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A sustainable life cycle for cosmetics: From design and development to post-use phase

Ana M. Martins, Joana M. Marto *

Research Institute for Medicines (iMed.ULisboa), Faculty of Pharmacy, Universidade de Lisboa, Av. Professor Gama Pinto, 1649-003, Lisboa, Portugal

A R T I C L E I N F O

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A B S T R A C T

The cosmetics industry is increasingly concerned with the environmental, social and economic impacts of the manufacture and use of its products. Sustainability in cosmetics is first addressed in the design phase, which influences all the subsequent phases. During selection and sourcing of raw materials, sustainability can be increased by substituting conventional ingredients by sustainable alternatives, use of fair-trade ingredients, synthesis of ingredients using green chemistry, upcycling of agro-food industry byproducts into added value ingredients, and development of waterless products to decrease water footprint. Sustainability during manufacture involves implementing innovative factories which reuse water and energy, for example. Furthermore, companies are also educating the consumer on how to sustainably use cosmetics. In the post-consumer phase, recycling, reusing or refilling the used packaging is preferred to landfill disposal. Finally, companies must also address the carbon footprint arising from the several distribution phases.

Here, we review the main strategies used by cosmetic companies to increase sustainability throughout the life cycle of their products. Real-life examples are presented, from multinational companies addressing sustainability at all levels, to smaller brands focusing in a single life cycle phase. We mainly focus on the environmental domain of sustainability, although social and economic problems are also tackled.

Abbreviations

ALS	Ammonium lauryl sulfate
APGs	Alkyl polyglucosides
BYO	Bring Your Own (water)
CSPO	Certified Sustainable Palm Oil
DES	Deep eutectic solvents
ECHA	European Chemicals Agency
EDDS	Ethylenediamine-N,N′-disuccinic acid
EDTA	Ethylenediaminetetraacetic acid

* Corresponding author. Research Institute for Medicines (iMed.ULisboa), Faculty of Pharmacy, Universidade de Lisboa, Av. Professor Gama Pinto, 1649-003, Lisboa, Portugal.

E-mail addresses: amtbs.martins@gmail.com (A.M. Martins), jmmarto@ff.ulisboa.pt (J.M. Marto).

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EU	European Union
FDA	Food and Drugs Administration
GLDA	Glutamic acid, N,N-diacetic acid
LNG	liquified natural gas
NaDES	Natural deep eutectic solvents
NGOs	Non-governmental organizations
OMWW	Olive mill wastewater
PCR	Post-consumer regrind (plastics)
PET	Poly(ethylene terephthalate)
QACs	Quaternary ammonium compounds
ROS	Reactive oxygen species
RSPO	Roundtable on Sustainable Palm Oil
SCG	Spent coffee grounds
SDG	Sustainable Development Goals
SLES	Sodium laureth sulfate
SLS	Sodium lauryl sulfate
SPICE	Sustainable Packaging Initiative for CosmEtics
SPOT	Sustainable Product Optimization Tool
TEWL	Transepidermal water loss
UN	United Nations

1. Introduction

Sustainability was defined by the United Nations (UN) Brundtland Commission, in 1987, as “meeting the needs of the present without compromising the ability of future generation to meet their own needs” (Keeble, 1988). As an English noun sustainability is defined by the Oxford dictionary as “the ability to be maintained at a certain rate or level”. Thus, sustainability is based on a dynamical equilibrium between development and growth and the resources needed to attain these. These are simplified definitions; sustainability is, in fact, a very complex concept comprising three dimensions: environmental responsibility, social solidarity and economic efficiency (Purvis et al., 2019).

In today's fast-paced, overpopulated world, resources are being depleted, the climate is changing, and sustainability is being challenged. Thus, concrete efforts are underway to ensure there is a return to equilibrium. In 2015, all member states of the UN adopted the 2030 Sustainable Development Agenda, which provides guidelines for the prosperity of people and the planet. This agenda contains 17 Sustainable Development Goals (SDG), which acknowledge that a sustainable development must balance environmental, social, and economic domains, and that action in one will affect the others. The 17 SDG are an urgent appeal to all countries to unite in a global partnership to find strategies to improve education and health, decrease inequalities, stimulate economic growth, and address climate changes, preserving oceans and forests (United Nations, 2022).

Businesses and companies are an essential part of sustainability changes, and sustainable enterprises are increasing worldwide. The objective of these companies is to reduce the environmental, social, and economic impacts of their products, using resources but not depleting them, avoiding pollution, contributing to a circular economy and considering all social aspects of their operations.

One of the reasons why companies are becoming increasingly interested in the sustainability aspects of their products is the consumer itself. Consumers are more aware of the environmental and social problems of the products they buy, leading to the exponential growth of the sustainable products market. According to data published by the Institute for Business Value in 2020, 60% of consumers said that they were willing to change the way they buy to reduce the environmental impact of their choices, while 80% claimed that sustainability is important for them. Most of the consumers in this last group indicated that they were willing to pay more for sustainable and environmentally friendly brands (Haller et al., 2020).

The cosmetics industry is also becoming more sustainable to address consumers’ concerns. According to the Regulation (EC) No 1223/2009 of the European Parliament and of the Council of 30 November 2009, a cosmetic product is defined as “any substance or mixture intended to be placed in contact with the external parts of the human body (epidermis, hair, nails, lips and external genital organs) or with the teeth and the mucous membranes of the oral cavity, with a view exclusively or mainly to cleaning them, perfuming them, changing their appearance, protecting them, keeping them in good condition or correcting body odours” (European Parliament 2009).

The consumer of cosmetics is more aware of the problems associated with these products, and searches for more *natural, green, organic* products, which are associated with a concept of *health*. Additionally, there is a greater awareness of the social problems associated with these products, such as child labor, and the environmental problems related to the use of synthetic ingredients, deforestation and animal exploitation, for example. Furthermore, raw materials suppliers can now offer a wider variety of sustainable ingredients and the legislation on sustainability has been changing and becoming stricter. The recent COVID-19 pandemic also contributed to this global change towards more sustainable lifestyle, across all consumer goods categories, including cosmetics. The pandemic increased the concern about the human and the planet's health, as stated by Oliver Wright, the managing director of the corporate consultancy company Accenture: “People have clearly made a link between the singularity event of COVID-19 and the fact this is linked to planetary change. We are seeing a lot more interest in understanding questions around sustainability and the impact on people's health" (Culliney, 2021a).

The transition to more sustainable products started by substituting synthetic materials/ingredients by more natural ones. Currently, the cosmetics industry is trying to address the whole life cycle of its products, including the ethical and responsible use of ingredients, fair trade, resources used during the manufacture, management of waste and residues, and the use of recyclable, reusable or biodegradable packaging. Hence, increasingly, cosmetic companies are addressing not only environmental sustainability options, but also embracing social and economic sustainability.

This review paper addresses the current advances in sustainability practices in the cosmetics industry, from the design to the post-use phase, and provides insightful examples on how companies have been increasingly turning to more sustainable processes and practices.

2. A sustainable life cycle for cosmetic products

The production of any manufactured good impacts sustainability at all its levels: environmental, social and economic (Bom et al., 2019; Cosmetics Europe, 2012). It starts by the development and design phase, where the product is designed, and continues throughout the selection of ingredients and supply of raw materials, the manufacture phase, the packaging, the transport and distribution, retail, use by the consumer and the post-use phase (Fig. 1). The sustainability of a cosmetic product is defined at the initial phase of its life cycle, the design phase, which influences all subsequent ones (Cosmetics Europe, 2012).

Nowadays, *organic, natural* and *green* labels are everywhere, in all kinds of products. But what is the difference between these and sustainable products? Although the terms are often used interchangeably, they are not synonyms. Usually, *organic, natural* and *green* refer to the origin and type of agricultural practices used to obtain the ingredients for the products and does not necessarily mean sustainable. Thus, green cosmetics are those mainly containing natural and/or organic ingredients and that avoid the use of synthetics. Sustainable ingredients, however, are those where all dimensions of sustainability (environmental, ethical and social, and economic) are addressed in all phases of the product lifecycle (Bom et al., 2019).

Currently there are hundreds of cosmetic companies that integrate sustainability in one or several phases of the life cycle of their products. For example, beauty giants such as Garnier and L'Oréal introduce sustainability along the entire life cycle of the product. In 2019, the L'Oréal group was recognized as *Global Compact LEAD,* due to its program "*L'Oréal For The Future* – Sustainability Commitments for 2030", reasoned on 3 different premises: (i) the transformation and evolution of the industry should respect the limits of the planet; (ii) the capacity building of the business ecosystem should be promoted to help the transition to a more sustainable world; (iii) there should be a contribution for the resolution of the challenges that the world is facing, supporting the urgent environmental and social needs. To address (i) L'Oréal defined clear objectives concerning the use of natural resources: to address climate change, the company compromised to reduce 50% of greenhouse gases per final product until 2030, contributing to the maintenance of the global temperature at no more than 1.5 °C above the pre-industrial levels; regarding water consumption, there are efforts to maintain a sustainable management of its consumption, with the implementation of waterloop factories which will substitute all conventional plants until 2030; respect of biodiversity, by eliminating all practices that lead to deforestation until 2030; preservation of natural resources, by implementing solutions that allow recycling and promote the development of a circular economy. Concerning (ii), L'Oréal believes it is its to involve consumers, suppliers and communities in the transformation processes, helping them transition to a more sustainable world by defining quantifiable objectives. Finally, about premise (iii), L'Oréal invested 150 million euros in this project, to address some of the more urgent current environmental and social needs, promoting programs to support extremely vulnerable women, to contribute to nature regeneration and to promote circular economy (L'Oréal, 2020). Garnier, a company belonging to the L'Oréal group, created Garnier's Green Beauty Initiative to address the whole value chain of the brand, decreasing or eliminating the environmental impact of its products (Garnier, 2020; L'Oréal, 2022b). The company aims to achieve several goals by 2025: (i) sustainable sourcing of raw materials and fair trade (Garnier already uses naturally sourced ingredients, such as South African bee wax, Hungarian acacia honey, calendula oil from France, and Aloe vera from Mexico, and intends to support 800 communities worldwide by 2025); (ii) decrease water consumption by creating solid products (e.g., 94% natural origin and 97% biodegradable ecological solid

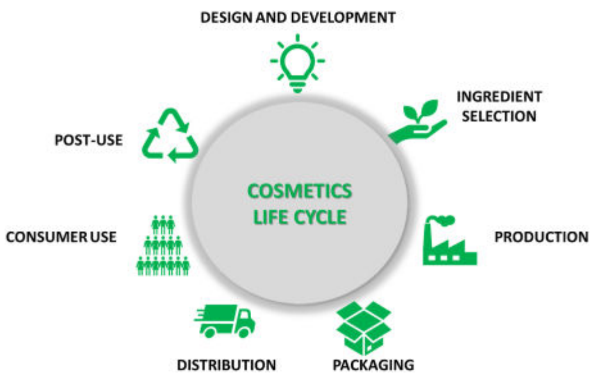

Fig. 1. Main phases of the life cycle of a cosmetic product.

shampoos which last longer than liquid shampoos); (iii) substitute all the packaging non-recyclable plastics for recyclable, biodegradable and/or reusable ones, thus reducing plastic production by 37 k tonnes per year; (iv) employ only renewable energy sources and 100% CO_2 neutral plants by 2025 (the CO_2 emissions have already decreased 72%); (v) decrease plastic pollution by teaming up with NGOs (e.g., Ocean Conservancy, Plastics for Change).

But not only giant cosmetic companies are addressing the sustainability of their products. Throughout this review paper, several smaller companies will be mentioned, which have been contributing to the sustainability of cosmetics.

3. Formulation of sustainable cosmetics

This section deals with formulation sustainability, from ingredient selection (sections 3.1., 3.2 and 3.3) to the introduction of innovative concepts, such as the waterless products (section 3.4). Sustainability strategies used in subsequent phases of the product's life cycle will be presented in the corresponding sections (sections 4 5 and 6).

3.1. Sustainable ingredients

The selection of raw materials as ingredients for cosmetic formulations is crucial to ensure their sustainability (Bom et al., 2020c). Nowadays, it is very clear that the planet's resources are finite, and some are rapidly getting depleted, leading to deforestation, decreased biodiversity and climate change. Simultaneously, consumers are increasingly demanding more sustainable products. The combination of these factors emphasizes the need to establish specific and differentiator criteria for a sustainable selection of raw materials, considering the environmental, social and economic impacts.

Key points that must be addressed when selecting sustainable raw materials have been discussed by our group (Bom et al., 2019, 2020a, 2020c, 2021): (i) what is the composition and biodegradability of the raw materials; (ii) what are the sources of the raw materials (natural – animal, vegetable or microbial origin, synthetic, naturally-derived, etc.); (iii) how were the raw materials synthesized, extracted, purified, etc.?; (iv) what are the social and economic impacts of obtaining and using such raw materials?

Concerning key-point (ii) different sources of raw materials are usually classified as natural, naturally derived, nature-identical, organic or synthetic. *Natural* ingredients are directly obtained from nature, by plant harvesting, from animals or microorganisms, or by mining in the case of minerals. These ingredients may be non-chemically processed to obtain one or more of the chemicals present in the original source. *Organic* ingredients are the same as the natural ones but obtained from organic agricultural practices (i.e., that avoid the use of synthetic fertilizers and pesticides, plant growth regulators, livestock feed additives; that employ crop rotation, integrated pest management, mechanical cultivation; that prohibit the use of GMOs, radiation, etc.) (Bom et al., 2019). The *naturally derived* ingredients are derived from those found in nature (100% natural, no synthetics allowed) but are chemically processed and may originate substances that are not present in the source. The *nature-identical* are substances synthesized in the lab to mimic natural ingredients (Bom et al., 2019; Natrue, 2022). Finally, *synthetic* ingredients are those that are chemically synthesized in the lab and do not exist in nature (Bom et al., 2019). There is no clear distinction between these groups, and sometimes some ingredients are classified as synthetic by some, while others consider them naturally derived. Examples of these are dimethicone and sodium lauryl sulfate (SLS) which are derived from silica (sand) and coconut oil, respectively. In our opinion, such ingredients should be considered synthetic since, although initially derived from natural materials, their production involves several reactions that completely transform the initial material. The classification of cosmetics ingredients is challenging, and different countries have different legislations. Currently, there are no European harmonized standard criteria for natural and organic cosmetics. In the USA, the USA Natural Cosmetics Act of 2019 indicates that a product is considered natural when containing at least 70% of natural substances (not processed), excluding water and salt (Cosmetics Business, 2020). The best option seems to be the standard ISO 16128, which provides technical definitions and guidelines to classify natural and organic ingredients in cosmetics (ISO, 2017). Most natural/organic certifications are provided by private companies, such as BDIH (Germany), the NaTrue (Belgium) and Ecocert Greenlife and CosmeBio (France) (Beerling and Sahota, 2014; Bom et al., 2019).

It is also important to note that not all natural ingredients are sustainable and not all synthetics are non-sustainable. This is exemplified by *mica* and *palm oil*, two natural raw materials that have sustainability problems. Mica is a natural mineral widely used in cosmetics, particularly in pigmented products such as powdered foundation. Mica sourced from India, however, raises several social and environmental sustainability problems such as the use of child mining labor and unsafe work conditions. To address such problems, L'Oréal actively pursues projects aiming to obtain responsibly sourced mica, such as the Responsible Mica Initiative (RMI), which warrantees a transparent life cycle, a strategy that ensures that currently 98% of all the mica used by this company is sustainable (L' Oréal, 2022e). The use of palm oil also poses several sustainability problems due to the deforestation of tropical forests, contributing to climate change, affecting biodiversity and the local populations. Sustainable companies have been increasingly using Certified Sustainable Palm Oil (CSPO), an accreditation issued by the Roundtable on Sustainable Palm Oil (RSPO) (RSPO, 2022). Criteria to obtain this certification include fair work conditions, rights of the local populations, land protection, no deforestation of primary forests, protection of wildlife in the plantations, reduced use of pesticides, reduction of the emission of greenhouse gases and improved waste management (RSPO, 2022). Similar strategies are used for soy (Round Table on Responsible Soy, RTRS) and cocoa (Round Table on Sustainable Cocoa; RTSC) (van den Berg et al., 2014).

Sustainable ingredients can also be obtained from alternative raw materials, either using green chemistry or upcycling. The American Chemical Society defines Green Chemistry as "the design, development and implementation of chemical products and processes that reduce or eliminate the use and generation of hazardous substances." (American Chemical Society, 2022). Basically, in green chemistry researchers design products and processes that minimize or eliminate practices that generate hazardous substances. One of the main strategies, which will be exemplified throughout this paper, is the use of renewable feedstock together with (usually enzymatic) catalysis to produce certain, more sustainable ingredients (Belousov et al., 2021; Culliney, 2021b). Several companies such as Natura-tec, Evonik, Earthoil Plantations and KLK Kolb have been using green chemistry to obtain sustainable ingredients that are an alternative to non-sustainable synthetic ones. The upcycling of industrial waste and byproducts mainly generated by the agro-food industry (e.g., spent coffee grounds, byproducts of the olive oil industry, skin of grapes and other fruits), is another economic and accessible way for cosmetic companies to obtain high value, more sustainable ingredients (see section 3.3)that can be used in cosmetic formulations (Culliney, 2021d). Although already used by some companies, this area may be expanded by the synergistic work of suppliers of raw materials, formulators and researchers. However, it is always necessary to consider that some of these alternatives are more expensive than the conventional raw materials, which contradicts the definition of sustainability.

3.2. Substituting conventional by sustainable ingredients

The ingredients in a cosmetic formulation fulfil several functions such as safety, efficiency, sensorial attributes, and physicochemical stability. A typical cosmetic product contains from 15 to 50 ingredients, including water, emollients, surfactants, solvents, preservatives, colorants, polymers, antioxidants, UV filters, fragrances, antioxidants, and chelators (Bom et al., 2019; Jones and Sellinger, 2022). In this section we will discuss possible sustainable alternatives to the different conventional cosmetic ingredients, summarized in Table 1.

When substituting any ingredient by a sustainable alternative it is always necessary to fully research how this substitution will affect the characteristics of the formulation, due to ingredient interaction. A good example of how this is done is reported in the study by Bom et al. (2020a). In this study the authors showed that the substitution of two emollients, petrolatum and dimethicone, and one preservative, phenoxytehanol, by several sustainable ingredients affected the characteristics of oil-in-water (O/W) emulsions and discussed strategies to keep the quality and characteristics of the products.

3.2.1. Emollients

Emollients or moisturizers are ingredients that soften the skin by preventing water loss and are, alongside emulsifiers and actives, the most important ingredients in a formulation (Alander, 2012; Jones and Sellinger, 2022). These ingredients give the formulations their sensorial properties such as feeling (softness, spreading and elasticity) and visual (matte or glossy, for example) characteristics, and determine their consistency (Douguet et al., 2017). Also, their polarity determines the solubility of actives and influence their bioavailability (Wiechers et al., 2004). According to Allander et al. (Alander, 2012), emollients can be classified in 4 different groups, according to their molecular structure: hydrocarbons, fat alcohols, esters, and silicone oils (Table 1).

Hydrocarbon-based emollients are widely used in the cosmetics industry due to their occlusive properties, hydration power, resistance to oxidation and long shelf-life (Bom et al., 2019; Chao et al., 2018). They include simple synthetic hydrocarbons, such as petrolatum and mineral oil, derived from mineral oil deposits, and squalane, derived from the hydrogenation of natural squalene (from animals or plants) (Alander, 2012). The main sustainability problem posed by petrolatum and mineral oil is their petrochemical origin. Although it is not easy to find an alternative to ingredients with such properties, recently Pinto et al. (2022) performed an *in vivo* assay in human volunteers and showed that several vegetable oils had occlusive effects comparable to that of petrolatum, even if took longer to obtain such effects. Squalane, the stable derivative of squalene, is an excellent emollient but when derived from animal sources poses exploitation problems, such as overfishing of deep-water sharks. Thus, it is preferred to use vegetable-derived squalanes or squalanes obtained from microbial fermentation. Vegetable-derived squalane is mainly obtained from olive oil deodorizer distillate, obtained from the olive oil industry, which can be upcycled (see section 3.3.2) (Bondioli et al., 1993). Squalane can also be obtained from renewable sugar sources (e.g., sugar cane) using modern biotechnology, by combining natural enzymatic reactions with traditional chemical steps. The American company Amyris uses this approach to obtain β-farnesene from the sugar fermentation of the yeast *Saccharomyces cerevisiae*, and then chemically obtain squalane (McPhee et al., 2014).

