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# The Effects of Cleaning and Cosmetic Products on the Microbiome and the Environment: Green Chemistry and Circular Economy Solutions

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**ABSTRACT:**
**Purpose:** This review does not aim to critically examine the existing literature on the dual impacts of conventional cosmetics and cleaning products on the human microbiome and planetary health, such as ecotoxicity, biodegradability issues and pollution. Rather, the main objective of this review is to comprehensively assess the potential, impacts, successes and limitations of green chemistry principles and circular economy models as integrated solutions to mitigate these negative impacts. By highlighting the intersection and synergies between these four critical areas (microbiome health, environmental sustainability, green chemistry practices and circular economy strategies), this study aims to make an original contribution to the literature.
**Material and Methods:** This research review adopted a narrative methodology. The study searched academic databases such as Scopus, Web of Science, PubMed, Google Scholar, Google Patents and Turkpatent patent databases. The literature review was primarily limited to publications between 2009 and 2024. Research articles, review articles and patent documents were analyzed. Keywords related to cosmetics, cleaning products, microbiome, environmental impact, green chemistry, circular economy, biosurfactants, and sustainable packaging were identified. The sources selected included peer-reviewed and theme-appropriate English and Turkish literature.
**Results:** The negative impact is associated with environmental issues such as aquatic toxicity, persistence and plastic waste, and microbiome dysbiosis of traditional product ingredients such as surfactants, preservatives, UV filters and microplastics. Green chemistry approaches emphasize alternatives such as biosurfactants, safer preservatives and renewable raw materials. In addition, circular economy strategies contribute to waste utilization, sustainable packaging and reuse models. However, these solutions face limitations such as cost, performance, scalability and lack of standard validation. The concept of "microbiome-friendly" products is evolving, but the lack of standardized testing protocols has led to microbiome laundering.
**Conclusion**: Conventional cosmetics and cleaning products have severe and unsustainable impacts on the human microbiome and environmental systems. Therefore, an integrated approach that integrates green chemistry and circular economy principles is critical for systemic transformation towards sustainability. Closing knowledge gaps, establishing standardized testing protocols, overcoming technical barriers to scalability, and implementing supportive regulatory structures are needed to develop safe and sustainable alternatives.
***Keywords:*** *Microbiome; cosmetics; cleaning products; green chemistry; circular economy; environmental health*

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## INTRODUCTION

Modern societies have increasingly depended on various cleaning and cosmetic products to raise hygiene standards and improve personal care. Supermarket shelves and our bathrooms are filled with countless chemical formulations, from surface cleaners and detergents to shampoos and creams. While these products play important roles in improving quality of life and preventing disease, their negative impact on our planet's microbiome and ecological balance is gaining increasing attention.

In particular, impacts on the microbiome are associated with how chemicals found in cleaning and cosmetic products alter the skin and gut microbiota. The potential risks of microbial-based cleaning products on human health have been examined regarding how they affect microbial diversity and possible toxicological consequences (La Maestra et al., 2021). Similarly, the effects of skincare products on skin chemistry and microbiome dynamics have been shown to affect skin health by destabilizing the skin microbiota (Bouslimani et al., 2019). Pilot studies have revealed that skincare products can alter the face's microbial structure and biophysical parameters (Hwang et al., 2021).

Furthermore, the environmental distribution of personal care products and their impact on human health is a significant concern, as the chemicals found in these products contribute to environmental pollution and create potential toxic effects (Khalid & Abdollahi, 2021). These findings suggest that more research is needed to understand better the effects of cleaning and cosmetic products on individual and environmental health.

The human body is a complex ecosystem home to trillions of microorganisms, and these microbial communities (microbiota) play critical roles in many fundamental physiological processes, from immune system regulation to food digestion (Gilbert et al., 2018; Dethlefsen et al., 2007). However, recent research suggests that antimicrobial agents (e.g., triclosan and benzalkonium chloride), preservatives, surfactants, and other synthetic chemicals found in cleaning and cosmetic products can disrupt this delicate microbial balance (fibrosis), leading to dysbiosis (Weatherly & Gosse, 2017; Espinosa-Marrón et al., 2022). Reduced microbial diversity and a disproportionate increase of particular species have been linked to a variety of chronic health problems such as allergic reactions, asthma, inflammatory bowel diseases, obesity, and even neurological disorders (Gilbert et al., 2018).

In addition to these health impacts, the environmental footprint of cleaning and cosmetic products is also a serious concern. The energy and water resources used in production processes, synthetic chemicals and microplastics in formulations that enter rivers, lakes and seas through wastewater after use, accumulation of persistent organic pollutants (POPs) in the food chain, and pollution caused by non-biodegradable packaging waste threaten the ecological health of our planet (Geyer et al., 2017; Berniak-Woźny, J., & Rataj, M., (2023)). In particular, phosphates, surfactants such as nonylphenol ethoxylates, and synthetic fragrances can cause eutrophication, hormonal imbalances, and toxicity in aquatic ecosystems (Roberts, 2020; Zhang et al., 2021). The impacts of microplastics and other anthropogenic wastes on marine ecosystems are also receiving increasing attention (Bergmann et al., 2015).

