by the presence of detergents or preservatives detrimental to microbial activity (Asgher et al. 2020). Therefore, a correct product design and packaging material need careful consideration based on the intrinsic instability of cosmetic formulation so that the property of a cosmetic product does not change on storage, transportation, or exposure to UV radiations.

Facing challenges of “going green”

Biocosmetics are environmentally friendly, protect our long-term health, nourish and heal the skin naturally, and do not mess up with natural hormone production and fertility.

However, gray areas do exist in the biocosmetic industry that needs future exploration: (1) the slowness of natural ingredients obtained from plants and animals, (2) the high cost of biocosmetic products, especially when pure/concentrated bioactive ingredients are to be used in the formulations, make them unaffordable to the majority of the customers, (3) low shelf life and non-vibrant colors with a limited number of shades available, (4) fear of blemishing brand reputation due to risk in the supply chain of raw material across continents, (5) environmental impact of using agricultural-based raw materials, (6) seasonal fluctuation in the desired compound production from plants, and (7) lack of unified international standard guidelines for “green cosmetic producers” and risk assessment approaches. The adverse effect has also been reported in the past from plant extracts (Franca and Ueno 2020) and some of the natural substances are found to be non-degradable; therefore, safety analysis and compliance with the green chemistry principle is essential even for biocosmetic products.

Conclusions

The review describes concerns with current cosmetics used in day-to-day life and justifies the move toward green cosmetics. The ingredients used in personal care products are silent killers and responsible for deteriorating human health without their awareness. Cosmetics companies are self-regulated for more than a century and enjoyed enough luxury of self-policing and weak regulations. But now, safety concerns must be addressed, and regulations the same as pharmaceutical drugs must be implemented. Today’s “well-informed” consumer is concerned about the origin, safety, environment, and sustainability. As discussed, the role of advanced technologies and industries in developing natural, sustainable, and healthier cosmetics is crucial to fulfilling consumer demand. Naturality with sustainability is the key to long-term survival for cosmetic companies, and they must set their products accordingly to compete in the fast-paced market. These companies must be accountable for their product designs, safety and efficacy of ingredients, and safe and recyclable packaging.

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