Fatty alcohols combine a long hydrocarbon chain with a primary hydroxyl group, and include cetyl alcohol, octyldodecanol, oleyl alcohol and isostearyl alcohol (Alander, 2012; Bom et al., 2019). Their main function is to stabilize the formulations and provide consistency but, when in low concentrations (1–2%), interact with emulsifier and provide emolliency and moisturization (Chao et al., 2018). Saturated fatty alcohols are obtained from saturated vegetable oils (palm, soybean) or by hydrogenation of animal fats. Oleyl alcohol, for example, exists in plants and animal waxes, and can be obtained from whale oil or jojoba oil. Depending on the raw material source, stearyl and cetyl alcohol are also present. Guerbet alcohols are also widely used in cosmetics. These branched alcohols include ethylhexanol, hexyldecanol and octyldodecanol and, being saturated, are usually resistant to oxidation (Alander, 2012). Octyldodecanol is a liquid, oxidatively stable alcohol, which can be plant-derived or chemically synthesized (The United States Pharmacopeial Convention, 2017). Obtaining these fatty alcohols poses sustainability problems, including animal exploitation (animal fats for the synthesis of oleyl and cetyl alcohols are obtained from dolphins and sperm whales), deforestation (palm and coconut oils) and the use of petrochemicals and heavy metals in chemical synthesis reactions (Bom et al., 2019). Alternatives to these practices include the use of fatty alcohols derived from plants obtained in sustainable agriculture practices (Bom et al., 2019) or the large-scale production of these compounds using genetically engineered microbial cell factories, as recently described by Krishnan et al. (2020). Bare Naked Botanicals, for example, uses sustainably sourced cetyl alcohol as one of the ingredients of their ECOMulse emulsifier, obtained from sustainable coconut and palm oils (Bare Naked Botanicals, 2022).

Esters are a very versatile ingredient in cosmetics, acting as emollients, actives, emulsifiers, etc., and being very important for the stability, sensory properties and aspect of these products (Douguet et al., 2017). Traditionally, esters result from a condensation reaction between an alcohol and a carboxylic acid or fatty acid in the presence of a strong acid catalyst at high temperatures (Veit, 2004). Thus, there is a wide range of combinations leading to esters with different properties. Esters used as emollients may be natural (animal- or plant-derived) or synthetic (Chao et al., 2018; Douguet et al., 2017). The most used esters in cosmetics industry are:

Table 1
Main cosmetic ingredients, sustainability challenges and possible sustainable alternatives (adapted from (Bom et al., 2019)).

Cosmetic ingrediente	Type	Conventional examples	Sources	Sustainability concerns	Possible sustainable alternatives
Emollients	Hydrocarbon-based	Petrolatum, mineral oil	Synthetic, naturally derived (mineral)	Petrochemical origin	Vegetable oils; squalanes obtained from byproducts of the olive oil industry (upcycling) or produced by microbial fermentation of renewable materials (e.g., by *S. cerevisiae* sugar fermentation combined with chemical transformation of the obtained products)
		Squalane	Naturally derived from squalene (animal or plant-based)	Animal exploitation or deforestation	
	Fatty alcohols	Cetyl alcohol, octyldodecanol	Natural (animal or plant-based) or synthetic	Animal exploitation, deforestation, use of heavy metals catalysts in chemical reactions	Fatty alcohols derived from sustainably sourced plants. Use of clay instead of heavy metals as a catalyst in chemical reactions to produce fatty alcohols.
	Ester-based	Isopropyl myristate (monoester), caprylic/capric triglyceride	Synthetic or naturally derived from animal or plant sources	Animal exploitation, deforestation	Use of biocatalytic processes instead of chemical production (e.g., Evonik's Tegosoft OER, produced by enzyme catalysis instead of chemical catalysis).
		Olive oil	Natural (plant-based)	Decreased production for food industry	Use of microbial cell factories to produce esters by fermentation of sustainable sources of sugars (e.g., RhYme Biotechnology's Actinowax™, produced by a genetically modified soil bacterium).
	Silicones and derivatives	Linear and cyclic silicones and derivatives	Synthetic, naturally derived from mineral (silicon)	Bioaccumulative, harmful to ecosystems and to human health	Polysaccharides of animal, plant or microbial origin; plant-derived nonpolar alkanes; products derived from green chemistry.
Surfactants	Anionic	Alkyl sulfates (SLS, ALS, SLES), etc.	Synthetic or naturally derived	Petrochemical origin, ethoxylation reactions may leave 1.4-dioxane and ethylene oxide in the products	Nonionic surfactants such as APGs. Naturally derived surfactants: polyglyceryl-based, glucoside-based, sucrose esters, olive oil esters. Amphoteric phospholipids (soy lecithin).
	Cationic	QACs	Synthetic	Non-biodegradable, harmful to marine life	
	Nonionic	PEG	Synthetic		
Solvents	–	Petroleum-derived glycols (PEG), ethanol, glycerin	Synthetic	Environmental pollution, harmful for human health	Green solvents such as ionic liquids, DES, NaDES. Use of supercritical fluids or liquified gases. Bio-based solvents obtained by microbial fermentation in sustainable raw materials.
Thickeners	Lipid	Cetyl alcohol, waxes	Natural	–	Substitute synthetic thickeners by natural or naturally derived ingredients, such as xanthan gum, gelatin, cellulose derivatives, carrageenan, chitosan, etc.
	Mineral	Silica, magnesium aluminum silicate	Natural	–	
	Naturally derived	Xanthan, cellulose derivatives, chitosan	Natural or semi-synthetic	–	
	Synthetic	Carbomers and other polymers	Synthetic	Not biodegradable, harmful in aquatic ecosystems	
Preservatives	–	Paraben esters, formaldehyde donors, phenol derivatives	Synthetic	Harmful to human health	Use of nature identical preservatives (benzoic acid/sodium benzoate, benzyl alcohol, sorbic acid/sodium sorbate, salicylic acid), natural preservatives (plant extracts and essential oils) or multifunctional ingredients.
Exfoliators	Physical	Microplastics	Synthetic	Not biodegradable, insoluble, bioaccumulative, pollution of oceans and rivers, deleterious to marine life and humans	Silica and other mineral microbeads (pumice, quartz sand, etc.), biodegradable microbeads of cellulose, exfoliator particles obtained from nut shells, fruit seeds, rice, organic microbeads derived from sugar.
	Chemical	Enzymes and mild acids (alpha-hydroxy acids, beta-hydroxy acids)	Natural or naturally derived	Do not pose main sustainability problems	–

(*continued on next page*)

Table 1 (*continued*)

Cosmetic ingrediente	Type	Conventional examples	Sources	Sustainability concerns	Possible sustainable alternatives
Colorants	Inorganic pigments	Complex minerals (e.g., mica)	Natural or naturally derived	Environmental and social sustainability concerns	Colorants derived from plants grown under sustainable conditions and using minimally impactful extraction methods.
	Organic pigments	Plant secondary metabolites, carmine	Plant or animal-based	Deforestation, animal exploitation	Microbial-derived colorants, either natural or produced using genetically engineered strains grown in renewable carbon and hydrogen sources.
	Organic dyes	Azo dyes, quinoline, xanthone	Synthetic	Derived from petrochemicals	
Fragrances	Natural	Derived from plant essential oils, derived from animals	Natural	Deforestation, ethical and animal exploitation concerns	Fragrances obtained from essential oils from plants grown under sustainable conditions.
	Synthetic	Chemically-modified naturally derived compounds, nature-identical	Synthetic	Skin sensitization, low biodegradability, volatility	Production of natural esters using microbial cell factories growing in renewable raw materials.
UV Filters	Inorganic	ZnO, TiO_2	Synthetic	Harmful to marine ecosystems; organic UV filters may be harmful to humans	Phytochemicals (polyphenols, vitamins, anthocyanidins), marine-derived compounds (carotenoids, sulfated polysaccharides, topsentin, ovothiols)
	Organic	Oxybenzone, ethylhexyl methoxycinnamate, ethylhexyl salicylate, octocrylene, homosalate			
Antioxidants		Butylated hydroxytoluene, butylated hydroxyanisole	Synthetic	Deleterious to human health	Vitamins, phenolic compounds (derived from plants)
Chelating agents		EDTA, citrates, phosphonates	Synthetic	Deleterious to human health, non-biodegradable	Phytic acid (plant-based), EDDS (biodegradable structural isomer of EDTA), biodegradable GLDA, Evonik's Dermofeel® PA (rice-derived)

ALS, ammonium lauryl sulfate; APGs, alkyl polyglucosides; DES, Deep eutectic solvents; EDDS, Ethylenediamine-N,N′-disuccinic acid; EDTA, Ethylenediaminetetraacetic acid; GLDA, Glutamic acid, N,N-diacetic acid; NaDES, Natural deep eutectic solvents; PEG, Propylene glycol; QACs, quaternary ammonium compounds; SLES, sodium laureth sulfate; SLS, sodium lauryl sulfate.

isopropyl myristate, a monoester resulting from the reaction of isopropyl alcohol and myristic acid, a natural fatty acid present in animals and plants; olive oil, the natural oil from olives, resistant to oxidation and with good cutaneous compatibility; caprylic/capric triglyceride, a synthetic compound vegetable-derived from palm or coconut oils and highly resistant to oxidation (Bom et al., 2019). Both olive oil and caprylic/capric triglyceride can be directly used in the formulation or be used as a starting point for the synthesis of other ingredients, using oleochemistry (Alander, 2012). Sustainability problems with this group include animal exploitation (when the myristic acid used in the synthesis of isopropyl myristate is derived from animals), deforestation (when the myristic acid is of vegetable origin; for obtaining palm and coconut oil) and/or diverting olive oil from the food industry to be used in cosmetic formulations (Bom et al., 2019). Furthermore, the conventional, acid-catalyzed and high temperature esterification reactions may degrade several starting materials, are energy-consuming and must include additional steps to remove the acid catalyst (Veit, 2004).

One alternative is to switch to biocatalytic processes, which involve milder reaction conditions, preserve the reactants and products and have lower environmental impact. One example is Evonik's Tegosoft OER, an emollient produced using enzymatic catalysis instead of chemical catalysts (metals, strong acids), which are deleterious for the environment (Bird, 2010). The use of enzyme catalysis also decreases the temperature of the process, saving about 60% of energy. Additionally, the company claims that the quality of the obtained products is better than when using chemical synthesis. Another alternative is the use of microbial cell factories, just previously mentioned for fatty alcohols. For example, RhYme Biotechnology created Actinowax™, based on wax esters, and produced by fermentation of sustainable sources of sugars using genetically modified strains of the soil bacterium *Rhodococcus* (Rhyme Biotechnology, 2021). Actinowax™ has excellent multifunctional cosmetic properties and can also be used as a stabilizer, co-emulsifier and wetting agent.

Silicones and their derivatives are widely used in cosmetics due to a combination of outstanding properties: they are chemically inert, resistant to oxidation and humidity, and are easily spreadable forming water-resistant but permeable films (Chao et al., 2018). Silicones are synthesized from silicon, oxygen and hydrocarbons and the most used in the cosmetic industry are the linear dimethicone, which reduces tackiness and leaves a smooth feel on skin, and the cyclic cyclomethicone, which increases the volatility of the formulation (Bom et al., 2019; Chao et al., 2018). However, the use of silicones has several sustainability problems, especially concerning the environment, and having been banned from rinse-off products in Europe since the beginning of 2020 (Paraszczuk et al., 2021). Silicones are very stable chemically and although this is a desired property for cosmetics ingredients, it is harmful for the environment due to bioaccumulation, especially in aquatic ecosystems (American Chemical Council, 2022; Goussard et al., 2022). Several alternatives to silicones have been researched, including natural products or those derived from green chemistry. Natural alternatives include polysaccharides derived from plants, animals, fungi and/or microorganisms, such as chitosan derivatives (e.g., chitosan succinimide from mushrooms) and carrageenan from red algae extracts (Cheong et al., 2018; Kanlayavattanakul and Lourith, 2021). Regarding products derived from green chemistry, the company Inolex provides an extensive portfolio of sustainable silicone alternatives and offers a guide on how to choose suitable replacements for each type of silicone (Inolex, 2022). Nonpolar alkane emollients have been widely used as alternatives to silicones because they are resistant to oxidation, chemically inert, biodegradable and nontoxic to marine life (Duprat-de-Paule et al., 2018). The company Seppic developed a range of liquid emollients, Emogreen™, derived from palm oil sustainable biomass, which respects the 6 principles of *Sustainable Biomass Cultivation,* and the production process is solvent-free (Duprat-de-Paule et al., 2018; Seppic, 2020). Another range of emollients from the same company, Emosmart™, are synthetic but chemically inert, and readily biodegradable (Seppic, 2016). BASF also provides several alternatives to silicones. A combination of undecane and tridecane, Cetiol® Ultimate, natural, and biodegradable, can substitute cyclomethicone, improving the performance and stability of sun care products. Another alternative to this cyclic silicone is Cetiol® C5, coco caprylate, a coconut-derived alkane. It provides a similar skin feel, supports the incorporation of powders and increases the solubility of crystalline UV filters. Cetiol® CC, chemically dicapryl carbonate, is a stable multifunctional dry emollient which can be used as substitute of linear silicones in deodorants and antiperspirants (Cosmetics Business, 2019b).

3.2.2. Surfactants

Surfactants fulfil several different functions in a cosmetic formulation, depending on their concentration and nature: they can act as emulsifiers (surfactants that stabilize emulsions), humectant agents, detergents or dispersants, solubilizers, penetration enhancers, etc., being used to control sensorial and functional properties of the product (Sakamoto et al., 2017). There are 4 classes of surfactants: anionic, cationic, nonionic and amphoteric (Romanowski, 2015).

The most widely used surfactants in cosmetics are anionic surfactants, particularly alkyl sulfates, which have good foaming and cleansing properties. Examples are SLS and ammonium lauryl sulfate (ALS). Sodium laureth sulfate (SLES) is less irritating than SLS, from which it derives via ethoxylation with ethylene oxide. This reaction, however, might leave 1,4-dioxane and ethylene oxide residues in the products. Other anionic surfactants include alkyl benzene sulfonate, isethionates, acyl sarcocinates, isethionates, etc. (Romanowski, 2015). Cationic surfactants, such as quaternary ammonium compounds (QAC), have low foaming ability, being mainly used in hair conditioning products to decrease static electricity and increase shine (Romanowski, 2015). However, they are not biodegradable and are harmful for marine life (Sar et al., 2019). Furthermore, they can cause skin irritation (Peyneau et al., 2022).

Nonionic surfactants, such as alkyl polyglucosides (APGs), are a good natural alternative to charged and synthetic nonioinic surfactants (e.g., polyethylene glycol, PEG), since they are made from 100% renewable plant-based raw materials, being readily biodegradable (Geetha and Tyagi, 2012; Paraszczuk et al., 2021). These compounds, which include coco, lauryl, decyl and caprylyl/capryl glucosides, are produced from fatty alcohols (derived from coconut and palm oils) and glucose (from corn or potato) (Beerling, 2014; Bom et al., 2019). In addition to their environmentally friendly nature, APGs have low toxicity, are mild and highly compatible with skin (Geetha and Tyagi, 2012).

Emulsifiers are surfactants used to stabilize emulsions; the most used conventional emulsifiers are ethoxylated surfactants and PEG, which share the sustainability problems discussed previously (Paraszczuk et al., 2021). Naturally derived alternative ingredients include polyglyceryl-based emulsifiers, glucoside-based emulsifiers, sucrose esters, sorbitan, glyceril, polyglyceril, alkylglucoside mixtures, and olive oil esters (Beerling, 2014; Paraszczuk et al., 2021). BASF offers Eumulgin® VL 75, a glucoside-based nonionic emulsifier, chemically lauryl glucoside (and) polyglyceryl-2 dipolyhydroxystearate (and) glycerin, which is suitable for skin care emulsions (Prospector, 2022b). Another option is soy lecithin, a natural and biodegradable amphoteric phospholipid but that may be difficult to formulate, besides being expensive (Beerling, 2014).

The use of microbial-derived surfactants and emulsifiers is also a good sustainable alternative to the conventional counterparts; in fact, these compounds, produced using biotechnology, have been called the multifunctional ingredients of the 21st century (Santos et al., 2016). Besides being more sustainable, they are biodegradable, have low toxicity and perform better in extreme conditions (Sałek and Euston, 2019). A recent article by Ahmadi-Ashtiani et al. (2020) provides a comprehensive review on several microbial-produced biosurfactants with potential use in cosmetics.

3.2.3. Solvents

Solvents, such as petroleum-derived glycols (propylene glycol, butylene glycol), ethanol and glycerin, are used to solubilize cosmetic ingredients (Bom et al., 2020c). Additionally, solvents are widely used during the manufacturing phase of the product to perform extractions, separations and synthesis processes (Bom et al., 2019). Solvents are some of the most problematic cosmetic compounds due to their petroleum origin, having a huge impact on environmental pollution, and contributing to climate change (Clarke et al., 2018; Welton, 2015). Additionally, they can affect human health, by causing cutaneous sensitivity and irritation and, because of their ability to cross the skin barrier, they can compromise the integrity of proteins and other cellular components (Beerling, 2014).

The use of alternative processes and solvents in the food and natural products industries was recently reviewed by Chemat et al. (2019). The main sustainability strategy consists in substituting conventional solvents by more sustainable ones. Ideally, the alternative solvent should be suitable for green extraction (green chemistry process), have high solvency and flash points, low toxicity, be biodegradable or easily recyclable, obtained from renewable sources and be relatively cheap. It is also possible to perform solvent-free extractions; a great example is the use of mechanical pressing to extract olive oil from olives. Water can also be used as a solvent in processes such as subcritical water extraction, micellar-assisted extraction, and hydrotropic extraction. However, the water footprint should always be kept to a minimum. The use of green solvents is another strategy: ionic liquid solvents, deep eutectic solvents (DES) and natural DES (NaDES) have been considered some of the most sustainable solvents (Chemat et al., 2019; Clarke et al., 2018). Another alternative is the use of biobased solvents, such as esters, ethers, terpenes or alcohols obtained from agro-based raw materials by fermentation (Chemat et al., 2019). For example, 1,3-propanediol can be obtained from glucose and molasses, or from glycerol, which is a byproduct of biofuel production, by fermentation. These processes need less energy and produce much lower amounts of greenhouse gases (Mendes et al., 2011; Moscoviz et al., 2016).

The use of alternative, greener solvents, is crucial to increase the sustainability of the cosmetics production processes, but the substitution must be carefully researched since it can significantly alter the properties of the products (Welton, 2015).

3.2.4. Preservatives

Cosmetic products, like any product containing water and organic/inorganic compounds, are prone to contamination by microbial strains. The use of preservatives is essential to maintain the properties of the products after the first use, avoiding microbial contamination and extending shelf life. The main groups of preservatives used in cosmetics are paraben esters (e.g., methylparaben), formaldehyde donors (imidazolidinyl urea, diazolidinyl urea), phenol derivatives (e.g., phenoxyethanol), alcohols, quaternary compounds, inorganics and organic acids and their salts (Halla et al., 2018).

Although crucial for the quality and stability of the cosmetic, most used preservatives have a synthetic origin, posing several problems (Halla et al., 2018). These compounds seem to be harmful to human health, although there are studies with contradictory results. Parabens, for example, are known to be absorbed through skin and by inhalation, and they seem to be endocrine disruptors and have genotoxic and carcinogenic potential (results obtained in *in vitro* studies). Due to these concerns the European Union (EU) banned the use of some parabens in personal care products, while others can be used but in limited amounts (Nowak et al., 2021).

The substitution of conventional preservatives is very challenging (Beerling, 2014; Beerling and Sahota, 2014) and current strategies include: (i) use of nature identical synthetic preservatives, such as benzoic acid/sodium benzoate, sorbic acid/sodium sorbate, benzyl alcohol, salicylic acid; (ii) use of natural preservatives from plants, such as plant extracts and essential oils (Nowak et al., 2021; Sakamoto et al., 2017); (iii) use of auto preservation techniques; and (iv) use of multifunctional ingredients.

Natural preservatives from plants, mainly extracts or essential oils, can be used in the cosmetics industry, with several studies showing their ability to inhibit microbial growth. In fact, plant metabolites such as alkaloids, terpenoids, polyphenols, polyacetylenes, lectins and others have antibacterial and antifungal properties. Several studies have shown the antimicrobial properties of plants such *Chamelia sinensis* (tea), *Cinnamomum* (cinnamon), *Allium sativum* (garlic), *Thymus vulgaris* (thyme) and *Curcuma longa* (turmeric). Additionally, some plant-derived antimicrobial ingredients are already used in cosmetics, such as extracts from *Carica papaya* (papaya), used in deodorants, lipsticks and face powders, and citrus extracts used in mouth hygiene products. Essential oils from thyme, carnation (*Syzgizum aromaticum*) and other plants have recently been introduced in cosmetics alongside chemical preservatives. They are especially efficient against fungi since they contain several active compounds that prevent the fungi to rapidly adapt (Nowak et al., 2021). A mixture of sodium levulinate and sodium anisate is also being used as a preservative in cosmetics. Sodium levulinate is the salt of levulinic acid, which is obtained from sugarcane, while sodium anisate is the salt of an organic acid derived from fennel. Both have antimicrobial and skin conditioning properties (Prospector, 2022a). Although promising, the complete replacement of chemical preservatives with natural ones is challenging since the latter are organic and it is unlikely they can be as efficient as the chemicals. Furthermore, essential oils have poor water solubility, may have a strong smell, and interact with other ingredients in the formulations. One strategy to avoid such challenges is to use these natural preservatives encapsulated in micro or nanocarriers, but this entails increases in the cost (Halla et al., 2018).