In the face of this dual threat of negative impacts on the human microbiome and planetary health, it is clear that current production and consumption models are not sustainable. At this point, green chemistry principles and circular economy models offer promising approaches to fundamentally transform the cleaning and cosmetics sectors (Netto et al., 2020). Green Laundering Concepts and Forms: A Systematic Review. Environmental Sciences Europe, 32(19). Green chemistry aims to reduce or eliminate the use or generation of hazardous substances in the design, production and application of chemical products and processes, while the circular economy, in contrast to the linear model of "take-make-dispose", aims to keep resources in the system by preserving their value for as long as possible and to minimize waste and pollution (Geueke et al., 2018; Kümmerer et al., 2018). These approaches are critical to protect both human health and environmental sustainability.

The key uniqueness of this review is that it addresses both the human microbiome and environmental impacts of cleaning and cosmetic products, and presents green chemistry and circular economy principles in an integrated manner as solutions to these complex problems. While studies in the literature often examine these topics separately, there is a lack of a comprehensive synthesis highlighting the intersection and synergy between these four critical areas (microbiome health, environmental sustainability, green chemistry practices, and circular economy strategies). This study aims to fill this gap (Budak & Yaşar, 2024; Budak & Sarıkaya, 2024). This review aims to synthesize existing knowledge and draw a roadmap for future research and sustainable practices by presenting this complex web of interactions in a holistic perspective.

This review aims to answer the following research questions:

1. Which chemical ingredients found in everyday cleaning and cosmetic products have adverse effects on the human microbiome, and what are the potential health consequences of these effects?
2. How do these products' production, use, and disposal processes threaten environmental sustainability (water, soil, biodiversity)?
3. How can the principles of green chemistry be applied to developing safer and more environmentally friendly cleaning and cosmetic products?
4. What strategies do circular economy models offer to improve resource efficiency and reduce waste in the cleaning and cosmetics sectors?
5. What are the current knowledge gaps and future research directions in these areas?

By answering these questions, the review aims to provide the scientific community with an up-to-date literature synthesis, raise awareness, and propose concrete solutions for industry professionals, policymakers, and consumers towards more sustainable and healthy practices.

## MATERIALS and METHODS

### Purpose and Type of Study

This review article aims to provide a comprehensive synthesis of the existing scientific literature covering the impacts of cleaning and cosmetic products on the human microbiome and the environment, and propose solutions in the context of green chemistry and circular economy. Rather than a systematic review strictly adhering to a specific protocol, a comprehensive narrative review methodology was adopted to provide a broad perspective on the topic. This paper will consider systematic approaches to ensure the comprehensiveness and objectivity of the literature review.

### Literature Review Strategy

The literature review was conducted using major scientific databases, covering studies published between January 2000 and March 2025. The central databases used were PubMed/MEDLINE (Biomedical and Health Sciences), Scopus (Interdisciplinary), Web of Science (Interdisciplinary), and Google Scholar (Broader search and supplementary for gray literature).

The screening strategy included various combinations of the following key phrases (using both English and Turkish equivalents):

Group 1 (Products): Cleaning products, detergents, disinfectants, cosmetics, personal care products, beauty products

Group 2 (Affected Areas): Microbiome, microbiota, gut microbiota, skin microbiome, human health, environment, environmental pollution, water pollution, soil pollution, ecotoxicity, biodiversity

Group 3 (Problematic Ingredients): Chemicals, surfactants, antimicrobials, preservatives, triclosan, parabens, phthalates, microplastics, endocrine disruptors

Group 4 (Solutions): Green chemistry, sustainable chemistry, circular economy, sustainability, biodegradable, bio-based, eco-friendly, waste management

In addition to keyword searches, reference lists of identified key articles (snowball method) and recent issues of relevant journals were also searched to ensure the inclusion of important studies that may have been missed.

### Inclusion and Exclusion Criteria

The following criteria were determined for the studies to be included in the review:

Inclusion Criteria:

Original research articles, reviews, meta-analyses, and significant book chapters published in peer-reviewed journals.

Studies that examine the chemical components, human microbiome (skin, gut, etc.), or environmental impacts (water, soil, air, biodiversity) of cleaning and/or cosmetic products.

Studies that discuss or demonstrate the

application of green chemistry or circular economy principles to the cleaning/cosmetics industry.

Studies published in English or Turkish.

Studies published between January 2000 and March 2025 (but earlier pioneering studies that made a fundamental contribution to the field are also cited).

Exclusion Criteria:

Conference abstracts, editorials, opinion pieces, and unpublished theses (unless published in a peer-reviewed journal).

Studies focusing on topics outside the scope of the review (e.g., food packaging only, occupational exposure to industrial chemicals, etc.).

Studies that are considered to be repetitive or have poor methodology.

Studies whose full text could not be accessed.