Auto-preservation techniques include: the use of raw materials that avoid the growth of microorganisms; decreasing the amount of water in the cosmetics by reducing their water activity by adding salts, polyols, amino acids, etc.; when possible formulate the cosmetics as water-in-oil (W/O) rather than as oil-in-water (O/W) emulsions, which minimize the risk of microbial contamination; adjust the pH of the product to acidic or alkaline: some deodorants have pH 3.5–4.5, cationic hair conditioners can have a pH of 4, while liquid soaps have pH ranging from 9.5 to 10.5 (Halla et al., 2018).

Multifunctional ingredients are added to the formulation to fulfill a main role but can contribute to other functions. For example, some emollients (e.g., glycol caprylyl glycol), some surfactants (e.g., the co-emulsifier glyceryl caprylate, phenylethyl alcohol), chelating agents (e.g., ethylenediaminetetraacetic acid, EDTA) and antioxidants (e.g., phenolic compounds) also have antimicrobial properties.

Although challenging, it is possible to partially substitute synthetic preservatives by more sustainable alternatives. In the previously mentioned research by Bom et al. (2020a), several alternatives to phenoxyethanol were tested as preservatives, such as Geogard® ECT (Benzyl Alcohol (and) Salicylic Acid (and) Glycerin (and) Sorbic Acid), Sensicare® C 2010 (Sodium Benzoate (and) Potassium Sorbate), Sensicare® C 3000 (Dehydroacetic Acid (and) Benzyl Alcohol), etc. These preservatives are made of compounds with wide global regulatory acceptance due to their low ecotoxicity.

3.2.5. Thickeners

Thickeners are ingredients that give cosmetic products consistency. According to Jones & Sellinger (Jones and Sellinger, 2022), there are four classes of thickeners: lipid-based, mineral, naturally derived and synthetic. Lipid thickeners are natural (e.g., cetyl alcohol, waxes) and solid at room temperature and can be added to the formulation after being liquefied. Mineral thickeners are also natural and absorb water and oil to increase the viscosity of the formulations; silica and magnesium aluminum silicate are examples. The other two groups mainly include polymers, which are widely used in cosmetics not only as thickeners but also as stabilizers, emulsifiers, and rheology modifiers (Lochhead, 2017). Naturally derived thickeners are polymers that absorb water and swell, thus increasing the viscosity of the formulation. They can be natural, such as xanthan gum, gelatin, guar gum, or semi-synthetic such as hydroxyethyl cellulose (Alves et al., 2020; Jones and Sellinger, 2022). Finally, synthetic thickeners are multifunctional synthetic polymers with several advantages such as excellent organoleptic properties, low cost, high viscosity at low concentration, and long-term stability (Alves et al., 2020; Bom et al., 2019). They are more often used in lotions and creams, and include carbomers, poloxamers, poly (ethylene, polyacrylamide) and ammonium acryloyldimethyltaurate. (Alves et al., 2020; Jones and Sellinger, 2022).

Synthetic thickeners have desirable properties for cosmetics, due to their multifunctionality, but can pose several sustainability problems since most are derived from petrochemicals and may contain impurities. A recent study found that carbomers and other water-soluble polymers can affect nitrifying microorganisms, and, because they are not biodegradable, are harmful in aquatic ecosystems (Rozman and Kalčíková, 2021).

Natural polymers are more sustainable due to their biodegradability, biocompatibility and non-toxicity; however, they usually have lower performance and may leave a sticky sensation on the skin (Bom et al., 2019). The most used natural or naturally derived thickeners in cosmetics are the cellulose-derived carboxymethylcellulose, hydroxyethylcellulose, the seaweed-derived carrageenan and alginate, chitosan obtained by the deacetylation of chitin, the fermentation-derived xanthan, gelatin, and others (Deckner, 2022; Gawade et al., 2020).

3.2.6. Exfoliators

Exfoliators are ingredients that remove dead cells from the upper part of the epidermis, preparing the skin to absorb cosmetics. Physical and chemical exfoliators fulfill this role by different mechanisms. Physical exfoliators contain abrasive bits and grainy particles and act mechanically by friction on skin, dislodging dirt and superficial dead cells. Chemical exfoliators break the connections between epidermal cells, peeling the more superficial layer of the epidermis. These include enzymes (fruit enzymes such as bromelain and papain, microbial proteases, keratinases) (Trevisol et al., 2022) and mild acids such as alpha-hydroxy acids (e.g., malic, glycolic and lactic acids) and beta-hydroxy acids (e.g., salicylic acid) (Kornhauser et al., 2010).

Physical exfoliators are responsible for most sustainability problems, since most contain synthetic plastic microbeads with diameters lower than 5 mm, which are water insoluble and not biodegradable, thus accumulating and polluting oceans and rivers. Furthermore, they end up being ingested by marine animals and, eventually, by humans (Rochman et al., 2015; Rosney, 2016; Smith, 2017). These problems led to several countries banning the use of plastic microbeads in cosmetics, particularly rinse-off products: in the USA the Microbeads Free Waters Act was legislated in 2015 (FDA, 2015); in the UK, the government implement a ban on microbeads in 2018 (Gov.UK, 2018); the EU has been working on further restrictions to microplastics intentionally added to cosmetics and other products, as proposed on the European Chemicals Agency (ECHA) website (ECHA, 2022).

Possible alternatives have been researched and, recently, Hunt et al. (2021) published an analysis paper on alternatives to the use of plastic microbeads in cosmetics, which ranked silica as the best based on the impact of their lifecycle on the environment and human health. Other alternatives are biodegradable microbeads of cellulose, those obtained from nut shells, fruit seeds, rice, organic microbeads derived from sugar and other mineral microbeads (pumice, quartz sand, etc.).

Cosmetic companies have been using some of these alternatives, such as ImerCare®, a range of exfoliating agents based on 100% natural perlite derived from volcano rock, which are Cosmos-certified, and can be used in face or body scrubs (Imerys, 2022). Holifrog's Como Popp-E Renewal Scrubby Wash contains poppy seeds and bamboo powder, Klur uses brown rice and rosehip seeds on its Skin Soil, and Reflekt 1 launched a daily exfoliating face wash containing jojoba esters-based biodegradable microbeads (Molvar, 2020). These are just a few examples, there is a world of alternatives in the cosmetics market!

3.2.7. Colorants

Colorants are used in cosmetics to either color the cosmetic product itself, enhancing its appearance, or to deliver color to the skin (foundation), nails (nail polish) or hair (hair color) of the consumer. Colorants may be synthetic or natural and, according to their solubility, they are categorized into either pigments or dyes. Pigments are made of solid, opaque inorganic insoluble particles disperse in a vehicle and are mainly present in makeup products and toothpastes. Dyes are organic molecules, hydro- or oil-soluble, usually found in skin care products or toiletries (Georgalas, 2014; Guerra et al., 2018).

Synthetic dyes are the most used colorants in cosmetics, because they are cheaper to produce, have a wide variety of colors and tones, and are stable and long-lasting (Guerra et al., 2018). Such dyes, which include azo dyes, quinoline and xanthone, are derived from petrochemicals, and present environmental and safety problems (Adeel et al., 2018; Mohana Priya et al., 2020). Due to such concerns, the use of azo dyes in cosmetics has already been banned in the EU, some USA states, China, Japan, etc.

The cosmetics industry has been researching natural multifunctional colorants which are biodegradable, renewable and non-toxic, and that simultaneously color, have anti-aging properties, act as preservative and UV filters in hair dyes, lipstick, foundations, and other products (Adeel et al., 2018; Bom et al., 2019; Patil and Datar, 2016). Inorganic pigments occur in nature as complex minerals, such as iron, zinc and chromium oxides, mica, etc. but although unexpensive, their extraction may have deleterious environmental and social impacts, as discussed previously (Bom et al., 2019). Organic dyes may be of plant, animal or microbial sources.

Plant-derived colorants are secondary metabolites (phytochemicals), part of the polyphenols, isoprenoids, N-heterocyclic compounds, melanin, or tetrapyrrole groups (Brudzyńska et al., 2021), which include carotenoids (orange), betalain (purple), lycopene (red), and anthocyanins (red to blue) (Mohana Priya et al., 2020). A widely used plant-derived colorant is indigo from *Indigofera tinctoria* (Adeel et al., 2018), but several others are available; the Formula Botanica company website, for example, lists 38 natural colorants used in organic skincare (Formula Botanica, 2022). Although plant-based colorants have several advantages compared to synthetic ones, sustainability is only achieved if the plants growth does not cause deforestation, and if the extraction methods have minimal impact on the environment (Bom et al., 2019). The French makeup company *Le Rouge Français* (Le Rouge Français, 2022) is specialist in "plant-based makeupology", having been pioneers (since the 1990s) in alternatives to chemical, non-renewable pigments. Similarly, 100% Pure (USA) uses only fruit pigments on their natural makeup products (100% Pure, 2019). These include lutein, carotenoids, flavonoids, anthocyanins, lycopene, etc., which can also provide active benefits to skin.

Animal-derived colorants have also been used as ingredients in cosmetics and are still used by some brands. The most used is carmine, produced from the carminic acid extracted from some scale insects such as the cochineal beetle *Dactylopius coccus* (Hunger and Herbst, 2000). Although safe and delivering an incredibly intense color, the main sustainability issues with the use of this, and other animal-derived colorants, are ethical exploitation and animal cruelty.

Microbial-derived colorants include secondary metabolites from bacterial species such as *Bacillus, Achromobacter* and *Brevibacterium* (Adeel et al., 2018; Aman Mohammadi et al., 2022). Natural melanin, for example, can be extracted from *Streptomyces bellus* strains isolated from marine sediments (Srinivasan et al., 2017). The production of such biocolorants may be transposed to the industrial scale using biotechnology approaches, such as the large-scale growth of the natural or genetically engineered microorganisms in renewable carbon and nitrogen sources (Aman Mohammadi et al., 2022).

3.2.8. *Fragrances*

Fragrances are made of small volatile molecules, such as esters, which provide cosmetic products with a pleasant smell (Calkin and Perfumery, 1994). Although they are used in low concentrations, fragrances are one of the ingredients more prone to cause skin sensitization (Nardelli et al., 2011), they can cause air pollution due to their volatility, and have low biodegradability (Bickers et al., 2003; Sakamoto et al., 2017). Additionally, it is difficult for the consumers to make an informed sustainable choice, since in the ingredient list of a cosmetic, fragrances are simply mentioned as *parfum*, without a detailed composition (Bom et al., 2019). However, according to the *International Fragrance Association*, regulations are being changed to include more transparency in the composition of a fragrance (International Fragrance Association, 2022).

There are natural and synthetic fragrances. Synthetic fragrances contain synthetic aromatic compounds, are more diverse, cheaper and may be more intense and long-lasting. These may be nature-identical, i.e., chemically synthesized from petrochemical materials to mimic natural aromas (e.g., synthetic linalool, which mimics linalool derived from lavender oil) or to create a new aroma which is not present in nature (e.g., methyl dihydrojasmonate), or chemically modified naturally-derived compounds (O'Lenick and Matson, 2011). Natural fragrances are complex mixtures of essential oils, exudates, concentrates, distillates, extracts and others (O'Lenick and Matson, 2011). Most natural fragrances are derived from plant essential oils, such as lavender, eucalyptus, bergamot, jasmine, and others. Essential oils not only provide a pleasant aroma to formulations but may act as active ingredients or preservatives. However, several essential oils are allergenic (Sharmeen et al., 2021). Natural fragrances may also be animal-derived, the best-known being musk, a secretion of the Asian musk deer. Other animal fragrances include ambergris, a hardened intestinal secretion of humpback whale, and *castoreum,* a fat oil secreted by the north American beaver. Such ingredients are expensive and have obvious ethical and animal exploitation problems. The musk deer is currently a protected species, thus musk trade has been prohibited. Synthetic alternatives, although not sustainable, include the chemical synthesis of white musk and ambergris, while an example of a natural alternative is the use of labdanum, a resin with an intense aroma, obtained from the *Cistus ladanifer* bush (La Carrément Belle, 2021).

Natural fragrances are perceived as more environmentally friendly, healthier, renewable, but they might pose sustainability problems, exemplified by the massive deforestation caused by the production of sandalwood and rosewood. Sustainable agriculture and biotechnology strategies may help mitigate such problems (Bom et al., 2019). In Australia, for example, new plantations of sandalwood based on sustainable agriculture practices have been introduced, from which essential oil is extracted (Utroske, 2019). The use of biotechnology encompasses the development of microbial cell factories, such as engineered *Escherichia coli* or *Saccharomyces cerevisiae*, to produce natural esters from renewable raw materials, as recently reviewed (Lee and Trinh, 2020).

Another strategy used by the fragrance industry is the headspace technology, introduced by Mookherjee in 1980. This technique is used to capture the odor components in the air around a plant, allowing its study without destroying the plant (Laudamiel et al., 2008).

3.2.9. *UV filters*

Several cosmetics on the market contain UV filters that protect the user against the harmful effects of the UV radiation, such as premature skin aging. The filters against UV radiation may be inorganic (sometimes referred to as physical or mineral) or organic (sometimes called chemical). Inorganic filters usually contain zinc and titanium oxides, and mainly work by reflecting and scattering the light (Chisvert and Salvador, 2007; Milito et al., 2021). Although they are more stable, lasting longer, they pose aesthetic problems since they leave a white residue on the skin (Majumdar and Chatterjee, 2017); recently this problem has been minimized using micronized formulations (Milito et al., 2021). Nevertheless, they are more difficult to formulate. Organic filters usually contain a chromophore, i.e., an aromatic molecule conjugated to carbonyl groups, being able to absorb sunlight and convert it to thermal energy. Examples of these filters are butyl methoxydibenzoylmethane, oxybenzone, ethylhexyl methoxycinnamate, ethylhexyl salicylate, octocrylene and homosalate (Chisvert and Salvador, 2007; Milito et al., 2021). They are photostable, provide a wider range of protection against UVA and UVB and are aesthetically more attractive than inorganic filters; however, they can cause skin irritation and allergies (Chisvert and Salvador, 2007; Majumdar and Chatterjee, 2017). Some recent studies have shown that all the organic UV filters mentioned previously are systemically absorbed into the body after only one use (Matta et al., 2020), while others have provided evidence that these filters can have estrogenic and antithyroid effects (Chisvert and Salvador, 2007). Both organic and inorganic filters can have negative environmental effects; their accumulation in coastal waters can, by bioaccumulation and biomagnification, affect marine life, causing hormonal changes and endocrine disruption in fish, abnormal development of sea urchins and bleaching of corals (Milito et al., 2021; Sánchez-Quiles and Tovar-Sánchez, 2015).

These problems led to the research of photoprotective natural or renewable-sourced ingredients, for example phytochemicals which can absorb UV light, such as polyphenols, anthocyanidins, vitamins, carotenoids, etc. (Beerling, 2014; Radice et al., 2016). Marto et al. (2016) used supercritical extraction with CO_2 to obtain the oil fraction of residues of the coffee industry and evaluated its impact in the development of UV filters for cosmetics. The research showed that emulsions containing this added ingredient had an overall better sun protection performance than formulations without it. Marine ecosystems are also an important source of natural UV filters. Amador-Castro et al. (2020) recently reviewed mycosporine-like amino acids and scytonemin produced by red macroalgae as potential new UV filters for sunscreen formulations. Marine organisms, such as seagrasses and halophytes, can also produce polyphenols, mainly flavonoids such as triphlotherol-A, phloroglucinol and phlorotannin eckol, which can act directly, absorbing UV radiation, or indirectly due to their antioxidant/ROS (reactive oxygen species) scavenging properties (Milito et al., 2021). Other natural compounds of marine origin with interesting UV-protection characteristics are carotenoids (cyanobacteria, micro and macroalgae), sulfated polysaccharides (red algae, green algae, brown algae), eumelanin (from sepia ink), topsentin (from the marine sponge *Spongosorites genitrix*) and ovothiols, amino acid derivatives produced by some cyanobacteria, microalgae and marine invertebrates (Milito et al., 2021). The use of natural UV filters is still limited because there are not enough *in vivo* results that prove their efficiency and these studies cannot be substituted by *in vitro* and/or *in silico* studies (Beerling, 2014; Pawlowski and Petersen-Thiery, 2020). However, ongoing research suggests that, although these ingredients should not be used as UV filters *per se*, their addition to sunscreen formulations enhances their sun protection (Marto et al., 2016).

Synthetic UV filters may also be substituted by new compounds obtained using green chemistry, via the transformation of renewable raw materials or residues into photostable molecules that can be used as sun protectors. Recently, Giacomo et al. (2020) published a preliminary study on the synthesis of photostable molecules from pentoses in residual biomass. The molecules had excellent absorption within the 300–400 nm range and were soluble in oil and other cosmetic formulation ingredients.

3.2.10. Antioxidants and chelating agents

Antioxidants and chelating agents are crucial ingredients to ensure the stability of cosmetic formulations. Antioxidants prevent the oxidation of the lipid ingredients (e.g., oils, fragrances) in a cosmetic formulation, and act as active substances, having an anti-aging role due to their ROS scavenging properties (Deckner, 2015). Synthetic antioxidants, such as butylated hydroxytoluene and butylated hydroxyanisole, are more widely used than natural ones, since they are cheaper and more stable during the manufacturing phase (Augustyniak et al., 2010). However, these is some evidence that these ingredients can cause allergies, endocrine disruption and even cancer (Okereke et al., 2015). The best natural alternatives to synthetic antioxidants are natural, plant-based, molecules, as recently reviewed by Hoang et al. (2021). These include vitamins, e.g., vitamin A (retinol palmitate), vitamin C (ascorbic acid), vitamin E (tocopherol), vitamin B (panthenol) and vitamin K (phytonadione), which can be obtained from plant extracts. Vitamins C and E are the most used antioxidants in anti-aging cosmetic formulations (Silva et al., 2019). Polyphenols can also be used as natural antioxidants in cosmetics. The phenolic compounds derived from grapes have anti-inflammatory and antimicrobial properties. For example, the French brand Caudalie®, known for its vinotherapy skincare, uses resveratrol (3,5,4′-trihydroxy-trans-stilbene), obtained from grape pomace, the main wine industry byproduct, as an ingredient in several of its products (Caudalie, 2020; Hoang et al., 2021). Other sources of phenolic compounds are pomegranate (the polyphenols ellagic acid and punicalagin), apple, chestnut, pineapple, basil, Goji berries, olives, papaya, eggplant skin, banana, peach, and *Gingko biloba* leaves (Hoang et al., 2021).

The presence of metal residues in cosmetic formulations promotes oxidation reactions which impact the functions of the ingredients, thus the addition of chelating agents is crucial for the stability of cosmetic products (Sakamoto et al., 2017). Furthermore, chelating agents boost the performance of antioxidants and preservatives in cosmetics (Siegert, 2014). One of the most efficient chelating agents is EDTA, but it is synthetic and non-biodegradable in natural environments and may cause health problems. Citrates and phosphonates are also widely used chelating agents (Beerling, 2014). Plant-derived molecules such as phytic acid, present in nuts, grains and seeds, are good natural alternatives but they may be expensive (Canan et al., 2011). The company Evonik Dr. Straetmans GmbH supplies phytic acid derived from rice as Dermofeel® PA, which acts in synergy with antioxidant ingredients, being an excellent alternative to EDTA (Omya Kinetic, 2019). A structural isomer of EDTA, ethylenediamine-N,N′-disuccinic acid (EEDS) is a biodegradable alternative, although not a natural molecule (Gluhar et al., 2020). Glutamic acid, N,N-diacetic acid (GLDA) and its salts are another biodegradable alternative to EDTA (Siegert, 2014).

3.3. Ingredient upcycling

The substitution of conventional ingredients, mainly synthetic compounds, by more sustainable natural, naturally derived or nature identical ingredients, is a strategy being used by several cosmetic companies, as discussed in the previous section. This search for more sustainable ingredients implies that supplier companies must keep on widening their set of products, looking for valuable ingredients everywhere, including in residuals or waste of industrial production, particularly of agro-food industry.

The recycling and reuse of industrial byproducts with the aim of generating new raw materials for the manufacture of products with added value is called *upcycling* or *creative reuse* (Givaudan, 2018; Goyal and Jerold, 2021). This process also significantly decreases expenses related to the treatment of residues before disposal and the deleterious impact of these residues on the environment, thus significantly contributing to a circular economy and environmental sustainability. Several of such byproducts are rich in bioactive compounds such as vitamins, minerals, phenolic compounds, which can be used as ingredients in cosmetic formulations.