**Data Synthesis and Analysis**

The selected articles were categorized according to the main themes of the review (microbiome impacts, environmental impacts, green chemistry solutions, circular economy solutions). Under each theme, key findings, trends, controversial points, and knowledge gaps from the relevant literature were identified. Rather than a quantitative meta-analysis, the data synthesis was a narrative synthesis, where findings were summarized qualitatively and critically interpreted. Evidence from different studies was brought together to form a holistic understanding of the subject's current state. Conflicting findings or differing views are also addressed in the Discussion section. This methodology covers a wide range of topics, making it possible to provide the reader with an in-depth summary of the topic.

**Effects Of Cleaning and Cosmetic Products on the Human Microbiome**

The human body is home to a highly complex and dynamic ecosystem, the microbiota, consisting of trillions of bacteria, archaea, viruses, fungi and other microorganisms that colonise various sites, particularly the gut, skin, mouth and respiratory tract (Human Microbiome Project Consortium, 2012; Gilbert et al., 2018). This microbial community maintains a mutually beneficial (symbiotic) relationship with the host, playing key roles in critical physiological processes such as the education and regulation of the immune system (Belkaid & Hand, 2014), colonization resistance to invasion by pathogenic microorganisms, production of important metabolites such as short-chain fatty acids through fermentation of indigestible food components, and synthesis of specific vitamins (Shreiner et al., 2015; Lynch & Pedersen, 2016). A healthy balance of microbial composition and functions is defined as "eubiosis", while disruption of this balance due to various intrinsic or extrinsic factors is called "dysbiosis" (Levy et al., 2017). Numerous chemical components found in the cleaning and cosmetic products we are exposed to daily, particularly antimicrobial agents (e.g., triclosan), preservatives, and surfactants, risk threatening this delicate microbial balance and potentially contributing to Dysbiosis (Weatherly & Gosse, 2017). Dysbiosis, characterised by a reduction in microbial diversity and a disproportionate increase of certain species, is increasingly being linked to the pathogenesis of a wide range of chronic health conditions, including inflammatory bowel diseases, obesity, type 2 diabetes, allergic diseases, and even some neurological and behavioral disorders (Shreiner et al., 2015; Levy et al., 2017).

***Antimicrobials and Preservatives: Effects on Microbiota and Development of Resistance***

Cleaning products (disinfectants, antibacterial soaps, etc.) and cosmetics (creams, lotions, shampoos, etc.) contain various antimicrobial agents and preservatives to extend shelf life and prevent microbial spoilage. The widespread use of these chemicals is the focus of scientific research due to their potential impact on the human microbiota and the development of antimicrobial resistance.

For example, the use of broad-spectrum antimicrobials such as triclosan has been restricted in many countries due to their potential endocrine-disrupting effects and growing evidence that they may promote the development of cross-resistance to antibiotics (Weatherly & Gosse, 2017). The indiscriminate targeting of such agents to pathogens and beneficial commensal bacteria can disrupt the balance of microbial ecosystems.

Parabens, which are frequently used in cosmetics and personal care products, are also being investigated for their potential effects on the endocrine system (Nowak et al., 2018).

Quaternary ammonium compounds (QACs), such as benzalkonium chloride (BAC), are commonly found in disinfectants and personal care products. The widespread use of QACs can lead to the selection of bacterial strains resistant to these compounds (Hegstad et al., 2010). Notably, the mechanisms associated with QAC resistance often confer resistance to clinically important antibiotics (cross-resistance), raising concerns that the widespread use of these compounds may contribute to the problem of antibiotic resistance (Wales & Davies, 2015). This reduced susceptibility to biocides has been observed in various bacteria and is associated with the spread of antibiotic resistance (Wales & Davies, 2015).

Consequently, the widespread and sometimes unnecessary use of antimicrobial agents and preservatives in cleaning and cosmetic products can upset the delicate balance of the human microbiota. Reduced microbial diversity and selection of resistant bacterial strains (especially those cross-resistant to biocides and antibiotics) can increase the risk of individual health problems and contribute to broader public health threats, such as the spread of antibiotic resistance (Horner et al., 2012). It is, therefore, important to carefully evaluate the use of these chemicals and explore microbiota-friendly alternatives.

***Surfactants and Their Effects on Microbiota***

Surfactants, the main components of detergents, shampoos, shower gels, and other cleaning products, provide an effective cleaning mechanism by removing grease and dirt with water. With their hydrophobic and hydrophilic properties, these compounds make cleaning possible by reducing surface tension. However, despite their high cleansing efficacy, anionic surfactants such as sodium lauryl sulfate (SLS) and sodium laureth sulfate (SLES) can damage skin barrier function. These surfactants can disrupt the lipid matrix of the stratum corneum, increasing transepidermal water loss and altering the natural balance of skin microbiota (Ananthapadmanabhan et al., 2013). Disruption of the skin barrier can predispose to irritation, dryness, and colonization of potentially pathogenic microorganisms. For example, it has been reported that SLS exposure can disrupt the balance of commensal bacteria in the skin, increasing inflammatory responses (Grice & Segre, 2011).

The effects of surfactants are not limited to the skin; their potential effects on the gut microbiota have also been investigated in recent years. In particular, surfactants that reach the intestinal epithelial barrier, either orally or through environmental exposure, may increase intestinal permeability and affect microbial diversity. It has been suggested that surfactants such as SLS may exhibit toxicity to intestinal epithelial cells and trigger inflammatory responses by altering gut microbiota composition (Chassaing et al., 2017). Furthermore, the antimicrobial properties of some surfactants may contribute to the selection of resistant bacterial strains. Surfactant derivatives, such as quaternary ammonium compounds, may promote the spread of antimicrobial resistance genes, leading to the emergence of multidrug-resistant pathogens (Tezel & Pavlostathis, 2015).

The environmental dimension is also an important issue. When surfactants are released into the environment through wastewater, they can cause toxicity in aquatic ecosystems and disrupt the balance of microbial communities. This is considered a threat to ecosystem health (Ivanković & Hrenović, 2010). Furthermore, chronic use of aggressive surfactants can cause long-term skin and gut microbiome changes. These changes can affect the overall health status of individuals and may be associated with health problems such as atopic dermatitis or gut inflammation (Sommer et al., 2017).

Studies on microbiota-friendly alternatives have intensified to mitigate these adverse effects in recent years. Sugar-based surfactants (e.g., alkyl polyglucosides) and less irritating formulations are emerging to clean without damaging the skin barrier (Seweryn, 2018). Furthermore, developing readily biodegradable surfactants is important in reducing environmental impacts. In conclusion, the widespread use of surfactants is an issue that needs to be carefully addressed in terms of both individual health and environmental sustainability.

***Other Ingredients: Phthalates, Fragrances, and Microplastics***

Phthalates used as solvents, plasticizers, or fragrance fixatives in cosmetics (e.g., perfumes, nail polishes, hair sprays) and some cleaning products are classified as endocrine-disrupting chemicals. The effects of phthalates on the hormonal system have been shown to disrupt estrogen and androgen receptors, leading to hormonal imbalances and adverse effects on reproductive health, developmental processes, and metabolic functions (Kay et al., 2013). In particular, common phthalates such as diethyl phthalate (DEP) and dibutyl phthalate (DBP) have been shown in animal models to alter the ratio of *Firmicutes* and *Bacteroidetes* in the gut microbiota and trigger systemic inflammation by increasing intestinal permeability (Zhang et al., 2021). These changes are thought to contribute to health problems such as obesity, metabolic syndrome, and inflammatory bowel diseases.

Synthetic fragrances are another group of ingredients commonly used in cosmetics and cleaning products. These fragrances are often complex mixtures of chemicals that can cause allergic reactions. Some volatile organic compounds (VOCs) in synthetic fragrances are thought to have adverse effects on skin and respiratory microbiota (Steinemann, 2016). However, the effects of these chemicals on gut microbiota are not yet fully understood. Some studies suggest these compounds indirectly increase inflammatory responses and reduce microbial diversity.

Microplastics are another important ingredient, especially in cosmetics (e.g., exfoliating products, toothpaste) and cleaning products. Microplastic particles are usually composed of polymers such as polyethylene (PE), polypropylene (PP), and polystyrene (PS). They are a significant concern due to their potential impact on human health and environmental pollution. It has been shown that microplastics can enter the body through ingestion or inhalation and affect the gut microbiota. Studies in animal models have revealed that microplastics reduce gut microbial diversity, impair gut barrier function, and trigger inflammatory responses (Prata et al., 2020). It has also been reported that microplastics may carry toxic chemicals and pathogenic microorganisms on their surfaces, further increasing the adverse effects on the microbiota (Leslie et al., 2022).

More research is needed to understand the consequences of these compounds' individual and cumulative effects on microbiome health. In particular, comprehensive studies assessing the effects of long-term exposure to phthalates, synthetic fragrances, and microplastics on the human microbiota would help us better understand the health risks of these chemicals.

***Health Consequences of Microbiome Dysbiosis***

Microbiome dysbiosis, which can result from chronic exposure to cleaning and cosmetic products, can have multifaceted and systemic effects on human health. The microbiome is a complex ecosystem of trillions of microorganisms in the human body, playing critical roles in different areas such as the skin, gut, and respiratory tract. When the microbiome is out of balance, i.e., dysbiosis develops, various health conditions can occur or worsen. This has particularly pronounced effects on the skin and gut microbiota.

Dysbiosis in the skin microbiota disrupts the balance of commensal microorganisms that support skin barrier function and protect against pathogens. Chemicals found in cleaning and cosmetic products (e.g., surfactants and preservatives) have been shown to disrupt the skin microbiota and trigger inflammatory skin diseases (Ananthapadmanabhan et al., 2013). Imbalances in the skin microbiota can contribute to developing or exacerbating dermatologic conditions such as acne, eczema (atopic dermatitis), rosacea, and psoriasis (Byrd et al., 2018). For example, an increase in pathogenic species such as Staphylococcus aureus has been associated with exacerbating inflammatory skin diseases such as atopic dermatitis. Furthermore, decreasing beneficial species (e.g., Staphylococcus epidermidis) in the microbiota can weaken the skin barrier and cause inflammation.