The agro-food industry greatly contributed to the increase of industrial residues in the last decades, by wasting about one third of the food it produces for human consumption, which corresponds to about 1.3 billion tonnes per year. These residues include seeds, fruit and vegetable skin, plant leaves and fruit pulp, which can amount to 3–69% of the total vegetable food (Dell'Acqua, 2017). If used as are, they can be employed as fertilizers or animal feed but still significantly contribute to the worldwide pollution levels, by producing significant amounts of methane when in landfill (Cullor, 2022b).

Several countries have developed programs to manage the reuse of industrial byproducts containing compounds of interest. The EU, for example, established Biowaste, financed by the EC Department of Agriculture, which includes programs such as Apropos to exploit agricultural residues with high concentrations of proteins and oils, and Transbio which aims to develop new ingredients from byproducts of the fruit and vegetables processing industries, using environmentally friendly biotechnological solutions (Dell'Acqua, 2017; Goyal and Jerold, 2021). Another EU project is VOLATILE, which was developed to optimize the production of volatile fatty acids from the anaerobic fermentation of biowaste; these fatty acids can then be used in the soap and detergent industry, for example (European Commission, 2021). Also funded by the EU, the project Oleaf4Value, by the biotech company Natac, started in 2021, and involves 9 countries (Schleicher, 2021). Its aim is to valorize the olive leaf biomass to obtain bioactive compounds with high market potential.

The food industry-derived residues most used in upcycling are those derived from coffee, olives and fruits, which are produced in great amounts and can have negative impacts at the economic and environmental levels. Extracts from these residues are rich in compounds such as fatty acids, vitamins, minerals and antioxidants, which have valuable biological activities (Marques et al., 2017; Marto et al., 2016; Nunes et al., 2022; Ribeiro et al., 2018). Some examples of these ingredients and how they are used in the cosmetics industry will be discussed (Happi, 2020) and are summarized in Table 2.

Upcycling is a great technique to address sustainability in industrial processes, but it faces some challenges, the main being the design and development of sustainable extraction methods by using, for example, green chemistry approaches, to obtain the maximum yield without compromising the stability of the extracts and their components, while minimizing the environmental impact. Another drawback of upcycling is that the logistic of high amounts of waste is still a roadblock to scalability (Cullor, 2022b).

3.3.1. *Coffee industry byproducts*

The consumption of coffee around the world is outstanding. Around 9 million tonnes of ground coffee are brewed each year, resulting in about 18 million tonnes of wet spent coffee grounds (SCG, the residue that remains after the coffee is brewed) per year, one of the highest industrial residues. This waste is typically treated and disposed of in the landfill, which can cause environmental problems due to the production of methane and other greenhouse gases during composting (Givaudan, 2020a; May and Folkerts, 2021; Ribeiro et al., 2018).

But coffee waste can and should be reused. In fact, coffee contains several compounds of interest such as flavor and fragrance molecules, oils, caffeine, and several antioxidants that are still present in significant amounts after brewing. By extracting these compounds from SCG, the value of this byproduct is reintroduced into the supply chain, serving as a natural flavor, being used as solid

Table 2
Ingredient upcycling as a strategy to produce more sustainable cosmetics.

Company	Upcycled ingredient	Source	Properties	Applications
Givaudan and Kaffe Bueno (Givaudan, 2020b)	Koffee'Up™ (Coffee oil)	Spent coffee grounds	Increased skin hydration and skin barrier against external aggressions.	Face and body cosmetics
O'right (O'Right, 2022)	Coffee oil	Spent coffee grounds	Hair anti-aging and root fortification, scalp invigoration and function regulation.	Hair care
UpCircle (UpCircle Beauty, 2022)	Coffee oil	Spent coffee grounds	Hydration, nurturing and skin damage protection	Face and body care
Sanam (Cullor, 2021)	Naox® Derma (antioxidant concentrate)	Coffee cherry (coffee pulp extract)	Antioxidant, skin protection against environmental aging factors	Active ingredient for skincare products
Mibelle Biochemistry (Mibelle Biochemistry, 2022)	SLVR'Coffee™	Coffee bean silverskin	Skin hydration	Active ingredient for skincare cosmetics
Laboratoires Expanscience (Culliney, 2020)	Number 6 (avocado polyphenols concentrate)	Downgraded avocados	Reduces dark circles by acting on microcirculation & pigmentation, depuffs under-eye bags.	Solid bar for eye contour
Givaudan (Givaudan, 2018)	Vetivyne™	Leftover vetiver roots from the fragrance industry	Improved skin hydration, wrinkle reduction, improved skin biomechanical properties, fragrance booster.	Dry skin and perilabial serums, night and day creams, anti-fatigue essence, skin tonifying mask, anti-acne cream, body lotion
Sophim (Premium Beauty News, 2021)	Phytosqualan® (squalane)	Byproducts of olive oil industry	Decreased TEWL, increased skin elasticity, strong moisturizing effect	Emollient in cosmetic formulations, such as oily face serums, eye care, anti-aging, and skin care products for mature skin; also hair care and make up formulations.
Circumference and Brightland (Sandler, 2021)	Extract of olive leafs	Byproducts of olive oil industry	Skin regenerative effects	Facial cleansing products
Rahn AG (Rahn AG, 2020)	Reforcyl®-Aion (pumpkin seed oil)	Pumpkin seed cake	Anti-aging, anti-wrinkle, firming and hydration	Facial cosmetic products
Givaudan (Givaudan, 2021)	Omegablue®	Bilberry seed	Hydration, skin barrier repair, anti-aging	Body and face care
Cargill Beauty (Cargill, 2022)	UNIPECTINE™ pectin	Apple pommace, citrines peel	Gel and film formation, stabilization of emulsions, suspensions and foams, control of rheological properties	Thickener and preservative in cosmetics
Caudalie (Caudalie, 2020)	Phenolic compounds	Grape pomace (byproduct of wine industry)	Firming and lifting properties	Facial and body products

biomass heating fuel or being processed and further upcycled into raw materials that can be used in other industries, such as polymers, packaging, textiles and cosmetics (May and Folkerts, 2021).

As previously discussed, our group recently evaluated the use of oil extracted from SCG or green coffee beans in Pickering emulsions to be used in sun protectors (Marto et al., 2016). These lab studies showed that formulations combining the oil obtained from SCG with unsaturated fatty acids and unsaponifiable material, had ideal characteristics for cosmetics intended to provide sun protection and hydration.

The Taiwanese company O'right was a pioneer in the upcycling of SCG, having developed, in 2006, a range of hair products called Hair O'right. This company, certified as carbon neutral and sustainable, also created *Recoffee Tree in the Bottle,* selling these products in bottles made from SCG and polylactic acid (PLA), which contain coffee seeds that germinate when the bottle is buried in soil. This product won the Gold Medal and Special Medal in the INPEX and RedDot Awards, among several other sustainability prizes, being the world's most awarded shampoo (O'Right, 2022). UpCircle Beauty, a company founded in 2015 by two siblings in the UK, also upcycles SCG collected in several coffeeshops around London, among several other byproducts (UpCircle Beauty, 2022). The repurposed SCG are used to make soaps, face masks, serums, and exfoliators. In 2020, the companies Givaudan (France) and Kaffe Bueno (Denmark) partnered to create a coffee oil from discarded SCG, a product named Koffee'Up™. This natural oil, which has been called the *new argan oil*, has skin hydrating, anti-aging, and protective effects (Givaudan, 2020b). The oil is obtained from the SCG using CO_2-cold supercritical extraction, which preserves the properties of the active molecules, while also being an environmentally friendly technique (Givaudan, 2020a).

Besides SCG, the industry also wastes about 60% of the coffee cherry (coffee fruit), after removing the seeds (coffee beans). The coffee fruit is rich in antioxidants and the Colombian company Sanam took advantage of this to produce a pulp extract, called Naox-Derma, with anti-aging, anti-inflammatory and antioxidant properties, which are excellent for cosmetic products (Cullor, 2021). SLVR'Coffee™ is another product derived from coffee cherry, developed by the company Mibelle Biochemistry (Mibelle Biochemistry, 2022). Silverskin is a thin protective layer that envelops the coffee seeds and falls off during the roasting process, being the main byproduct of this process, and being produced in high amounts in roasteries worldwide. *In vitro* and *in vivo* studies have shown that the product protects the skin from stressors and prevents transepidermal water loss (TEWL), thus increasing hydration. A recent study suggested that these actions are due to the interaction of several antioxidant compounds such as chlorogenic acids, caffeine, melanoidins and others (Bessada et al., 2018). SLVR'Coffee™, which won the BSB Innovation Award in 2022, in the category Raw Materials, was also a finalist in the category "sustainable ingredient" in the *Sustainable Beauty Awards, 2022*, organized by Eccovia Intelligence (Sustainable Beauty Awards, 2022) (Fig. 2).

3.3.2. *Olive oil industry byproducts*

The olive oil industry, like the coffee industry, produces high amounts of byproducts such as olive pomace, olive leaves and olive meal wastewater (OMWW). As recently reviewed by our group (Nunes et al., 2022), these byproducts have a negative impact on the soil and in the air and aquatic environments, but they are rich in molecules of interest, such as phenolic compounds, which can be recovered, treated and reused as bioactives in the cosmetics industry.

Sophim (France), an ingredient supplier company for cosmetics, created Phytosqualan®, a squalene derived from olive oil industry byproducts, which can substitute animal-derived squalene as an emollient in cosmetic formulations (Premium Beauty News, 2021).

Circumference, a sustainable USA company founded by a Korean entrepreneur, developed a regenerative daily cleanser with extracts of olive leaf, in collaboration with the olive oil Californian company Brightland, which supplies the byproducts for upcycling (Sandler, 2021).

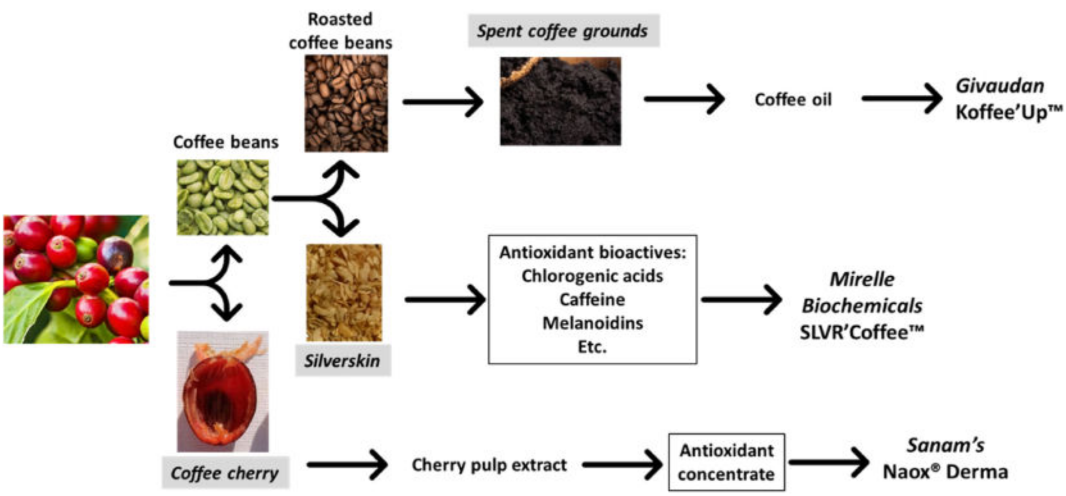

Fig. 2. Upcycling of ingredients for the cosmetics industry from byproducts of the coffee industry. The boxes shaded in grey show the byproducts: coffee cherry, spent coffee grounds and silverskin.

3.3.3. Others

Laboratoires Expanscience (France) created several cosmetic active and sensorial ingredients from the upcycling of downgraded avocados, that cannot be sold as fruit (Expanscience, 2022b). These ingredients include organic virgin avocado oil, avocado oil, avocado powder, polyphenol extract concentrate, etc. that can be used for skin and hair care. The avocados are obtained from valleys in Peru, thus contributing to social and economic sustainability in this country. One of these ingredients, Number 6, is a concentrated polyphenol extract that is used in concentrations of 1–3% in products for eye contour (Culliney, 2020). Avocados are not the only natural source of ingredients for this company, which also uses the root maca, wheat germ oil, and passion fruit, among others (Expanscience, 2022b).

The previously mentioned company Givaudan developed an upcycling product called Vetivyne™, made from a concentrated aqueous extract of Haiti vetiver roots, a byproduct of the fragrance industry (Givaudan, 2018). This active ingredient acts in the skin lipids, increasing skin hydration and revealing anti-aging properties. The vetiver roots are certified by the organic and fair-trade standard *Fair for Life*, being obtained from a cooperative of producers in Haiti, assuring environmental and social responsibility. This product won the first prize in the Natural Products, Raw Materials, actives category at the *European BSB Innovation* Awards in 2018. Givaudan also used upcycled bilberries seeds to develop Omegablue®, an ingredient that can be used for advanced skin repair. While bilberries are used for food industry, anthocyanidins can be extracted from the fruit skin to be used in the supplement and pharmaceutical industries. The seeds are a byproduct but due to their optimal omega 6: omega 3 ratio, they are a valuable source of ingredients for the cosmetics industry, improving hydration and skin barrier function (Givaudan, 2021).

Grapes and grape-related industries (e.g., wine) also provide plenty of byproducts that can be used by other industries for upcycling of ingredients. As previously mentioned, one alternative to conventional antioxidant ingredients are the phenolic compounds from red grapes, such as Caudalie's resveratrol, which has anti-aging, antimicrobial and anti-inflammatory properties (Caudalie, 2020).

Another example of upcycling comes from the Swiss company Rahn AG. This company used wasted pressed pumpkin seeds cake to create a bioactive – Reforcyl®-Aion – which is commercialized according to circular economy principles. Clinical studies showed that the ingredient possesses hydration, antioxidant, and anti-aging properties, by activation of a healthy autophagy process in the skin cells. The product was awarded the *BSB Innovation Prize* in 2020, in the category *Environment* (Rahn AG, 2020; Behrens, 2020). The USA company Cargill Beauty extracts pectin from apple pomace or citrine peel, leftovers from the food industry, to create UNIPECTINE™, which can be used as a thickener and as a stabilizer in cosmetic formulations. Pectin is obtained by aqueous extraction, a sustainable and environmental-friendly process which does not resource to organic solvents (Cargill, 2022).

3.4. Water as a sustainable ingredient in cosmetic formulations

Water plays a critical role in the cosmetics industry, being involved in all phases of the product life cycle, starting by being the main ingredient in the cosmetic formulations.

However, potable water scarcity is one of the main problems that humanity faces. Although 70% of the planet's surface is covered in water, only 3% of these is fresh water and, from these 3%, only a part is accessible to the organisms who depend on it. Excessive water consumption is due to a growing population, urbanization and economic development. Water is mainly used in agriculture (70%) but also in industry (20%), both of which are relevant for cosmetics (Hoekstra et al., 2012; United Nations, 2020; United Nations, 2010).

The water used in the cosmetics industry is not only the "visible water" contained in the formulations and applied during the use phase, but also the "virtual water" that is indirectly used during the life cycle of the product, including water for agricultural irrigation, water used in the industrial manufacturing process (e.g., cooling and heating processes, equipment cleaning, etc.), packaging manufacture, product transport, and post-use phase (treatment of residues, recycling, etc.). The strategies to decrease the amount of water during the life cycle of a cosmetic product has been recently reviewed by our group (Aguiar et al., 2022) and is summarized in Fig. 3. Furthermore, some of these strategies will be discussed in the following sections. Here, we focus on the current and innovative cosmetic products which are based on the concept of *waterless beauty*.

Water is present in all cosmetics products, from creams and lotions, to shampoos, conditioners, deodorants, etc., usually being the ingredient present in highest amount. Cleansing products such as shower gels and shampoos contain about 80–90% of water, which considerably contributes to the water sustainability challenges of the cosmetics industry (Aguiar et al., 2022). This problem led to the development of waterless beauty, a concept originating in South Korea in 2015 (Radin, 2020), and which includes all types of cosmetics developed with the aim of decreasing or eliminating the water used in the formulations, the production and the use phases (Yu and Anigbogu, 2020).

The waterless products (Table 3) were initially developed to be more efficient in their skin action since they are more concentrated. However, because they contain less water, being more concentrated, they are smaller, need less packaging, which greatly reduces the economic and environmental costs of their transport and the pollution caused by the packaging disposal (Aguiar et al., 2022). Thus, these products are also more sustainable.

The first generation of waterless products included anhydrous or concentrated formulations. The first group does not contain any water and includes oils and serums, powders, solid bars, butters, among others. The concentrated formulations contain a smaller amount of water than the conventional products and comprise concentrated serums, masks and exfoliators, deodorants, foundations, etc. (Cosmetics Business, 2019a). Some of these products can be used without water, while others, such as cleansing powders and exfoliators need to be rehydrated (Aguiar et al., 2022). The water used by the consumer, however, is always less than the water used by the cosmetic industry to create a conventional product. One example of a waterless product is the previously mentioned Klur's Skin

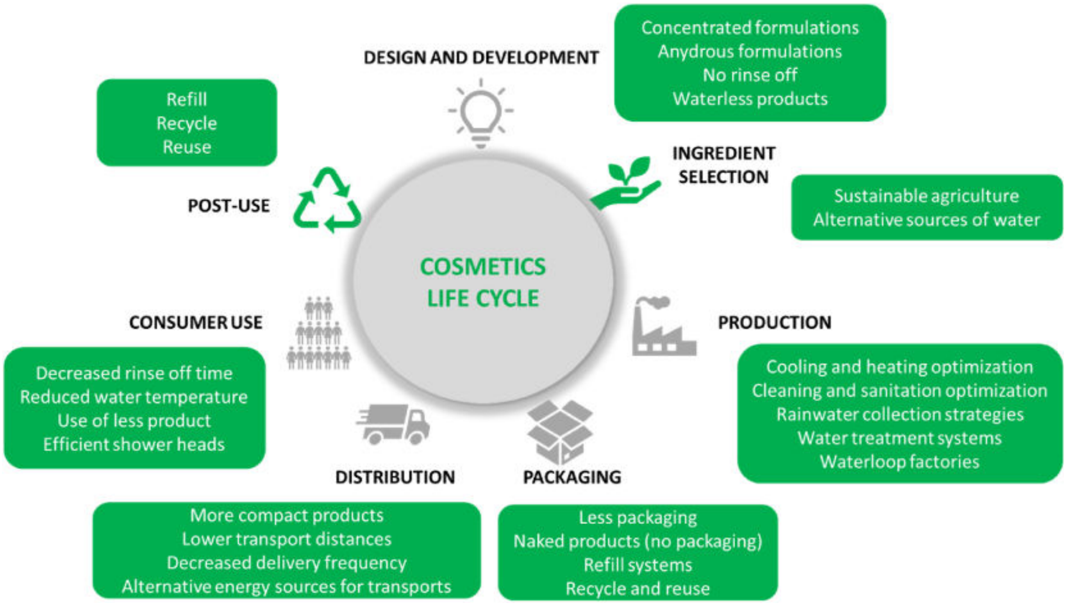

Fig. 3. Strategies to increase water sustainability during the life cycle of a cosmetic product Adapted from Aguiar et al. (Aguiar et al., 2022).

Table 3
Waterless cosmetics (adapted from (Aguiar et al., 2022)).

Formula	Possible cosmetics	Examples
Solid bar	Face and body creams	
	Body wash	Mintasy Solid Shampoo (Ethique)
	Deodorants	Ultimate Blends Shampoo Bar (Garnier)
	Shampoos	Solid Night Cream (Balade en Provence =
	Conditioners	Rejuvenating Night Balm (Sbtrct)
Solid stick	Body moisturizing	
	Deodorants	Body Cream Stick (Ethique)
	Lip balm	Butter Up Moisturizing Body Stick (Formula 10.0.6)
	Parfum	
	Make-up illuminators	
Butter	Body cleansing butters	
	Body hydrating butters	Shea Body Butter (The Body Shop) Camomile Sumptuous Cleansing Butter (The Body Shop)
Oil	Make-up remover	
	Shower oils	Lait-en-Huile Demaquillant (L'Occitane en Provence)
	Hair oils	
	Body oils	Huile Confort Absolu (Weleda)
	Sun protector oils	SPF25 with Raspberry Seed Oil (UpCircle)
Powder	Facial and hair masks	
	Solid shampoos and conditioners	No Drought Dry Shampoo (Lush)
	Body exfoliators	Translucent Loose Set Powder (Laura Mercier)
	Sun protectors	
	Makeup foundation, blush	
Tablets	Toothpaste tabs	
	Shampoos	Natural Toothpaste (Georganics)
	Body cleansing	Shower Tablets (Earth Suds)

Soil, a dry powder containing brown rice and rosehip seeds, which when mixed with water creates a low-friction exfoliator (Molvar, 2020).