The gut microbiota affects immune system regulation, metabolic processes, and neurological functions. Dysbiosis, characterized by a decrease in beneficial bacteria and an increase in pathogenic species in the gut microbiota, has been associated with neuropsychiatric disorders such as inflammatory bowel disease (IBD), irritable bowel syndrome (IBS), obesity, type 2 diabetes, allergies, asthma, autoimmune diseases and depression (Gilbert et al., 2018; Cryan et al., 2019). For example, changes in the ratio of Firmicutes and Bacteroidetes in the gut microbiota are associated with obesity and metabolic syndrome (Turnbaugh et al., 2006). Furthermore, a decrease in metabolites such as short-chain fatty acids (SCFAs) produced by the gut microbiota can lead to immune system overactivation and inflammation (Koh et al., 2016). A bidirectional communication system known as the gut-brain axis explains the effects of gut microbiota on the central nervous system. Dysbiosis can trigger neuroinflammation through increased gut permeability and systemic inflammation. This has been linked to neurodegenerative disorders such as depression, anxiety, and Alzheimer's disease (Cryan et al., 2019).

The effects of chemicals found in cleaning and cosmetic products on the microbiome may play an important role in developing these health problems. For example, surfactants have been shown to negatively impact the skin microbiota by disrupting the skin barrier and triggering inflammatory skin diseases. Endocrine-disrupting chemicals such as phthalates have been suggested to cause dysbiosis in the gut microbiota, triggering metabolic and inflammatory diseases. Microplastics may contribute to inflammation and immune system dysfunction by disrupting the gut microbiota. Volatile organic compounds (VOCs) in synthetic fragrances are also thought to affect skin and respiratory microbiota negatively.

Protecting and supporting the microbiome is a potential target in preventing and treating these health problems. In particular, developing probiotics, prebiotics, and microbiota-friendly products is a promising strategy to support microbiome health. Furthermore, replacing chemicals used in cleaning and cosmetic products with microbiota-friendly alternatives could be important to protect microbiome health.


**Figure 1.** Impact of Cleaning and Cosmetic Products on Human Microbiome and Environment

## Environmental Impacts of Cleaning and Cosmetic Products

The life cycle of cleaning and cosmetic products is complex, from extracting raw materials to product formulation, packaging, distribution, use, and disposal. This process has the potential to create severe environmental pressures on ecosystems. The environmental impacts of the ingredients, production processes, and post-use wastes of products can be examined in many dimensions, such as water pollution, ecotoxicity, air pollution, resource consumption, and persistent organic pollutants.

### *Water Pollution and Ecotoxicity*

Water pollution is one of the most significant environmental impacts of cleaning and cosmetic products that enter wastewater systems from sink or shower drains after using these products, reach rivers, lakes, and seas by exceeding the capacity of treatment plants or not being entirely removed from treatment processes. This creates serious ecotoxic effects in aquatic ecosystems.

*Surfactants (Surfactants)*

Anionic and nonionic surfactants commonly used in detergents and cleaners can be toxic to aquatic organisms. Some nonionic surfactants, especially nonylphenol ethoxylates, break down in water to nonylphenols, which are more toxic and persistent. Nonylphenols mimic or inhibit hormone systems in fish and other aquatic organisms, showing endocrine-disrupting effects (Soares et al., 2008). The bioaccumulation potential of these chemicals can have long-term effects on aquatic ecosystems.

*Phosphates and Nitrogen Compounds*

Phosphates and nitrogen-based compounds found in dishwashing and laundry detergents cause eutrophication in aquatic ecosystems. An overabundance of these nutrients leads to algal blooms. Algal blooms lead to depletion of oxygen levels in the water (hypoxia), fish mortality, and severe deterioration of water quality (Schindler et al., 2008). Eutrophication threatens biodiversity by disrupting ecosystem balance, especially in closed-water bodies.

*Antimicrobials and Preservatives*

Antimicrobials such as triclosan, triclocarban, and quaternary ammonium compounds have been detected in effluents and surface waters. These compounds can affect natural microbial communities in water, be toxic to algae and invertebrates, and contribute to the spread of antibiotic resistance (Singer et al., 2016). The spread of antibiotic resistance poses a serious threat to the environment and public health.

*Microplastics*

Primary microplastics are intentionally added to cosmetics (e.g., peels and toothpaste) and some cleaning products, as well as secondary microplastics from washing synthetic textiles, escaping from wastewater treatment plants, and reaching aquatic environments. Marine organisms can ingest microplastics, clogging their digestive tracts and transferring toxic chemicals (e.g., phthalates and BPA) to organisms (Cole et al., 2011; Rochman et al., 2013). Microplastic pollution has become a global problem and has the potential to threaten human health through the food chain.