The second, more recent, generation of waterless products is the "**B**ring **Y**our **O**wn Water". These products are designed to be reconstituted with water by the consumer, at home, and usually have cleansing functions, including shampoos, conditioners and toothpaste in solid forms (Merabet, 2022). They offer several advantages, some in common with the first generation of waterless products. Both have a longer shelf-life since the ingredients are more stable in a low water or no-water environment. The first BYO Water product was developed in 2018 by the Swedish brand Forgo: a hand soap starter kit, supplied with an empty glass bottle and the powder, supplied in plastic-free paper refills. Their new product is a body wash also supplied as a powder accompanied by a stainless-steel reusable bottle, which is currently in pre-order (Forgo, 2022). The UK brand Haeckels, which uses seaweed for all its skincare products, created the 60% H_2O Ocean Cleanse Concentrate + Allantoin, in the form of a pill that can be activated by adding boiled water, creating a body cleanser. Furthermore, the formula is vegan and cruelty free, and does not contain silicones, alcohol, oil, gluten or soy (McQuarrie, 2020). OWA haircare developed the Moondust Collection of powdered shampoos, free from artificial fragrances. One bottle containing 56 g of powder is equivalent to four standard bottles of liquid shampoo. The product is used by sprinkling into the hands, activated by adding some water and massaging through the hair (Bennet, 2021). Toothpaste and mouthwash are also available in powder versions by Humankind (Bennet, 2021).

Some brands allow the consumer to decide which product to obtain, depending on the amount of water added. For example, Sunapee Sacred-C Brightening Powder Wash from Holifrog is a facial cleansing product that can also be used as exfoliator, depending on how much water the consumer adds. It is supplied as a concentrated powder which is activated by water addition immediately before use, thus ensuring the stability of the labile vitamin C (Holifrog, 2022). Another example is Lina Hanson's Global Face Trio which can be used as a cleanser, an exfoliator or a mask (Merabet, 2022). Another advantage of the BYO Water formulas is that they allow the consumer to use alternative reconstitution agents, such as oil, yoghurt, or honey.

4. Sustainability in the production phase: manufacture and distribution

The production of a cosmetic product is regulated by the ISO standard *Good Manufacturing Practices* ISO 22716:2007 (Bom et al., 2019; ISO, 2007). These rules control the variables involved in the production process in order to obtain high quality products (ISO, 2007), contributing for the UN Sustainable Development Goals (SDG) 3 and 8: Good Health and Well-being, and Decent Work and Economic Growth, respectively (ISO, 2007, 2022).

4.1. Manufacture

The main sustainability issues during the manufacture of cosmetics are related to energy consumption, water use, and waste management (Cosmetics Europe, 2019). Thus, industries are increasingly pursuing the development and use of innovative technologies that reduce the environmental, carbon and water footprints.

Recently, our group reviewed the main strategies being adopted by the cosmetics industry to address sustainability concerns during the production phase (Aguiar et al., 2022; Bom et al., 2019). These include: (i) use of renewable energy sources, such as wind, solar and geothermal, to power industrial processes; (ii) insulation of buildings to reduce energy consumed in climatization; (iii) decrease of temperature during manufacturing by relying, for example, on cold emulsification processes, thus decreasing energy consumption and CO_2 emissions; (iv) use of more energy-efficient modern equipment; (v) decrease water use during the product manufacture (e.g., waterless products, optimization of production and cleaning processes, develop strategies for capturing and storing rainwater, implement waterloop factories with a circular water management, where the water used in production is continuously recirculated and reused). A summary of these strategies is presented, alongside some examples, in Table 4.

A great example that integrates several of the strategies referred previously is the environmentally responsible building developed by L'Oréal to recover a former, very polluted, scrap yard in Chevilly-Larue, France (L'Oréal, 2022a). This R&D L'Oréal Center was carefully designed to be sustainable: (i) the design of the building considered the results of a previous biodiversity assessment; (ii) it is powered by one large geothermal energy network located in the same city, generating low amounts of greenhouse gases; (iii) uses an ecological earth air-heat exchanger system that naturally preheats or cools ventilated air into the building; (iii) uses argon-filled double glazing windows; (iv) has a 1000 m^2 green rooftop that provides improved thermal and acoustic insulation while enhancing atmospheric dust retention, contributing to CO_2 absorption by plants and improving biodiversity; (v) possesses a rainwater harvesting system,which is used to supply the building's toilets; (vi) possesses wastewater phytoremediation tanks, which use plants for water purification; the water is then reused for watering of green spaces and local gardens. Besides creating waterless formulas, L'Oréal has also been addressing the problem of water consumption during the manufacture phase, and has managed to decrease it by about one third over the past decade. The L'Oréal group introduced the waterloop factory concept and opened its first waterloop factory ISO, 2017, in Spain (Shincci Global, 2021). Waterloop factories contribute to the UN SDGs 6 - Clean Water and Sanitation, 9 – Industry, In-

Table 4
Sustainability strategies for the manufacture of cosmetic products.

	Strategy	Examples	Companies
Energy	Use of renewable energy sources	Geothermal	L'Oreal group
		Solar	Aveda, Burt's Bees, Biolage
		Wind	Aveda, L'Oréal Brazil
	Decrease energy loss during the manufacture	Insulation of buildings and water pipes	L'Oreal group
	Decrease temperature of processes	Cold emulsification	Shiseido
	Use of energy-efficient equipment	Energy management systems to control heating, ventilation, air conditioning	Lush
Water	Use of different water sources	Capture and storage of rainwater	Givaudan
	Recycle and reuse production water	Waterloop factories	L'Oreal group
	Waterless products	Solid bars, sticks, oils and butters, powders, BYO Water products	Examples in Table 3
	Optimization of production and cleaning processes	Sequential production of batches of the same product	
Waste	Treat and reuse wastewater	Wastewater treated in phytoremediation tanks	L'Oreal group
		Zero-waste policy	Burt's Bees Several examples in section 6

novation and Infrastructure, 12 – Responsible Consumption and Production, and 13 – Climate Action (Jain, 2021). Nowadays, the L'Oréal group retains six waterloop factories worldwide, the last one in China, which is also the first one in North Asia (L'Oréal, 2022f). L'Oréal started monitoring water consumption along the lifecycle of its products after introducing a waterscan tool in 2011. This eventually led to a strategy to start recycling wastewater that could be used during the manufacture phase, to clean equipment or produce steam (Shincii Global, 2021). These approaches will certainly help L'Oréal achieve its water sustainability commitments for 2030: transform all the factories into waterloop factories to ensure that 100% of the water used in the industrial processes is recycled and reused, and guarantee that all the company suppliers will use water sustainable practices wherever in the world they are located (L'Oréal, 2022d).

Other companies have also made progress in increasing sustainability during the manufacturing of their products. Shiseido, for example, patented a low-energy manufacturing emulsifier technology that reduces both power consumption during manufacturing and the amount of water used for cleaning procedures (Wipo Green, 2023).

Concerning renewable energies, several cosmetic companies are part of the RE100 Initiative, a global corporate leadership aiming to accelerate the transition to zero-carbon energy by using renewable electricity (RE100, 2023). Examples include Givaudan and L'Occitane-en-Provence. The American company Aveda manufactures all its products using exclusively solar and wind energy (Safdie, 2022). Another great example is L'Oréal Brazil, which partnered with ENGIE, to reduce its carbon footprint (ENGIE, 2021). ENGIE's wind farms supply L'Oréal with 100% renewable electricity for its manufacturing plants, research and distribution centers, and offices. Such a strategy prevents the release of 7000 tonnes of CO_2 to the atmosphere per year.

A Givaudan Green Team in Cuernavaca, Mexico, created a 1000 m^3 rainwater collection system on the plant's rooftop, to profit from the heavy rainy months in the region, from July to October. The water can be stored in a tank at the plant's fire protection system or be used in the bathroom facilities or in the boiler, where steam for manufacturing is generated (Givaudan, 2023). This strategy decreased municipal water use, thus contributing to the company's sustainability and economy.

4.2. Distribution

The distribution phase also greatly affects the sustainability of cosmetic products, mainly the carbon footprint due to the combustion of fossil fuels, one of the main causes of global warming (Cosmetics Europe, 2019). Although distribution usually refers to the transport of the finished product, a more realistic approach is to consider the transport throughout the life cycle of the products, as represented in Fig. 4. This includes: transport of raw materials to either the production plant or to another factory where the ingredients are first transformed; transport involved in the manufacture of packaging materials and packing; transport of the packaging to the cosmetics factory; transport of the finished packaged products to distribution centers and, from there, to retailers; the transport associated to the consumer use; the transport involved in the post-use phase (transport of used packaging to landfill, composting facilities or recycling facilities and, in this latter case, transport of the recycled materials back to the packaging factory).

To address the sustainability of the transport phases related to the life cycle of cosmetic products, companies may choose to switch from trucks and planes to trains and ships. Another alternative is to introduce electrical, hybrid or alternative energy vehicles (Cosmetics Europe, 2019). In the previously mentioned program "*L'Oréal for the Future – Sustainability Commitments for 2030*", one of the focuses of the company is to decrease the greenhouse gases emitted during transportation by 50% per finished product (compared to 2016). To achieve this, supply chain teams have been turning to green transportation, using sea and rail freight whenever possible, or trucks powered by liquified natural gas (LNG) and intending to start using hydrogen-fueled vehicles. For short distances, the company has also turned to LNG-powered vehicles and zero-emission transport, such as bicycles. Additionally, the Vichy plant in France employs 100% green transportation, using vehicles powered by gas derived from canola oil, a totally biodegradable fuel that significantly decreases CO_2 emissions and pollution due to particulate matter (L'Oréal, 2022c).

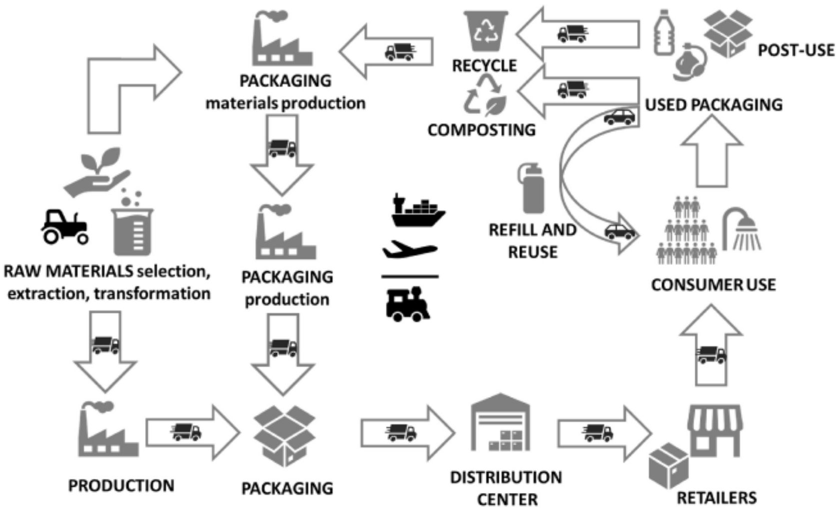

Fig. 4. Summary of possible transport phases involved in the life cycle of a cosmetic product. The transport phases are shown in black.

The use of larger trucks to transport more compact products also reduces the number of journeys needed, since more products are transported per journey. Another approach that several companies use is to reduce the distance between distribution centers and retailers by building large-scale warehouses where the products are stored until needed by the retailers (Cosmetics Europe, 2019).

5. The consumer use phase

The consumer use phase presents multiple variables such as the habits and lifestyle of the consumer, if the product is applied by the consumer or by a professional, the type of product (rinse-off or leave-on), the amount used and the frequency of use, among others (Bom et al., 2020c). The impact of this phase on the sustainability of a cosmetic product highly depends on the design and marketing of the product, which are responsibility of the industry (Mahler et al., 2012).

Cleansing products are the main concern in this phase because water is used to apply and/or rinse-off the product, alongside with water heating in some cases, which consumes energy (Cosmetics Europe, 2019). Furthermore, the water that goes down the drain affects the aquatic environment due to the presence of non-sustainable ingredients, such as the microsplastics mentioned previously (Rochman et al., 2015; Rosney, 2016; Smith, 2017). Such products include soaps, shampoos, gels, conditioners, toothpastes, scrubs, etc. It has been estimated that the use phase of a shampoo accounts for about 90% of the total CO_2 emissions along its life cycle, due to the use of water and heating (Cosmetics Europe, 2019).

Leave-on products do not present these problems but to be effective and safe, the consumer must know how to use them, in terms of amount and frequency of use (Cosmetics Europe, 2012). How can industry address these problems and find strategies to decrease the environmental impact of the use of such products?

For rinse-off products, the strategy is to develop products of fast rinse-off, more concentrated formulas or 2-in-1 products, such as those combining shampoo and conditioner that only require a single lather. The conditioning foams by Pantene, for example, allow a 50% faster rinse-off compared to cream conditioners. These foams are considered water-efficient products, since the consumers can reduce up to 15 L of the water used for rinsing (Procter and Gamble, 2020). Investment in new technology also helps tacking the problem of the water footprint of cosmetics. The water-tech company Gjosa partnered with L'Oreal to create a *Water Saver Portfolio,* including an innovative equipment for hairdresser salons, which can save up to 80% of the water used in hair washing (Culliney, 2021c). This system combines up to 3 products in a micronized water jet, creating a “foam cloud” made of small droplets that allow a faster rinse-off.

For both rinse-off and leave-on, consumer education also plays a fundamental role. Most companies’ websites provide suggestions on how to decrease water consumption while using the product and instructions for the use of leave-on. Furthermore, brand beauty experts can help customers at the point-of-sale, providing additional tips (Cosmetics Europe, 2019). Another strategy for both types of products is to enhance the biodegradability of the formulations, which is crucial for the sustainability of the cosmetic products (Campion et al., 2014).

6. Post-use phase: packaging and its destiny

The function of packaging is the protection of the product, by maintaining the formulation quality. Additionally, it fulfils an informative role, by providing the consumer with instructions on how to use the product and how to dispose of it. Furthermore, the design of the packaging is an important element of communication with the consumer.

The packaging has such a strong impact on the sustainability of the cosmetic products that there are initiatives dedicated to dealing only with this. For example, SPICE – **S**ustainable **P**ackaging **I**nitiative for **C**osm**E**tics, created by a partnership between L’Oréal and Quantis, and which currently includes 29 cosmetic brands, aims at creating methods and tools for sustainable packaging for cosmetics. The members work collaboratively “to develop and publish business-oriented methodologies and data to support resilient decision making to improve the environmental performance of the entire packaging value chain” (SPICE, 2022).

Most cosmetic products are still provided in plastic packaging (Wakefield-Rann, 2017). Plastics have several desirable properties such as being resistant, flexible, and having a good strength-to-weight ratio, protecting the perishable cosmetic products. Petrochemical-based plastics, in particular, are employed in the packaging of these products because they are cheaper, have good mechanical performance, are easily available, and are good barriers to gases and volatile compounds (Cinelli et al., 2019). Plastics are the number one enemy of the environment, polluting ecosystems, and threatening biodiversity, but they are not easily substitutable.

Several global initiatives to decrease plastic use, including in the cosmetics industry, exist, among them *The Ellen MacArthur Foundation* (Circular Economy) and the *Alliance to End Plastic Waste*. The *Ellen MacArthur Foundation* works to accelerate the transition to a circular economy, including for plastics. The foundation leads, in partnership with the UN Environment Programme, the *Global Commitment* and *Plastics Pact Network,* which joins more than 1000 members, including governments and companies, and aims at attaining a circular economy for plastics by 2025 (The Ellen MacArthur Foundation, 2022). The signatories are committed to “eliminate all problematic and unnecessary plastic items, innovate to ensure that the plastics we do need are reusable, recyclable, or compostable and circulate all the plastic items we use to keep them in the economy and out of the environment” (Cosmetics Europe, 2019). The *Alliance to End Plastic Waste* is a global non-profit partnership created in 2019 and headquartered in Singapore, which aims to “develop and bring to scale solutions that will minimize and manage plastic waste and promote solutions for used plastics by helping to enable a circular economy.” (Cosmetics Europe, 2019). Henkel and Procter & Gamble are members of this alliance (Alliance to End Plastic Waste, 2022).

The post-use phase has a great impact on sustainability and any successful sustainability strategy is based on the so-called 3 Rs: Reduce, Recycle and Reuse (Sahota, 2014): reducing the amount of packaging, reusing by refilling the packaging, and recycling the packaging after use. Additionally, it is possible to use materials that are biodegradable and can be disposed of in the environment (Fig. 5).

6.1. Reduce

The type of packaging material is very important for sustainability but so is the amount of material used. During the development and design phase, this should be considered, since using less material is cheaper, less polluting and is advantageous in terms of transport, due to decreased weight and space. For example, companies such as Beiersdorf created packaging containing 50% less plastic than conventional ones (Packaging Europe, 2020). Another interesting strategy followed by Caudalie was the elimination of all inside information leaflets, which are now printed on the inside of the packing. This approach saves 23 tonnes of paper per year (Hannah, 2019). Possibly the most radical strategy of reducing packaging is that followed by Lush, which completely eliminated the packaging of some of its products (Lush, 2022). The company, which invented the first solid bar shampoo, sells its handmade "naked" cosmetic products without packaging or in recycled packaging, if required. Additionally, Lush uses the same plastic for the container, lid and label to facilitate recycling (Coelho et al., 2020). The company saves water, energy and materials and greatly contributes to a sustainable development (Lush, 2022). Such tendency has been followed by other brands such as the New Zealand Ethique, which also produces cosmetic products in bar, such as shampoos and conditioners (Ethique, 2021).

6.2. Refill and reuse strategies

Reusing packaging is another efficient strategy to decrease carbon footprint and address sustainability in the post-use phase. Some brands commercialize cosmetics in packs that can be refilled. The Ellen Macarthur Foundation found that if all beauty and personal care products bottles were refillable, the greenhouse gases emissions would decrease by 80–85% (Cullor, 2022b).

The company Expanscience, previously mentioned in section 3.3.3 implemented a refill system for Mustela baby and maternity products in pharmacies as part of their sustainable development approach (Expanscience, 2022a). Rituals (Netherlands) sells refill containers to be placed inside the parent container of its body cream products (Coelho et al., 2020). The Body Shop, a UK-based founded by an environmental and human rights activist in 1976, and a pioneer and leader in sustainable cosmetics, relaunched its pioneer product refill scheme in 2019 and are hoping to have it implemented in 500 stores globally by the end of this year (The Body Shop, 2022). The color cosmetics brand Izzy Beauty created an innovative way to reuse or recycle old packaging: its mascara, brow gel and gloss products, mostly use stainless steel packaging (with recyclable parts) which, after use, the consumer can return using a subscription model (Cullor, 2022a). The stainless-steel parts can then be sterilized and reused, while the applicator parts are recycled. In 2020, Shiseido (Japan), which aims to achieve 100% sustainable packaging of its products by 2025, created the refill service Ultimune Fountain at its global flagship store Tokyo, so consumers can refill their bottles of Shiseido's Ultimune Power Infusing Concentrate (Nichol, 2022).

Besides their environmental advantages, the refill systems are also valuable for the companies, because they engage client loyalty, and decrease packaging and transport costs.

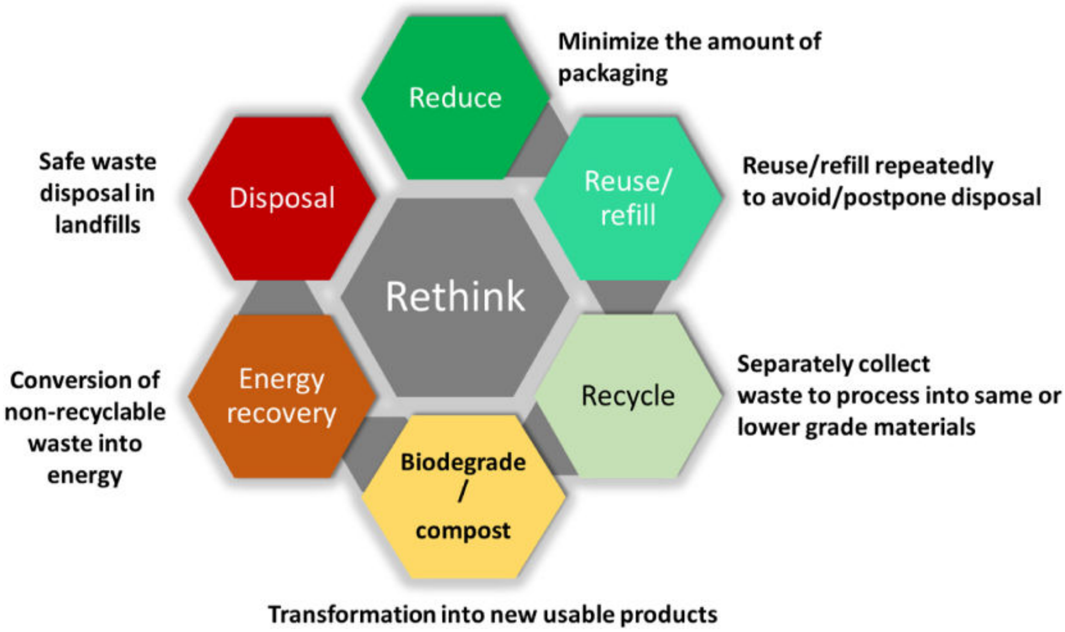

Fig. 5. Waste disposal scheme. Cosmetic companies aim at the 3Rs during the post-use phase: reduce packaging, reuse and refill, or recycle. Whatever is left should be biodegradable or compostable, and disposal should be kept to a minimum.