***Persistent Organic Pollutants (POPs) and Bioaccumulation***

Chemicals in some cleaning and cosmetic products or produced during manufacturing processes are classified as Persistent Organic Pollutants (POPs). When released into the environment, these substances remain undegraded for a long time, can spread over large areas, and tend to accumulate in the fatty tissues of living organisms (bioaccumulation). Their concentrations increase as they move up the food chain (biomagnification). POPs such as dioxins, furans, some pesticides, and polychlorinated biphenyls (PCBs) are known for their endocrine-disrupting, carcinogenic, and immunotoxic effects (Jones & de Voogt, 1999). In addition, some synthetic fragrances, UV filters, and other components may also show persistence and bioaccumulation potential. This threatens not only aquatic ecosystems but also terrestrial ecosystems.

***Packaging Waste and Resource Consumption***

The cleaning and cosmetics industry relies heavily on single-use plastic packaging. Bottles, cans, tubes, and films are usually made from petroleum-derived plastics such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET). The production of these packages consumes significant amounts of fossil fuels and water. In contrast, a considerable amount of post-use waste, especially in regions with low recycling rates, ends up in landfills or the oceans, increasing plastic pollution (Geyer et al., 2017). Moreover, the raw materials used in the formulation of products (e.g., palm oil) are sourced from unsustainable sources, leading to additional environmental problems such as deforestation, biodiversity loss, and increased carbon emissions (Vijay et al., 2016).

### *Air Pollution and Volatile Organic Compounds (VOCs)*

Cleaning products in spray form, air fresheners, perfumes, and hair sprays can release chemicals known as Volatile Organic Compounds (VOCs) into the atmosphere. VOCs such as ethanol, isopropanol, acetone, and limonene can reduce indoor air quality and cause respiratory irritation and headaches. Outside, VOCs can react with sunlight and nitrogen oxides to form ground-level ozone (smog). Ozone is a major air pollutant that causes respiratory problems in humans and damages vegetation (Nazaroff & Weschler, 2004; McDonald et al., 2018). Reducing VOC emissions is critical to improving both indoor and outdoor air quality.

## Green Chemistry: Applications In the Cleaning and Cosmetics Industry

Green chemistry is a design philosophy that aims to minimize the negative impact of chemical products and processes on human health and the environment throughout their life cycle. The 12 core principles Paul Anastas and John Warner set out provide a roadmap for developing more sustainable and safer alternatives in the cleaning and cosmetics industry. These principles provide a comprehensive framework for reducing the environmental impact of chemical processes and developing safer products (Anastas & Eghbali, 2010; Ivanković et al., 2017).

### *Application of Green Chemistry Principles*

The principles of green chemistry can be applied at many stages, from formulation to production of cleaning and cosmetic products. These principles offer significant advantages in terms of environmental sustainability and human health. These principles are as follows (not item by item as in the original text, but combined into a more streamlined narrative):

Waste prevention is at the heart of green chemistry; chemical processes should be designed to minimize waste or by-products. In the cleaning and cosmetics sector, the development of concentrated products, reduced water use, and reduced packaging align with this principle. For example, solid shampoos and detergents minimize environmental impact by reducing water consumption and packaging waste (Ivanković et al., 2017). The principle of atomic economy requires the design of synthetic methods to ensure that a large proportion of the starting materials are incorporated into the final product, thus reducing waste. For example, enzymatic processes that produce biodegradable polymers achieve high atomic economy. The less hazardous chemical synthesis principle encourages the use of non-toxic substances or substances with low toxicity to human health and the environment. An example of this principle is using water or bio-based solvents instead of harsh organic solvents (Clark et al., 2018; Mammino, 2022). Designing safer chemicals aims to design chemical products to minimize toxicity while maintaining efficacy; selecting microbiome-friendly ingredients contributes to this principle. Using safer solvents and excipients is important, making excipients unnecessary or favoring harmless ones. Alternative solvents such as water-based formulations or supercritical carbon dioxide are examples of applying this principle (Jessop, 2011; Kreuder et al., 2017). Designing for energy efficiency aims to minimize energy requirements regarding their environmental and economic impact; biocatalysts reduce energy consumption by allowing chemical reactions at low temperature and pressure (Sheldon & Woodley, 2018). Use of renewable raw materials promotes the use of renewable raw materials instead of depleting resources; biodegradable surfactants and vegetable oil polymers are examples of this principle (Ivanković et al., 2017). Derivative reduction increases the efficiency of chemical processes by reducing unnecessary derivatization steps. The catalysis principle offers a superior approach over stoichiometric reagents; biocatalysts such as enzymes increase energy efficiency and reduce environmental impacts (Clark et al., 2018; Whittaker, 2019). Design for degradation requires that chemical products be designed to decompose into environmentally benign degradation products after they have completed their function (Anastas & Eghbali, 2010). Real-time analysis for pollution prevention aims to develop analytical methodologies to monitor and control the formation of hazardous substances in real time (Kreuder et al., 2017). Finally, inherently safer chemistry for accident prevention emphasizes the selection of substances used in chemical processes in a way that minimizes the potential for accidents (Jessop, 2011).

***Green Chemistry Application Examples***

*Bio-based and Biodegradable Surfactants:* Instead of petroleum-derived surfactants, more biodegradable and less toxic alternatives such as alkyl polyglucosides (APGs) or methyl ester sulfonates (MES) derived from vegetable oils or sugars are being developed (Ivanković et al., 2017).

*Natural Preservatives:* Instead of synthetic preservatives such as parabens, ingredients with antimicrobial and antioxidant properties of natural origin, such as grapefruit seed extract, rosemary extract, vitamin E (tocopherol), or lactic acid, are used (Ivanković et al., 2017).

*Green Solvents:* Instead of solvents containing volatile organic compounds (VOCs), more environmentally friendly solvents such as water, ethanol, glycerol, or supercritical CO2 are preferred (Jessop, 2011).

*Microbiome-Friendly Formulations:* Formulations that do not disrupt the natural microbial balance of the skin or gut or even support the microbiome by adding prebiotics or postbiotics, are being developed.

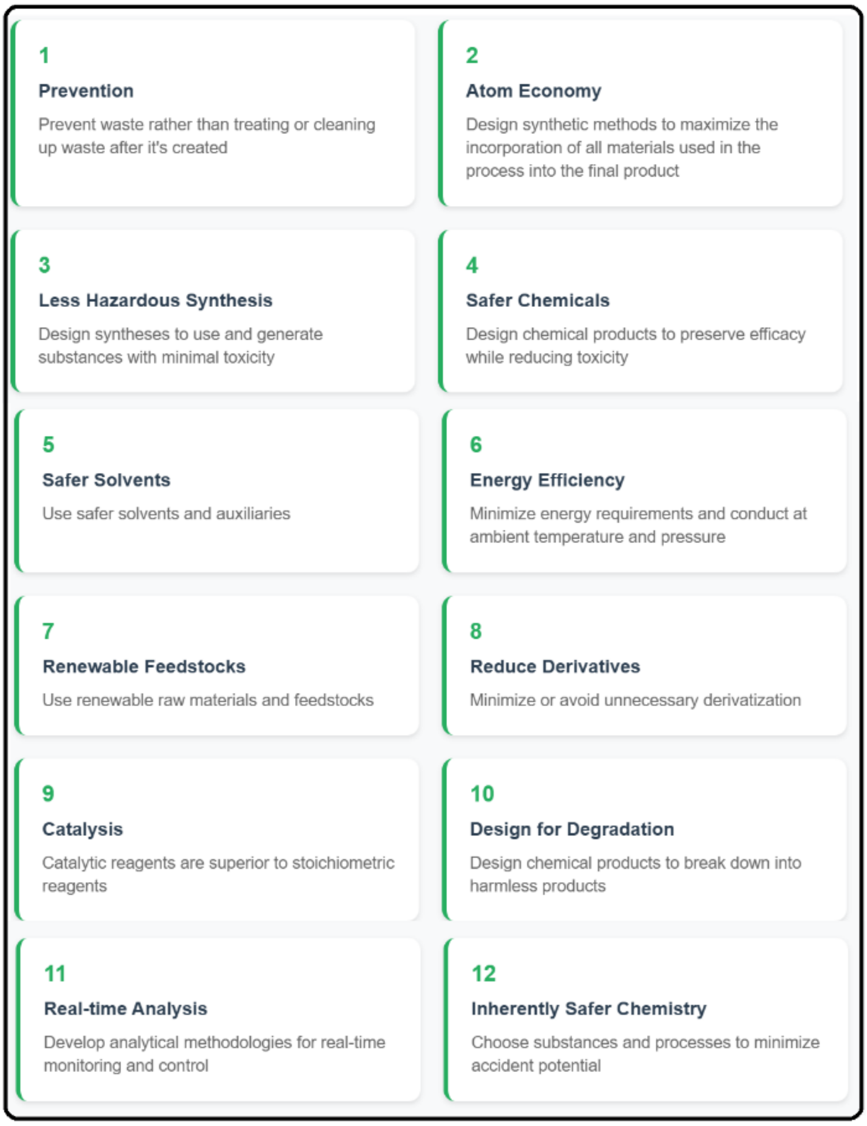


**Figure 2.** 12 Principles of Green Chemistry

*Water-Free or Low-Water Products:* Solid shampoos, solid detergents, or concentrated formulas help reduce water consumption, packaging, and transportation costs (Mammino, 2022).

Adopting green chemistry principles significantly contributes to reducing environmental and health risks. These principles not only support the achievement of sustainability goals but also offer the potential for companies to develop innovative products and processes, reduce production costs, and respond to growing consumer demand for environmentally friendly products.

**Circular Economy: Resource Efficiency and Waste Reduction**

The traditional linear "take-make-dispose" economic model has been unsustainable, leading to the rapid depletion of natural resources and the generation of large amounts of waste. This model accelerates environmental degradation and exacerbates economic and social problems. In contrast, the circular economy is an innovative approach that aims to preserve the value of resources for as long as possible, eliminate waste and pollution by design, and revitalize natural systems. The circular economy revitalizes environmental sustainability and creates new business models and innovation opportunities that support economic growth. The cleaning and cosmetics sector can significantly reduce its environmental footprint and contribute to sustainable development by applying circular economy principles.