6.3. Recycle

Until recently, only a small percentage of cosmetics packaging was recyclable, because they are too small and/or too complex due to multiple layers of different materials, etc. This tendency is changing towards a better recyclability of cosmetics packaging (Lagarde, 2020).

As previously mentioned, most products are still provided in plastic containers. However, companies are substituting non-recyclable petrochemical-based polymers by recyclable bioplastics, such as poly(lactic) acid (PLA), polyhydroxyalkanoates and polysaccharide-based polymers (Cinelli et al., 2019).

Post-consumer regrind (PCR) plastics have gained popularity as a sustainable option for cosmetic packaging. These materials are made from recycled plastic waste, such as used water bottles or food containers, that have been processed and cleaned to remove impurities. The use of PCR plastics in cosmetic packaging reduces the demand for virgin plastic and helps to keep plastic waste out of landfills and the environment. PCR plastics are a great option for sustainable cosmetic packaging, as they help to reduce waste and promote a circular economy (Sahota, 2014).

The cosmetic companies have been introducing several programs to stimulate consumers to recycle. The UK-based Lush created the program *Bring it Back* in 2021, which encourages consumers to return used recyclable plastic packaging, receiving a reimbursement or being offered a fresh facial mask (Lush, 2021). O Boticário (Brazil) also promotes initiatives to increase recycling while simultaneously engaging in social sustainability. Its system *Boti Recicla*, the largest recycling program in Brazil, consists in collecting empty product packaging in collection points located in stores all over the country, and transport them to recycling facilities, where they are transformed in materials that will be used, for example, as building materials in O Boticário stores (Boticário, 2022a). Furthermore, *Boti Recicla* also has a social impact, since part of the recycled packaging is used to develop pedagogical spaces and furniture for public schools, libraries and labs (Boticário, 2022b). Henkel (Germany) also allies environmental and social sustainability when dealing with its products packaging. In 2017, it developed a social project called *Social Plastic*, in partnership with the social enterprise Plastic Bank, which establishes waste collection protocols with poor countries which do not have adequate waste management systems (e.g., Haiti), paying the collectors a premium for their work. This helps reduce plastic residues in the oceans, while also contributing to better living conditions of poor populations. Furthermore, the collected plastic is recycled and reused as packaging for products of the brand, contributing to a circular economy (Cosmetics Europe, 2021). The already mentioned The Body Shop launched the Community Fair Trade recycled plastic program, buying plastic from waste pickers in India, which is then recycled and used in shampoo and conditioner bottles This way, the company is contributing for all 3 dimensions of sustainability of its products (The Body Shop, 2022).

Some companies have been turning into non-plastic recyclable materials, because plastic recycling is a more recent trend than glass, aluminum or paper, which have been recycled for decades (Sahota, 2014). Although there are several recyclable plastics nowadays, companies are increasingly turning into infinite recyclable packaging options. The problem is that several plastics lose structural integrity when recycled and their quality decreases. Thus, an alternative is to use aluminum; 75% of all produced aluminum is still in use today (Cullor, 2022b). Caudalie has also been changing the packaging of some of its products from plastic to glass, which is infinitely more recyclable. Additionally, it removed the plastic spatulas that were used to apply the products (Hannah, 2019).

Finally, a very interesting example of what might be possible in the near future – transform plastic waste into valuable ingredients for cosmetics, i.e., plastic upcycling. Sadler et al. (Sadler and Wallace, 2021) reported, for the first time, the biotransformation of plastic, poly(ethylene terephthalate) (PET), which is widely used in industry, into vanillin. Traditionally, the recycling of PET yields monomers that are then used to produce more PET or other recycled materials. In this work, the authors used terephthalic acid monomers resulting from the recycling of PET and created a novel pathway in engineered *Escherichia coli* to produce vanillin, a flavor ingredient used in food and cosmetics industries. Furthermore, the authors coupled the novel pathway with enzyme-catalyzed PET hydrolysis, allowing the direct use of post-consumer PET to produce vanillin.

For products that cannot be recycled using the regular domestic programs, an alternative is TerraCycle which cooperates, for example, with L'Occitane en Provence, Caudalie and Garnier (TerraCycle, 2022; Hannah, 2019; Lagarde, 2020). Pump bottles, toothbrushes, lipsticks, among others may be recycled through TerraCycle, being transformed into innovative new materials.

6.4. Biodegrade/composting

Another tendency is to use biodegradable or compostable materials, which can be naturally recycled without the need for additional resources (Cinelli et al., 2019; Koopmans et al., 2019). Examples of such alternatives to plastics include biopolymers and bioplastics derived from plants and natural materials such as bamboo and wood fiber (Bom et al., 2020b). The Finnish company Sulapac®, for example, develops sustainable compostable packaging which are already used by some cosmetic brands such as Shiseido, Chanel and Marimekko (Nylanden, 2020). The packaging provided by Sulapac® is made from sustainable responsible origin raw materials, such as FSC (Forest Stewardship Council)-certified wood chips, and biodegradable natural binders. This alternative to plastics is 100% biodegradable and can degrade to CO_2, water or biomass in nature, however Sulapac® has been designed to undergo organic recycling by industrial composting. This technology is already available in several countries and EU legislation to make separate biowaste collection mandatory is underway (Sulapac, 2021). The Japanese company Shiseido partnered with Kaneka Corporation to use a biodegradable packaging made of Biodegradable Polymer Green Planet™ (PHBH) produced using a microbial fermentation process employing plant-based raw materials (Nichol, 2022). Another example, mentioned previously, are the truly genius O'right SCG and PLA bottles – the *Recoffee Tree in the Bottle,* which are not only biodegradable but can originate a coffee tree when buried in soil (O'Right, 2022).

In summary, companies have a crucial role in the post-use phase of their products. By choosing the right packaging materials, the weight, size and label of their products, companies can contribute to an environmentally responsible post-consumption phase. Responsible companies have been devoting significant time to develop sustainable strategies for this phase, which include packaging material selection, quantity, and use and/or disposal strategies (refill and reuse, recycle, compost, etc.).

7. General discussion

Sustainability is a 'hot' subject this millennium. While reviewing sustainability related to the cosmetic industry, we observed that there is an enormous amount of information in research and review papers, scientific and non-scientific (beauty, well-being, etc.) websites, online articles, and periodicals, etc. Furthermore, new information kept on being added while we were researching and writing the manuscript. When writing a review like this it is extremely challenging to keep focused and not being overwhelmed by the amount of information. Thus, we used a previous paper by our group (Bom et al., 2019) as a guide, and investigated what had been done during the 3–4 years since this paper was published. The general conclusion of our research is that sustainability is indeed a trendy topic that got stronger during the Covid-19 pandemic, with an increasing number of consumers demanding more sustainable products. We also noticed that, although much information is available everywhere, there are still gaps that must be addressed:

(a) Most consumers cannot distinguish between green, organic, environmental-friendly and sustainable. While the first three usually refer to ingredients, sustainability is being implemented throughout the life cycle of the products. There is a need to educate consumers about this.
(b) Although there is a huge amount of information available in several formats, as mentioned previously, there is a poor organization of such information. It is our opinion that the world of sustainability in cosmetics would greatly benefit from a dedicated database (or databases), which should include quantitative data.
(c) Quantitative data is lacking at all levels, or the data is not easily accessible. Companies' websites are trustworthy but, again, quantitative data is mainly available for beauty giants, such as L'Oréal. Table 5 summarizes the state of the company in 2022 and the goals for 2030.
(d) Most research focuses on environmental sustainability: the effects of cosmetics production and use on environmental problems such as climate change, water scarcity, biodiversity decrease, among others. It is necessary to further address economic and social sustainability.
(e) Although there are several assessment tools for sustainability, how can companies be compared?

In the previous sections, several companies have been mentioned as examples of sustainability in cosmetics, from the international giants L'Oréal and Garnier to smaller ones such as Sophim and O'right. Some companies, particularly the beauty giants, apply sustainability concepts along the entire life cycle of their products, because they have more resources. We observed there is no "most sustainable cosmetics company", and that such evaluation depends on which institution, website, etc. is evaluating, what is being evaluated (the whole life cycle of the cosmetic product, certain phases only), which criteria are being used, etc. For example, the nonprofit environmental organization Earth.org, based in Hong Kong, which aims to alert to the degradation of ecosystems worldwide, considered the 2022 most sustainable cosmetic brands as: REN, Aveda, Lush, Herbivore, Giorgio Armani, L'Occitane en Provence, Clarins, Origins, Weleda, axiology, Burt's bees, Ilia, UpCircle Beauty and Tata Harper (Earth.org, 2022). Greenly, a carbon accounting platform for businesses, on the other hand considered the 5 most sustainable makeup and cosmetics brands as: Arbonne, Aveda, The Body Shop, Burt's Bees and INIKA (Safdie, 2022). Other organizations choose the most sustainable beauty brands based on categories, such as makeup, skincare, body care, dental care, etc. According to stylist.co.uk, the more sustainable beauty brands are (Ibraheem, 2022): UpCircle, SBTRCT, BYBI and Neal's Yard Remedies for skincare; Garnier, Beauty Kubes, Ethique and Davines for haircare; Axiology, Odylique, PHB Ethical Beauty and Nudi Goods for makeup; Soaper Dupe, KanKan and Wild Deodorant for body care. The 2022 Sustainable Beauty Awards organized by Eccovia Intelligence awarded prizes in various categories, two of which are *Sustainability Pioneer* and *Sustainability Leadership* (Sustainable Beauty Awards, 2022). Sustainability Pioneer is awarded to a beauty company/industry that is a leader in some aspects of sustainability, while Sustainability Leadership is awarded to a company/industry leading an overall leadership in sustainability, not confined to just a few areas. Last year's finalists for the first category were AAK Personal Care, Arles SAS, Lumene, Lush Cosmetics, O'right and Weleda. For the leadership category the nominated finalists were AAK Personal Care, Apivita, Fattoria La Vialla, Guerlain, Lumene and O'right. Some of these brands have been mentioned previously in this paper. Lush has also been nominated in the categories *New Sustainable Product*, with its Naked Mascara and *New Sustainable Ingredient* with the Lush Blockchain Frankincense Oil. The Taiwan company O'right was nominated for the first award with the Caffeine Melanin Botanical Scalp Revitalizer, and for the category *Sustainable Packaging* with the Sorghum Radiance Banana Fiber Sheet Mask.

Table 5
Sustainability strategies of the L'Oréal group: current state (2022) and 2030 goals (L'Oréal, 2022g).

Sustainability strategy	Current state (2022)	Objective by 2023
Use of renewable energy	65%	100%
Reduction of greenhouse gases emission	−24%	−25%
Water recycled and reused in a loop	13%	100%
Biobased ingredients and packaging materials from sustainable sources	92%	100%
Biobased formula ingredients derived from minerals or circular processes	61%	95%
Packaging plastic recycled or biosourced	26%	100%
Generated waste recycled or reused	61%	100%
Eco-designed products	97%	100%

In summary, although there is no single "most sustainable cosmetics company", there are some brands that are considered sustainable by several entities, such as Lush and Weleda.

8. Conclusions and final remarks

This review presents and discusses several strategies employed throughout the whole life cycle of cosmetic products to make them more sustainable. Although it mainly focuses on the environmental domain, examples of social and economic sustainability are also discussed.

Consumers of cosmetics have been increasingly demanding *green, environmentally friendly* and/or *organic* products, a tendency that was exacerbated in this post-COVID19 era. Thus, industries are more aware of the impact of their products in the environment and in society and have been modifying their policies accordingly.

A sustainable transformation begins by defining and addressing realistic objectives that lead to doable changes while maintaining the quality and functionality of the products. It starts with the ingredients, which must be as natural as possible and come from responsible, sustainable sources. Synthetic ingredients that are extremely challenging to substitute, such as solid surfactants for solid shampoos and preservatives, may benefit from compounds developed by green chemistry. The production processes must be optimized to save energy and resources, while producing less waste and contributing to a circular economy. Making packaging more sustainable includes using less packaging (or no packaging at all), using innovative materials that are recyclable or compostable, and/or reuse and refill solutions. As important as the previously mentioned approaches is the role that companies have in the consumer education: how to use the product in the most sustainable way and how to deal with the packaging, emphasizing how these practices affect the environment and the society.

The future of cosmetics depends on more sustainable approaches, applied throughout the entire life cycle of the products. In this sense, it is more important that an increasing number of companies take steps, even if small, to increase the sustainability of their products, than to know which companies are the most sustainable.

While writing this paper, it was very clear that there is an increasing number of cosmetic companies worried about sustainability, and many are already applying sustainability strategies to their products, especially concerning the environmental domain. By adopting sustainability strategies at this level, but also at the economic and social levels, cosmetic companies can globally contribute to a more sustainable future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

Adeel, S., Abrar, S., Kiran, S., Farooq, T., Gulzar, T., Jamal, M., 2018. Sustainable application of natural dyes in cosmetic industry. In: Yusuf, M. (Ed.), Handbook of Renewable Materials for Coloration and Finishing. Scrivener Publishing LLC, Massachussets, pp. 189–211.

Aguiar, J.B., Martins, A.M., Almeida, C., Ribeiro, H.M., Marto, J., 2022. Water sustainability: a waterless life cycle for cosmetic products. Sustain. Prod. Consum. 32, 35–51. https://doi.org/10.1016/j.spc.2022.04.008.

Ahmadi-Ashtiani, H.-R., Baldisserotto, A., Cesa, E., Manfredini, S., Sedghi Zadeh, H., Ghafori Gorab, M., Khanahmadi, M., Zakizadeh, S., Buso, P., Vertuani, S., 2020. Microbial biosurfactants as key multifunctional ingredients for sustainable cosmetics. Cosmetics 7 (2020), 46. https://doi.org/10.3390/cosmetics7020046.

Alander, J.T., 2012. Chemical and physical properties of emollients. In: Lodén, M., Maibach HI, H.I. (Eds.), Treatment of Dry Skin Syndrome. Springer, Berlin, Heidelberg, pp. 399–417.

Alliance to End Plastic Waste, 2022. We are working together to end plastic waste. https://endplasticwaste.org/en. (Accessed 28 November 2022).

Alves, T.F.R., Morsink, M., Batain, F., Chaud, M.V., Almeida, T., Fernandes, D.A., et al., 2020. Applications of natural, semi-synthetic, and synthetic polymers in cosmetic formulations. Cosmetics 7, 75. https://doi.org/10.3390/cosmetics7040075.

Amador-Castro, F., Rodriguez-Martinez, V., Carrillo-Nieves, D., 2020. Robust natural ultraviolet filters from marine ecosystems for the formulation of environmental friendlier bio-sunscreens. Sci. Total Environ. 749, 141576. https://doi.org/10.1016/j.scitotenv.2020.141576.

Aman Mohammadi, M., Ahangari, H., Mousazadeh, S., Hosseini, S.M., Dufossé, L., 2022. Microbial pigments as an alternative to synthetic dyes and food additives: a brief review of recent studies. Bioproc. Biosyst. Eng. 45, 1–12. https://doi.org/10.1007/s00449-021-02621-8.

American Chemical Council, 2022. Silicones environmental, health, and safety center (SEHSC). https://www.americanchemistry.com/industry-groups/silicones-environmental-health-and-safety-center-sehsc. (Accessed 16 September 2022).

American Chemical Society, 2022. What is green chemistry. https://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry.html. (Accessed 16 November 2022).

Augustyniak, A., Bartosz, G., Čipak, A., Duburs, G., Horáková, L.U., Łuczaj, W., Majekova, M., Odysseos, A.D., Rackova, L., Skrzydlewska, E., Stefek, M., Štrosová, M., Tirzitis, G., Venskutonis, P.R., Viskupicova, J., Vraka, P.S., Žarković, N., 2010. Natural and synthetic antioxidants: an updated overview. Free Radic. Res. 44, 1216–1262. https://doi.org/10.3109/10715762.2010.508495.

Bare Naked Botanicals, 2022. Fatty alcohols & food grade emulsifiers. https://www.barenakedbotanicals.com/fatty-alcohols/. (Accessed 25 November 2022).

Beauty, UpCircle, 2022. Our ingredients. https://upcirclebeauty.com/pages/our-ingredients. (Accessed 3 November 2022).

Beerling, J., 2014. Green formulations and ingredients. In: Sahota, A. (Ed.), Sustainability: How the Cosmetics Industry Is Greening up. John Wiley & Sons, New Jersey,

pp. 197–215.
Beerling, J., Sahota, A., 2014. Green standards, certification and indices. In: Sahota, A. (Ed.), Sustainability: How the Cosmetics Industry Is Greening up. John Wiley & Sons, New Jersey, pp. 217–238.
Behrens, M., 2020. Rahn's reforcyl-aion awarded for upcycling. In: Cosmet. Toilet. [Internet]. https://www.cosmeticsandtoiletries.com/formulas-products/anti-aging-face/news/21843721/rahn-ag-rahns-reforcyl-aion-awarded-for-upcycling. (Accessed 7 September 2022).
Belousov, A.S., Esipovich, A.L., Kanakov, E.A., Otopkova, K.V., 2021. Recent advances in sustainable production and catalytic transformations of fatty acid methyl esters. Sustain. Energy Fuels 5, 4512–4545. https://doi.org/10.1039/D1SE00830G.
Bennet, E., 2021. Powdered BYO water products are the future of sustainable beauty. https://www.elle.com/uk/beauty/a35627658/byo-water-beauty-products/. (Accessed 7 December 2022). Elle [Internet]. [.
Bessada, S.M.F., Alves, R.C., Oliveira, M.B.P.P., 2018. Coffee Silverskin: a review on potential cosmetic applications. Cosmetics 5, 5. https://doi.org/10.3390/cosmetics5010005.
Bickers, D.R., Calow, P., Greim, H.A., Hanifin, J.M., Rogers, A.E., Saurat, J.-H., et al., 2003. The safety assessment of fragrance materials. Regul. Toxicol. Pharmacol. 37, 218–273. https://doi.org/10.1016/S0273-2300(03)00003-5.
Biochemistry, Mibelle, 2022. SLVR'Coffee™ - deep comfort with upcycled coffee silverskin. https://mibellebiochemistry.com/slvrcoffeetm]. (Accessed 2 November 2022). Available at:
Bird, K., 2010. Emolliet ester produced by green chemistry launched by Evonik. https://www.cosmeticsdesign-europe.com/Article/2010/03/31/Emollient-ester-produced-by-green-chemistry-launched-by-Evonik. (Accessed 9 November 2022). Cosmetics Design Europe [Internet].
Bom, S., Jorge, J., Ribeiro, H.M., Marto, J., 2019. A step forward on sustainability in the cosmetics industry: a review. J. Clean. Prod. 225, 270–290. https://doi.org/10.1016/j.jclepro.2019.03.255.
Bom, S., Fitas, M., Martins, A.M., Pinto, P., Ribeiro, H.M., Marto, J., 2020a. Replacing synthetic ingredients by sustainable natural alternatives: a case study using topical O/W emulsions. Molecules 25, 4887. https://doi.org/10.3390/molecules25214887.
Bom, S., Ribeiro, H.M., Marto, J., 2020b. Embracing sustainability: important practices and impact in cosmetics. Cosmet. Toilet. 135, 41–47.
Bom, S., Ribeiro, H.M., Marto, J., 2020c. Sustainability calculator: a tool to assess sustainability in cosmetic products. Sustainability 12, 1437. https://doi.org/10.3390/su12041437.
Bom, S., Gouveia, L.F., Pinto, P., Martins, A.M., Ribeiro, H.M., Marto, J., 2021. A mathematical modeling strategy to predict the spreading behavior on skin of sustainable alternatives to personal care emollients. Colloids Surf., B 205, 111865. https://doi.org/10.1016/j.colsurfb.2021.111865.
Bondioli, P., Mariani, C., Lanzani, A., Fedeli, E., Muller, A., 1993. Squalene recovery from olive oil deodorizer distillates. JAOCS (J. Am. Oil Chem. Soc.) 70 (1993), 763–766. https://doi.org/10.1007/BF02542597.
Formula Botanica, 2022. 38 natural colourants for organic skincare. https://formulabotanica.com/38-natural-colourants-skincare/. (Accessed 15 November 2022).
Boticário, O., 2022a. Boti Recicla - programa de Reciclagem. https://www.boticario.com.br/boti-recicla/. (Accessed 25 September 2022).
Boticário, O., 2022b. Boti Recicla - transformando a educação. https://www.boticario.com.br/sustentabilidade/. (Accessed 25 September 2022).
Brudzyńska, P., Sionkowska, A., Grisel, M., 2021. Plant-derived colorants for food, cosmetic and textile industries: a review. Materials 14, 3484. https://doi.org/10.3390/ma14133484.
Business, Cosmetics, 2019a. Blue Gold: water in cosmetics. https://www.cosmeticsbusiness.com/news/article_page/Blue_gold_Water_in_cosmetics/156328]. (Accessed 17 March 2022).
Business, Cosmetics, 2019b. Smooth closer: the latest in silicones and silicone alternatives. https://cosmeticsbusiness.com/news/article_page/Smooth_closer_The_latest_in_silicones_and_silicone_alternatives/157719. (Accessed 10 November 2022).
Business, Cosmetics, 2020. How is 'natural' regulated in the US? https://www.cosmeticsbusiness.com/news/article_page/How_is_natural_regulated_in_the_US/165850. (Accessed 30 September 2022).
Calkin, R.R., Perfumery, Jellinek J.S., 1994. Practice and Principles. John Wiley & Sons, New York.
Campion, J.-F., Barre, R., Gilbert, L., 2014. Innovating to reduce the environmental footprint, the L'Oreal example. In: Sahota, A. (Ed.), Sustainability: How the Cosmetics Industry Is Greening up. John Wiley & Sons, New Jersey, pp. 31–46.
Canan, C., Cruz, F.T.L., Delaroza, F., Casagrande, R., Sarmento, C.P.M., Shimokomaki, M., et al., 2011. Studies on the extraction and purification of phytic acid from rice bran. J. Food Compos. Anal. 24, 1057–1063. https://doi.org/10.1016/j.jfca.2010.12.014.
Cargill, 2022. Pectins. https://www.cargill.com/personal-care/hydrocolloids/pectins. (Accessed 29 September 2022).
Caudalie, 2020. Caudalie - a Arte das Vinhas. https://pt.caudalie.com/a-marca/a-nossa-historia.html. (Accessed 20 September 2022).
Chao, C., Génot, C., Rodriguez, C., Magniez, H., Lacourt, S., Fievez, A., et al., 2018. Emollients for cosmetic formulations: towards relationships between physico-chemical properties and sensory perceptions. Colloids Surf., A 536, 156–164. https://doi.org/10.1016/j.colsurfa.2017.07.025.
Chemat, F., Abert Vian, M., Ravi, H.K., Khadhraoui, B., Hilali, S., Perino, S., Tixier, A.F., 2019. Review of alternative solvents for green extraction of food and natural products: panorama, principles, applications and prospects. Molecules 24. https://doi.org/10.3390/molecules24163007.
Cheong, K.L., Qiu, H.M., Du, H., Liu, Y., Khan, B.M., 2018. Oligosaccharides derived from red seaweed: production, properties, and potential health and cosmetic applications. Molecules 23. https://doi.org/10.3390/molecules23102451.
Chisvert, A., Salvador, A., 2007. 3.1 - UV Filters in sunscreens and other cosmetics. Regulatory aspects and analytical methods. In: Salvador, A., Chisvert, A. (Eds.), Analysis of Cosmetic Products. Elsevier, Amsterdam, pp. 83–120.
Cinelli, P., Coltelli, M.B., Signori, F., Morganti, P., Lazzeri, A., 2019. Cosmetic packaging to save the environment: future perspectives. Cosmetics 6, 26. https://doi.org/10.3390/cosmetics6020026.
Clarke, C.J., Tu, W.-C., Levers, O., Bröhl, A., Hallett, J.P., 2018. Green and sustainable solvents in chemical processes. Chem. Rev. 118, 747–800. https://doi.org/10.1021/acs.chemrev.7b00571.
Coelho, P.M., Corona, B., ten Klooster, R., Worrell, E., 2020. Sustainability of reusable packaging–Current situation and trends. Resour. Conserv. Recycl. X. 6, 100037. https://doi.org/10.1016/j.rcrx.2020.100037.
Culliney, K., 2020. Smashed avocado: French firm develops eye care active from by-product. https://www.cosmeticsdesign-europe.com/Article/2020/04/14/Laboratoires-Expanscience-develops-avocado-by-product-active-for-eyes. (Accessed 22 May 2022). Cosmetics Design Europe [Internet].
Culliney, K., 2021a. Earth Day 2021: a circular snapshot and look at beauty's future. https://www.cosmeticsdesign-europe.com/Article/2021/04/22/Earth-Day-2021-CosmeticsDesign-Europe-circular-sustainable-beauty-snapshot-and-brainstorm. (Accessed 22 May 2022). Cosmetics Design Europe [Internet].
Culliney, K., 2021b. Green chemistry can 'future proof' cosmetics: expert. https://www.cosmeticsdesign-europe.com/Article/2021/10/08/Green-chemistry-innovation-in-cosmetics-preservation-can-future-proof-industry-says-expert. (Accessed 6 September 2022). Cosmetics Design Europe [Internet].
Culliney, K., 2021c. L'Oréal unveils smart Water Saver hair care system at CES 2021: 'Every drop of water is precious'. In: Cosmetics Design USA. https://www.cosmeticsdesign.com/Article/2021/01/20/L-Oreal-Water-Saver-launches-at-CES-2021-for-salons-with-at-home-device-launch-set-for-later-date]. (Accessed 24 April 2022).
Culliney, K., 2021d. Waste stream ingredients for cosmetics has massive opportunity but hurdles remain. https://www.cosmeticsdesign-europe.com/Article/2019/10/01/Waste-stream-ingredients-for-cosmetics-has-massive-opportunity-but-hurdles-remain?utm_source=copyright&utm_medium=OnSite&utm_campaign=copyright. (Accessed 24 April 2022). Cosmetics Design Europe [Internet].
Cullor, R., 2021. Coffee cup to cosmetics: Colombian company introduces coffee cherry ingredient with big protective claims. In: CosmeticsDesign USA. https://www.cosmeticsdesign.com/Article/2021/11/24/Colombian-coffee-antioxidant-ingredients-hits-beauty-market. (Accessed 7 September 2022).
Cullor, R., 2022a. How Izzy is using a subscription model to close the sustainability loop. In: CosmeticsDesign USA. https://www.cosmeticsdesign.com/Article/2022/05/17/izzy-using-a-subscription-model-to-close-the-loop?utm_source=copyright&utm_medium=OnSite&utm_campaign=copyright. (Accessed 22 May 2022).
Cullor, R., 2022b. What upcycling, waste reduction looks like with cosmetic products today. In: CosmeticsDesign USA. https://www.cosmeticsdesign.com/Article/2022/11/08/upcycling-in-cosmetics-ingredients-and-formulation?utm_source=newsletter_daily&utm_medium=email&utm_campaign=10-Nov-2022&cid=DM1041983&bid=2079326512. (Accessed 16 November 2022).
Deckner, G., 2015. Antioxidants: powerful skin care actives & stabilizers. https://knowledge.ulprospector.com/2963/pcc-antioxidants-powerfulskin-care-actives-

stabilizers/. (Accessed 25 August 2022). UL Prospector Knowledge Center [Internet].
Deckner, G., 2022. Natural-based thickeners. https://knowledge.ulprospector.com/3937/pcc-natural-based-thickeners/. (Accessed 2 December 2022). UL Prospector Knowledge Center [Internet].
Dell'Acqua, G., 2017. Garbage to glamour: recycling food by-products for skin care. https://www.cosmeticsandtoiletries.com/research/methods-tools/article/21836720/garbage-to-glamour-recycling-food-byproducts-for-skin-care. (Accessed 3 October 2022). Cosmet. Toilet. [Internet].
Douguet, M., Picard, C., Savary, G., Merlaud, F., Loubat-Bouleuc, N., Grisel, M., 2017. Spreading properties of cosmetic emollients: use of synthetic skin surface to elucidate structural effect. Colloids Surf., B 154, 307–314. https://doi.org/10.1016/j.colsurfb.2017.03.028.
Duprat-de-Paule, S., Guilbot, J., Roso, A., Cambos, S., Pierre, A., 2018. Augmented bio-based lipids for cosmetics. OCL 25, D503. https://doi.org/10.1051/ocl/2018036.
Earth.org, 2022. 14 of the best sustainable beauty brands in 2022. https://earth.org/best-sustainable-beauty-brands/. (Accessed 2 November 2022).
ENGIE, 2021. ENGIE x L'Oréal – Brazil. https://www.engie.com/en/business-case/engie-x-loreal. (Accessed 1 June 2023).
Ethique, 2021. Saving water. https://ethique.co.uk/pages/saving-water. (Accessed 25 September 2022).
Europe, Cosmetics, 2012. Good Sustainability Practice (GSP) for the Cosmetics Industry. https://www.cosmeticseurope.eu/files/4214/6521/4452/GSP_Brochure.pdf (Accessed 21 April 2022).
Europe, Cosmetics, 2019. Environmental Sustainability: the European Cosmetics Industry's Contribution 2017-2019; Brussels: Cosmetics Europe.
Europe, Packaging, 2020. New Nivea bottle design results in 50% plastics reduction. https://packagingeurope.com/new-nivea-bottle-design-results-in-50-plastics-reduction/1443.article. (Accessed 21 September 2022).
Europe, Cosmetics, 2021. Henkel: circular solutions for sustainable packaging. In: Cosmetics Europe - the Personal Care Association. https://cosmeticseurope.eu/green-action-case-studies-environmental-sustainability-cosmetics-industry/henkel/. (Accessed 3 October 2022).
European Chemicals Agency (ECHA), 2022. Microplastics. https://echa.europa.eu/hot-topics/microplastics. (Accessed 17 October 2022).
European Commission, 2021. Upcycling innovation to extract value from biowaste. https://ec.europa.eu/research-and-innovation/en/projects/success-stories/all/upcycling-innovation-extract-value-biowaste. (Accessed 3 October 2022).
European Parliament, 2009. Regulation (EC) No 1223/2009 of the European Parliament and of the Council of 30 November 2009 on Cosmetic Products. Off. J. Eur. Union.
Expanscience, 2022a. Act together for well-being. https://www.expanscience.com/en. (Accessed 2 November 2022).
Expanscience, 2022b. Cosmetic active ingredients. https://www.expanscience-ingredients.com/en/cosmetic-active-ingredients/ingredients. (Accessed 2 November 2022).
Food and Drugs Administration (FDA), 2015. The microbead-free waters act: FAQs. In: US Food and Drugs Administration. Availble from: https://www.fda.gov/cosmetics/cosmetics-laws-regulations/microbead-free-waters-act-faqs. (Accessed 29 September 2022).
Forgo, 2022. Just add water. https://www.forgo.se/. (Accessed 29 November 2022).
Garnier, 2020. Naturalmente eficaz - shampoo sólido. https://www.garnier.pt/as-nossas-marcas/ultra-suave/shampoo-solido. (Accessed 25 May 2022).
Gawade, R.P., Chinke, S.L., Alegaonkar, P.S., 2020. Polymers in cosmetics. In: AlMaadeed, M.A.A., Ponnamma, D., Carignano, M.A. (Eds.), Polymer Science and Innovative Applications. Elsevier, Amsterdam, pp. 545–565.
Geetha, D., Tyagi, R., 2012. Alkyl poly glucosides (APGs) surfactants and their properties: a review. Tenside Surfactants Deterg. 49 (2012), 417–427. https://doi.org/10.3139/113.110212.
Georgalas, A., 2014. Formulating with natural colors. In: Cosmet. Toilet. https://www.cosmeticsandtoiletries.com/formulas-products/color-cosmetics/blog/21837775/formulating-with-natural-colors. (Accessed 25 August 2022).
Giacomo, B., Luca, B., Nicola, L., Luigi, R., 2020. Development of an innovative and eco-friendly UV radiation absorber, based on furan moieties. Cosmetics 7, 6. https://doi.org/10.3390/cosmetics7010006.
Givaudan, 2018. Upcycled vetiver roots deliver sustainable beauty ingredients. https://www.givaudan.com/sustainability/creations/heritage-action/upcycled-vetiver-roots-delivery-sustainable-beauty-ingredients. (Accessed 3 October 2022).
Givaudan, 2020a. Active Beauty. Koffee'Up™ - the upcycled coffee oil for well-ageing. https://www.scsformulate.co.uk/wp-content/uploads/sites/13/2021/08/KoffeeUp.pdf. (Accessed 7 September 2022).
Givaudan, 2020b. Givaudan launches Koffee'Up™, a new sustainable beauty elixir crafted from upcycled Arabica coffee. https://www.givaudan.com/media/media-releases/2020/givaudan-launches-koffeeuptm-new-sustainable-beauty-elixir-crafted-upcycled. (Accessed 7 September 2022).
Givaudan, 2021. Omegablue®, an upcycled ingredient dedicated to skin repair. https://www.givaudan.com/media/trade-media/2021/givaudan-active-beauty-presents-omegablue. (Accessed 2 November 2022).
Givaudan, 2023. Heavy rains inspire water collection project. https://www.givaudan.com/sustainability/nature/water/water-collection-from-heavy-rains. (Accessed 31 May 2023).
Global, Shincci, 2021. Working to protect earth's most precious raw material - L'oréal's 'waterloop'' factories. https://shincci-global.com/news/Dry-Factory. (Accessed 18 November 2022).
Gluhar, S., Kaurin, A., Lestan, D., 2020. Soil washing with biodegradable chelating agents and EDTA: technological feasibility, remediation efficiency and environmental sustainability. Chemosphere 257, 127226. https://doi.org/10.1016/j.chemosphere.2020.127226.
Goussard, V., Aubry, J.-M., Nardello-Rataj, V., 2022. Bio-based alternatives to volatile silicones: relationships between chemical structure, physicochemical properties and functional performances. Adv. Colloid Interface Sci. 304, 102679. https://doi.org/10.1016/j.cis.2022.102679.
Gov, U.K., 2018. World leading microbeads ban comes into force. https://www.gov.uk/government/news/world-leading-microbeads-ban-comes-into-force. (Accessed 17 October 2022).
Goyal, N., Jerold, F., 2021. Biocosmetics: technological advances and future outlook. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-021-17567-3.
Green, Wipo, 2023. Method for producing O/W emulsion composition_1 - Shiseido company ltd. https://wipogreen.wipo.int/wipogreen-database/articles/10816?query=shiseido&type=BASIC&pagination.size=10&pagination.page=0&sort.0.field=ALL&sort.0.direction=DESC. (Accessed 31 May 2023).
Guerra, E., Llompart, M., Garcia-Jares, C., 2018. Analysis of dyes in cosmetics: challenges and recent developments. Cosmetics 5, 47. https://doi.org/10.3390/cosmetics5030047.
Halla, N., Fernandes, I.P., Heleno, S.A., Costa, P., Boucherit-Otmani, Z., Boucherit, K., Rodrigues, A.E., Ferreira, I., Barreiro, M.F., 2018. Cosmetics preservation: a review on present strategies. Molecules 23 (2018). https://doi.org/10.3390/molecules23071571.
Haller, K., Lee, J., Cheung, J., 2020. Meet the 2020 consumers driving change. https://www.ibm.com/thought-leadership/institute-business-value/report/consumer-2020. (Accessed 25 August 2022). IBM Institute Business Value [Internet].
Hannah, L., 2019. From a new eco-friendly facility to reformulated products: Caudalie's ambitious plans for addressing sustainability. https://fashionmagazine.com/beauty-grooming/caudalie-sustainability/. (Accessed 25 August 2022). Fashion Magazine [Internet].
Happi, 2020. 'Upcycled' ingredients in cosmetics. https://www.happi.com/contents/view_breaking-news/2020-08-28/upcycled-ingredients-in-cosmetics/. (Accessed 27 September 2022). 1.
Hoang, H.T., Moon, J.-Y., Lee, Y.-C., 2021. Natural Antioxidants from plant extracts in skincare cosmetics: recent applications, challenges and perspectives. Cosmetics 8, 106. https://doi.org/10.3390/cosmetics8040106.
Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2012. The Water Footprint Assessment Manual. Earthscan Ltd, London.
Holifrog, 2022. Sunapee Sacred C Powder Wash. [. https://holifrog.com/products/sunapee-sacred-c-powder-wash (Accessed 15 July 2022).
Hunger, K., Herbst, W., 2000. Pigments, organic. In: Ley, C. (Ed.), Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH. https://doi.org/10.1002/14356007.a20_371.
Hunt, C.F., Lin, W.H., Voulvoulis, N., 2021. Evaluating alternatives to plastic microbeads in cosmetics. Nat. Sustain. 4, 366–372. https://doi.org/10.1038/s41893-020-00651-w.
Ibraheem, H., 2022. A guide to the most sustainable beauty brands and their environmentally friendly initiatives. https://www.stylist.co.uk/beauty/sustainable-beauty-brands/455404. (Accessed 2 November 2022). Stylist.co.uk [Internet]. [.

Imerys, 2022. A natural alternative to microplastic beads. https://www.imerys.com/markets/cosmetics-personal-care/benefits/exfoliation. (Accessed 20 October 2022). [.
Inolex, 2022. Sustainable silicone alternatives. https://inolex.com/products/sustainable-silicone-alternatives. (Accessed 10 November 2022).
International Fragrance Association, 2022. The IFRA transparency list. https://ifrafragrance.org/priorities/ingredients/ifra-transparency-list. (Accessed 27 September 2022).
ISO, 2007. Cosmetics — Good Manufacturing Practices (GMP) — Guidelines on Good Manufacturing Practices. International Organization for Standardization. [. https://www.iso.org/standard/36437.html (Accessed 25 August 2022).
ISO, 2017. ISO 16128-2:2017. Cosmetics — Guidelines on Technical Definitions and Criteria for Natural and Organic Cosmetic Ingredients — Part 2: Criteria for Ingredients and Products. International Organization for Standardization. https://www.iso.org/standard/65197.html (Accessed 30 September 2022).
ISO, 2022. Sustainable development goals. International organization for standardization. https://www.iso.org/sdgs.html. (Accessed 25 August 2022).
Jain, N., 2021. Water Loop Factory: turning cosmetics waste water into reusable water. https://www.amsterdamiww.com/best-practices/water-loop-factory-turning-cosmetics-waste-water-into-reusable-water/]. (Accessed 2 December 2022). Amsterdam International Water Web [Internet]. [.
Jones, O., Sellinger, B., 2022. The chemistry of cosmetics. https://www.science.org.au/curious/people-medicine/chemistry-cosmetics]. (Accessed 19 October 2022). Australian Academy of Sciences [Internet].
Kanlayavattanakul, M., Lourith, N., 2021. Biopolysaccharides for skin hydrating cosmetics. In: Ramawat, K.G., Mérillon, J.-M. (Eds.), Polysaccharides: Bioactivity and Biotechnology. Springer International Publishing, Switzerland, pp. 1–23.
Keeble, B.R., 1988. The Brundtland report: 'Our common future'. Med. War 4, 17–25.
Kinetic, Omya, 2019. Natural chelating agents for cosmetics. https://omyakinetik.com/blog/natural-chelating-agents-for-cosmetics/. (Accessed 20 September 2022).
Koopmans, R., Doorsselaer, K., Velis, C., et al., 2019. In: Linder, M., De Smet, M. (Eds.), A Circular Economy for Plastics : Insights from Research and Innovation to Inform Policy and Funding Decisions. European Commission Directorate General for Research Innovation Publications Office.
Kornhauser, A., Coelho, S.G., Hearing, V.J., 2010. Applications of hydroxy acids: classification, mechanisms, and photoactivity. Clin. Cosmet. Invest. Dermatol. 3, 135–142. https://doi.org/10.2147/ccid.S9042.
Krishnan, A., McNeil, B.A., Stuart, D.T., 2020. Biosynthesis of fatty alcohols in engineered microbial cell factories: advances and limitations. Front. Bioeng. Biotechnol. 3. https://doi.org/10.3389/fbioe.2020.610936.
L'Oréal, 2022a. Chevilly-larue: an innovative and responsible building. https://www.loreal.com/en/articles/sharing-beauty-with-all/chevillylarue-an-innovative-and-responsible-building/. (Accessed 18 November 2022). [.
L'Oréal, 2022b. Discover garnier green beauty initiative. https://www.loreal.com/en/adria-balkan/articles/brands/green-beauty-garnier-bh/. (Accessed 21 November 2022).
L'Oréal, 2022c. L'Oréal embraces green transportation to meet environmental challenges. https://www.loreal.com/en/articles/commitments/green-transportation/. (Accessed 28 November 2022). [.
L'Oréal, 2022d. Managing water sustainability. https://www.loreal.com/en/commitments-and-responsibilities/for-the-planet/managing-water-sustainably/. (Accessed 3 December 2022).
L'Oréal, 2022e. Mica. https://inside-our-products.loreal.com/ingredients/mica. (Accessed 4 May 2022).
L'Oréal, 2022f. Yichang waterloop plant: a journey towards sustainable factories. https://www.loreal.com/en/articles/commitments/yichang-waterloop-plant/. (Accessed 18 November 2022). Available at:
L'Oréal, 2022g. 2022 annual report 2022 - social & environmental performance. https://www.loreal-finance.com/en/annual-report-2022/social-environmental-performance/. (Accessed 31 May 2023). Available at:
La Carrément Belle, 2021. Animal notes in perfumery. https://www.carrementbelle.com/blog/en/2021/05/19/animal-notes-perfumery/. (Accessed 27 September 2022).
Lagarde, É., 2020. Sustainable beauty packaging: five trends to watch in 2022. https://www.premiumbeautynews.com/en/sustainable-beauty-packaging-five. (Accessed 29 November 2022). Premium Beauty News [Internet].
Laudamiel, C., Hornetz, C., Mookherjee, B.D., Patel, S., 2008. From virgin education to real education. Chem. Biodivers. 5, 1159–1169. https://doi.org/10.1002/cbdv.200890093.
Lee, J.-W., Trinh, C.T., 2020. Towards renewable flavors, fragrances, and beyond. Curr. Opin. Biotechnol. 61, 168–180. https://doi.org/10.1016/j.copbio.2019.12.017.
Lochhead, R.Y., 2017. The use of polymers in cosmetic products. In: Sakamoto, K., Lochhead, R.Y., Maibach, H.I., Yamashita, Y. (Eds.), Cosmetic Science and Technology: Theoretical Principles and Applications. Elsevier, Amsterdam, pp. 171–221.
Lush, 2021. Bring it back - our new-look recycling scheme for 2021. https://www.lush.com/uk/en/a/bring-it-back-our-new-look-recycling-scheme. (Accessed 25 September 2022).
Lush, 2022. Our environmental policy. https://weare.lush.com/lush-life/our-policies/environmental-policy/. (Accessed 25 September 2022).
L'Oréal, 2020. Product environmental & social impact labelling methodologies. https://www.loreal.com/-/media/project/loreal/brand-sites/corp/master/lcorp/documents-media/publications/loreal-pil-methodologie-en01.pdf. (Accessed 29 August 2022).
Mahler, D., Aurik, J., Hembert, E., Schrieber, K., 2012. A product lifecycle approach to sustainability. Supply Chain Manag. Rev. 16, 50–51.
Majumdar, B., Chatterjee, G., 2017. Sunscreen - the double edged sword. Clin. Oncol. 2, 1263.
Marques, P., Marto, J., Gonçalves, L.M., Pacheco, R., Fitas, M., Pinto, P., et al., 2017. Cynara scolymus L.: a promising Mediterranean extract for topical anti-aging prevention. Ind. Crop. Prod. 109, 699–706. https://doi.org/10.1016/j.indcrop.2017.09.033.
Marto, J., Gouveia, L.F., Chiari, B.G., Paiva, A., Isaac, V., Pinto, P., et al., 2016. The green generation of sunscreens: using coffee industrial sub-products. Ind. Crop. Prod. 80, 93–100. https://doi.org/10.1016/j.indcrop.2015.11.033.
Matta, M.K., Florian, J., Zusterzeel, R., Pilli, N.R., Patel, V., Volpe, D.A., Yang, Y., Oh, L., Bashaw, E., Zineh, I., Sanabria, C., Kemp, S., Godfrey, A., Adah, S., Coelho, S., Wang, J., Furlong, L.A., Ganley, C., Michele, T., Strauss, D.G., 2020. Effect of sunscreen application on plasma concentration of sunscreen active ingredients: a randomized clinical trial. JAMA 323 (2020), 256–267. https://doi.org/10.1001/jama.2019.20747.
May, G., Folkerts, J., 2021. Breaking new grounds for coffee. Food Sci. Technol. 35 (2021), 28–31. https://doi.org/10.1002/fsat.3502_8.x.
McPhee, D., Pin, A., Kizer, L., Perelman, L., 2014. Deriving renewable squalane from sugarcane. Cosmet. Toilet. 129.
McQuarrie, L., 2020. Waterless cleansing tablets. https://www.trendhunter.com/trends/cleansing-tablet. (Accessed 7 December 2022). Trend Hunter Inc. [Internet].
Mendes, F., González-Pajuelo, M., Cordier, H., Francois, J., Vasconcelos, I., 2011. 1,3-Propanediol production in a two-step process fermentation from renewable feedstock. Appl. Microbiol. Biotechnol. 92, 519–527. https://doi.org/10.1007/s00253-011-3369-1.
Merabet, M., 2022. BYO Water: Clean Beauty in London. https://www.cleanbeautyinlondon.com/2021/12/08/byo-water/ (Accessed 15 July 2022).
Milito, A., Castellano, I., Damiani, E., 2021. From sea to skin: is there a future for natural photoprotectants? Mar. Drugs 19. https://doi.org/10.3390/md19070379.
Mohana Priya, M., Chidambara Rajan, P., Lavanya, M., 2020. Use of natural pigments as colorants in cosmetics – a review. JETIR 7, 907–917.
Molvar, K., 2020. To scrub, slough, or chemically dissolve? Experts weigh in on the ultimate guide to winter exfoliation. https://www.vogue.com/article/skincare-mechanical-vs-chemical-vs-physical-exfoliation. (Accessed 20 October 2022). Vogue [Internet].
Moscoviz, R., Trably, E., Bernet, N., 2016. Consistent 1,3-propanediol production from glycerol in mixed culture fermentation over a wide range of pH. Biotechnol. Biofuels 9. https://doi.org/10.1186/s13068-016-0447-8.
Nardelli, A., Drieghe, J., Claes, L., Boey, L., Goossens, A., 2011. Fragrance allergens in 'specific' cosmetic products. Contact Derm 64, 212–219. https://doi.org/10.1111/j.1600-0536.2011.01877.x.
Natrue, 2022. What makes the NATRUE Label unique? https://www.natrue.org/why-us/what-makes-the-natrue-label-unique/. (Accessed 19 October 2022).
Nichol, K., 2022. Shiseido to launch in-store refills, biodegradable packs. https://www.luxepackaginginsight.com/article/shiseido-to-launch-in-store-refills-biodegradable-packs.57479. (Accessed 21 October 2022). Luxe Packaging Insight [Internet].
Nowak, K., Jabłońska, E., Ratajczak-Wrona, W., 2021. Controversy around parabens: alternative strategies for preservative use in cosmetics and personal care products. Environ. Res. 198, 110488. https://doi.org/10.1016/j.envres.2020.110488.
Nunes, A., Marto, J., Gonçalves, L., Martins, A.M., Fraga, C., Ribeiro, H.M., 2022. Potential therapeutic of olive oil industry by-products in skin health: a review. Int. J.

Food Sci. Technol. 57, 173–187. https://doi.org/10.1111/ijfs.15384.
Nylanden, N., 2020. Sustainable at heart – three cosmetics companies explain why they choose compostable packaging. https://www.sulapac.com/blog/cosmetics-companies-explain-why-they-choose-compostable-packaging/. (Accessed 21 September 2022).
O'Lenick, A.J., Matson, E., 2011. Comparatively speaking: natural vs. synthetic fragrance. https://www.cosmeticsandtoiletries.com/cosmetic-ingredients/sensory/article/21834851/comparatively-speaking-natural-vs-synthetic-fragrance. (Accessed 27 September 2022). Cosmet. Toilet. [Internet].
O'Right, 2022. Clean products - exceeding Your and nature's expectations of a heathier future. https://www.oright.inc/en/about/4. (Accessed 7 September 2022).
Okereke, J.N., Udebuani, A.C., Ezeji, E.U., Obasi, K.O., Nnoli, M.C., 2015. Possible health implications associated with cosmetics: a review. Sci. J. Publ. Health 3, 58–63. https://doi.org/10.11648/j.sjph.s.2015030501.21.
Paraszczuk, N., Nicolini, R., Miller, A., Cwienkala, H., 2021. Formulating with alternatives in personal care products. https://www.happi.com/issues/2021-04-04/view_features/formulating-with-alternatives-in-personal-care-products/. (Accessed 23 August 2022). happi [Internet]. [.
Patil, N.N., Datar, A.G., 2016. Applications of natural dye from Ixora coccinea L. in the field of textiles and cosmetics, Color. Technol. 132, 98–103. https://doi.org/10.1111/cote.12193.
Pawlowski, S., Petersen-Thiery, M., 2020. Sustainable Sunscreens: a challenge between performance, animal testing ban, and human and environmental safety. In: Tovar-Sánchez, A., Sánchez-Quiles, D., Blasco, J. (Eds.), Sunscreens in Coastal Ecosystems: Occurrence, Behavior, Effect and Risk. Springer International Publishing, Switzerland, pp. 185–207.
Peyneau, M., de Chaisemartin, L., Gigant, N., Chollet-Martin, S., Kerdine-Römer, S., 2022. Quaternary ammonium compounds in hypersensitivity reactions. Front. Toxicol. 4, 4. https://doi.org/10.3389/ftox.2022.973680.
Pinto, J.R., Monteiro, E.S.S.A., Holsback, V.S.S., Leonardi, G.R., 2022. Skin occlusive performance: sustainable alternatives for petrolatum in skincare formulations. J. Cosmet. Dermatol. https://doi.org/10.1111/jocd.14782.
Premium Beauty News, 2021. Upcycled olive squalane for clean beauty. https://www.premiumbeautynews.com/en/upcycled-olive-squalane-for-clean. (Accessed 29 September 2022).
Procter & Gamble, 2020. https://us.pg.com/environmental-sustainability/. (Accessed 14 July 2022). Environmental Sustainability Report 2020.
Prospector, 2022a. Cosphaderm® sodium LAAS, UL prospector. https://www.ulprospector.com/en/eu/PersonalCare/Detail/113627/4271077/Cosphaderm-Sodium-LAAS?st = 1&sl = 146485380&crit = a2V5d29yZDpbTEFBU10%3d&ss = 2&k = LAAS&t = LAAS. (Accessed 5 December 2022).
Prospector, 2022b. Eumulgin® VL 75, UL prospector. https://www.ulprospector.com/en/na/PersonalCare/Detail/75/109523/Eumulgin-VL-75. (Accessed 10 November 2022).
100% Pure, 2019. 100% PURE legacy story: fruit Pigmented® natural makeup. https://www.100percentpure.com/blogs/feed/100-pure-legacy-story-fruit-pigmented-makeup. (Accessed 15 November 2022).
Purvis, B., Mao, Y., Robinson, D., 2019. Three pillars of sustainability: in search of conceptual origins. Sustain. Sci. 14 (2019), 681–695. https://doi.org/10.1007/s11625-018-0627-5.
Radice, M., Manfredini, S., Ziosi, P., Dissette, V., Buso, P., Fallacara, A., et al., 2016. Herbal extracts, lichens and biomolecules as natural photo-protection alternatives to synthetic UV filters. A systematic review. Fitoterapia 114, 144–162. https://doi.org/10.1016/j.fitote.2016.09.003.
Radin, S., 2020. Waterless beauty can help save the planet, and Your skin. In: Vogue. https://www.vogue.co.uk/beauty/article/waterless-beauty. (Accessed 17 March 2022).
Rahn, A.G., 2020. REFORCYL®-AION. Garb'Ageing clean-up. https://www.rahn-group.com/en/cosmetics/product/36/. (Accessed 7 September 2022).
RE100, 2023. We are accelerating change towards zero carbon grids at scale. https://www.there100.org/. (Accessed 31 May 2023).
Rhyme Biotechnology, 2021. Actinowax™. https://www.rhymebiotechnology.com/technology/. (Accessed 19 September 2022).
Ribeiro, H.M., Allegro, M., Marto, J., Pedras, B., Oliveira, N.G., Paiva, A., et al., 2018. Converting spent coffee grounds into bioactive extracts with potential skin antiaging and lightning effects. ACS Sustain. Chem. Eng. 6, 6289–6295. https://doi.org/10.1021/acssuschemeng.8b00108.
Rochman, C.M., Kross, S.M., Armstrong, J.B., Bogan, M.T., Darling, E.S., Green, S.J., et al., 2015. Scientific evidence supports a ban on microbeads. Environ. Sci. Technol. 49, 10759–10761. https://doi.org/10.1021/acs.est.5b03909.
Romanowski, P., 2015. An introduction to cosmetic technology. https://www.aocs.org/stay-informed/inform-magazine/featured-articles/an-introduction-to-cosmetic-technology-april-2015?SSO = True. (Accessed 29 October 2022). INFORM Magazine [Internet].
Rosney, D., 2016. Why microbeads in shower gels are bad for marine life - BBC newsbeat: BBC. https://www.bbc.com/news/newsbeat-35261018]. (Accessed 10 June 2022).
Rouge Français, Le, 2022. Le Rouge Français - plant based makeupology. https://lerougefrancais.com/]. (Accessed 20 October 2022).
Roundtable on Sustainable Palm Oil (RSPO), 2022. Making sustainable palm oil the norm. https://rspo.org/]. (Accessed 2 December 2022).
Rozman, U., Kalčíková, G., 2021. The first comprehensive study evaluating the ecotoxicity and biodegradability of water-soluble polymers used in personal care products and cosmetics. Ecotoxicol. Environ. Saf. 228, 113016. https://doi.org/10.1016/j.ecoenv.2021.113016.
Sadler, J.C., Wallace, S., 2021. Microbial synthesis of vanillin from waste poly(ethylene terephthalate). Green Chem. 23, 4665–4672. https://doi.org/10.1039/d1gc00931a.
Safdie, S., 2022. https://greenly.earth/en-us/blog/ecology-news/top-5-sustainable-makeup-cosmetic-brands?2ac0f94c_page = 11&2ac0f94c_page = 11&3caa887c_page = 2&3caa887c_page = 2&98dbe491_page = 5&98dbe491_page = 5&c0d8a10d_page = 1&c0d8a10d_page = 2. (Accessed 31 May 2023). Top 5 Sustainable Makeup/Cosmetic Brands [Internet].
Sahota, A., 2014. Sustainable packaging. In: Sahota, A. (Ed.), Sustainability: How the Cosmetics Industry Is Greening up. John Wiley & Sons, New Jersey, pp. 127–154.
Sakamoto, K., Lochhead, R.Y., Maibach, H.I., Yamashita, Y., 2017. Cosmetic Science and Technology: Theoretical Principles and Applications. John Fedor, Amsterdam.
Sałek, K., Euston, S.R., 2019. Sustainable microbial biosurfactants and bioemulsifiers for commercial exploitation. Process Biochem. 85, 143–155. https://doi.org/10.1016/j.procbio.2019.06.027.
Sánchez-Quiles, D., Tovar-Sánchez, A., 2015. Are sunscreens a new environmental risk associated with coastal tourism? Environ. Int. 83, 158–170. https://doi.org/10.1016/j.envint.2015.06.007.
Sandler, E., 2021. From apples to olive leaves: 'Upcycled' food ingredients gain traction among beauty brands. https://www.glossy.co/beauty/upcycled-ingredients-gain-traction-as-beauty-brands-seek-sustainability-storytelling/. (Accessed 29 September 2022). Glossy [Internet].
Santos, D.K., Rufino, R.D., Luna, J.M., Santos, V.A., Sarubbo, L.A., 2016. Biosurfactants: multifunctional biomolecules of the 21st century. Int. J. Mol. Sci. 17 (2016), 401. https://doi.org/10.3390/ijms17030401.
Sar, P., Ghosh, A., Scarso, A., Saha, B., 2019. Surfactant for better tomorrow: applied aspect of surfactant aggregates from laboratory to industry. Res. Chem. Intermed. 4. https://doi.org/10.1007/s11164-019-04017-6.
Schleicher, A., 2021. Zero-waste project upcycles olive leaves for health and pharma applications. https://www.nutritioninsight.com/news/zero-waste-project-upcycles-olive-leaves-for-health-and-pharma-applications.html. (Accessed 16 November 2022). Nutrition Insight [Internet].
Seppic, 2016. Seppic unveils two emollients ranges, EMOSMART™ and EMOGREEN. https://www.seppic.com/en/beauty-care/seppic-unveils-two-emollients-ranges-emosmarttm-and-emogreentm. (Accessed 10 November 2022).
Seppic, 2020. eLeaflet HYDRALIXIR range and products. https://www.seppic.com/en/eleaflet-hydralixir-range-and-products. (Accessed 10 November 2022).
Sharmeen, J.B., Mahomoodally, F.M., Zengin, G., Maggi, F., 2021. Essential oils as natural sources of fragrance compounds for cosmetics and cosmeceuticals. Molecules 26. https://doi.org/10.3390/molecules26030666.
Siegert, W., 2014. Boosting the antimicrobial efficiency of multifunctional additives by chelating agents. SOFW-Journal 140 (2014).
Silva, S., Ferreira, M., Oliveira, A.S., Magalhães, C., Sousa, M.E., Pinto, M., et al., 2019. Evolution of the use of antioxidants in anti-ageing cosmetics. Int. J. Cosmet. Sci. 41, 378–386. https://doi.org/10.1111/ics.12551.
Smith, M., 2017. Factsheet on microplastics - NATRUE position. https://www.natrue.org/uploads/2019/02/natrue_factsheets_microplastics_apr_17.pdf. (Accessed 10 June 2022).
SPICE, 2022. What is Spice? https://open-spice.com/about-spice/what-is-spice/. (Accessed 25 November 2022). [.
Srinivasan, M., Merlyn Keziah, S., Hemalatha, S.M., Subathra Devi, C., 2017. Pigment from Streptomyces bellus MSA1 isolated from marine sediments. IOP Conf. Ser.

Mater. Sci. Eng. 263, 022049.
Sulapac, 2021. A Brief Guide on Compostability. 2021. https://www.sulapac.com/compostability/ (Accessed 21 September 2022).
Sustainable Beauty Awards, 2022. Sustainable Beauty Awards...Pushing the boundaries of sustainability in the beauty industry. http://www.sustainablebeautyawards.com/index.htm. (Accessed 2 November 2022). [.
TerraCycle, 2022. Recycle the unrecyclable with TerraCycle. https://www.terracycle.com/en-US/. (Accessed 29 November 2022). [.
The Body Shop, 2022. Our sustainability commitments. https://www.thebodyshop.com/en-gb/about-us/brand-values/sustainability/sustainability-commitments/a/a00063. (Accessed 24 October 2022).
The Ellen MacArthur Foundation, 2022. Designing out plastic pollution. https://ellenmacarthurfoundation.org/topics/plastics/overview. (Accessed 25 November 2022).
The United States Pharmacopeial Convention, 2017. Octyldodecanol, Interim Revision Announcement. Maryland. https://www.uspnf.com/notices/octyldodecanol (Accessed 28 September 2022).
Trevisol, T.C., Henriques, R.O., Souza, A.J.A., Furigo, Jr, A., 2022. An overview of the use of proteolytic enzymes as exfoliating agents. J. Cosmet. Dermatol. 21, 3300–3307. https://doi.org/10.1111/jocd.14673.
United Nations - Department of Economic and Social Affairs, 2022. Sustainable development. https://sdgs.un.org/. 11, 2022.
United Nations, 2020. https://www.unwater.org/publications/world-water-development-report-2020/. (Accessed 4 October 2022). United Nations World Water Development Report 2020 - Water and Climate Change [Internet]. [.
United Nations, World Health Organization, 2010. The Right to Water, Fact Sheet No. 35. United Nations High Comm. Human Rights. Geneva: United Nations. https://www.ohchr.org/documents/publications/factsheet35en.pdf.
Utroske, D., 2019. Sustainably sourced sandalwood oil coming to the fragrance industry. In: Cosmetics Design USA. https://www.cosmeticsdesign.com/Article/2015/04/01/Sustainably-sourced-sandalwood-oil-coming-to-the-fragrance-industry. (Accessed 28 September 2022).
van den Berg, J., Ingram, V.J., Judge, L.O., Arets, E.J.M.M., 2014. Integrating Ecosystem Services into Tropical Commodity Value Chains - Cocoa, Soy and Palm Oil; Dutch Policy Options from an Innovation System Approach. Statutory Research Tasks Unit for Nature & the Environment, Wageningen UR. WOt-Technical Report 6 2014.
Veit, T., 2004. Biocatalysis for the production of cosmetic ingredients. Eng. Life Sci. 4, 508–511. https://doi.org/10.1002/elsc.200402148.
Wakefield-Rann, R., 2017. More than skin deep: a service design approach to making the luxury personal care industry more sustainable. In: Gardetti, M. (Ed.), Sustainable Management of Luxury Environmental Footprints and Eco-Design of Products and Processes. Springer, Singapore, pp. 211–231.
Welton, T., 2015. Solvents and sustainable chemistry. Proc. R. Soc. A: Math. Phys. Eng. Sci. 471, 20150502. https://doi.org/10.1098/rspa.2015.0502.
Wiechers, J.W., Kelly, C.L., Blease, T.G., Dederen, J.C., 2004. Formulating for efficacy. Int. J. Cosmet. Sci. 26 (2004), 173–182. https://doi.org/10.1111/j.1467-2494.2004.00211.x.
Yu, C., Anigbogu, C., 2020. How waterless beauty is chaging consumer behavior and addressing sustainability. Cosmet. Toilet. 135, 51–52.