***Circular Economy Strategies***

The circular economy is based on a set of approaches commonly known as "R" strategies. These strategies aim to use resources more efficiently and minimize waste generation. These strategies are summarized below in a more streamlined way:

The circular economy is based on "Refuse", avoiding unnecessary products or excessive packaging, and favoring durable alternatives to single-use products. For example, using refillable glass bottles instead of single-use plastic packaging in the cosmetics industry fits this strategy (Geissdoerfer et al., 2017). The "Reduce" strategy aims to reduce consumption and the quantity of products by using concentrated products or less frequently; it optimizes the use of raw materials and energy in production.


**Figure 3.** 12 Principles of Green Chemistry: A Simplified Overview

For example, waterless solid shampoos and detergents reduce water use during production and minimize the need for packaging (Stahel, 2016). "Reuse" involves designing packaging or containers to be refillable (refill systems) and extending the life of products. For example, systems where consumers can bring empty containers back to stores and refill them are an important application of the circular economy (Kirchherr et al., 2017). "Repair" refers to repairing broken products instead of throwing them away. "Refurbish/Remanufacture" refers to the reuse of old products or components by refurbishing them. "Repurpose" is using a product or material for a purpose other than its original purpose. For example, the use of by-products from cosmetics production in the production of bioplastics fits this strategy (Bocken et al., 2016). "Recycle" is the collection of used materials (especially packaging) and their transformation into new products, aiming for closed-loop recycling while maintaining the quality of the materials. For example, cosmetic packaging made from recycled plastic is an application of this strategy (Ghisellini et al., 2016). Finally, "Recover" refers to the recovery of energy or materials from non-recyclable waste.

***Circular Practices in the Cleaning and Cosmetics Sector***

Circular economy principles can be realized through various practices in the cleaning and cosmetics sector. These practices focus on sustainable packaging, resource efficiency, waste management, and new business models.

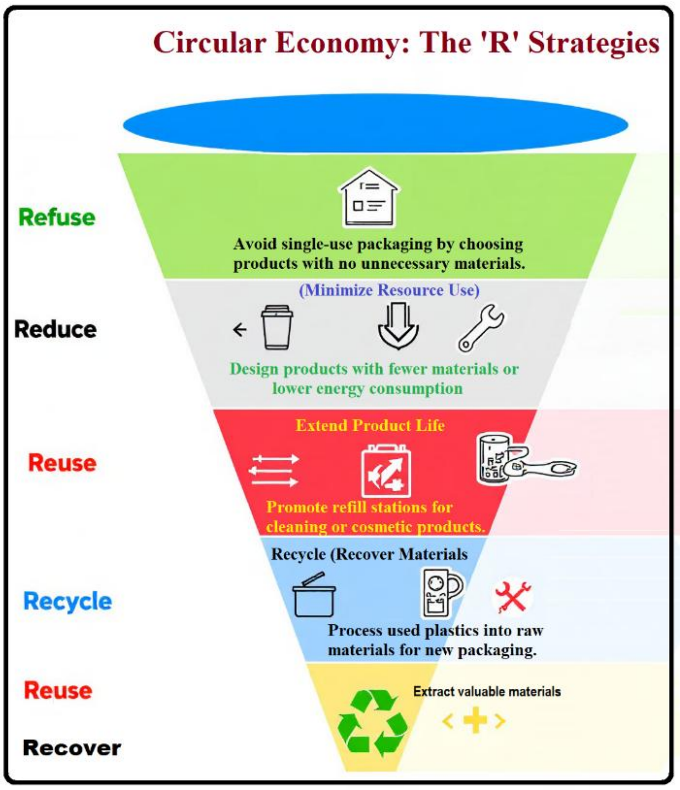


**Figure 4.** Circular Economy's Hierarchy or Cycle of 'R' Strategies

*Sustainable Packaging:*

*Reduction:* Eliminate unnecessary secondary packaging (e.g., boxes and plastic films). Reduce packaging size and weight using concentrated products or solid formulations (anhydrous) (Lacy & Rutqvist, 2015).

Reuse Offer refillable packaging systems. Design packaging from reusable materials such as glass or durable plastics (Kirchherr et al., 2017).

Recycling Design mono-material (one type of plastic) packaging that is easy to recycle. Increase the use of recycled content (PCR - Post-Consumer Recycled). Provide clear recycling instructions on packaging (Kirchherr et al., 2017).

*Resource Efficiency and Waste Management:*

*Water Reduction:* Optimize water use in production processes. Develop water-free or low-water product formulations (Stahel, 2016).

*Renewable Raw Materials:* With green chemistry, turn to sustainable, certified raw materials or alternative biomass sources (Anastas & Eghbali, 2010).

*Utilization of By-Products:* Investigate using by-products or waste from production processes as raw materials for other industries (industrial symbiosis) (Bocken et al., 2016).

*New Business Models:*

*Product as a Service:* Develop models where consumers purchase a cleaning or personal care service (e.g., refill subscriptions) instead of buying the product. This model offers economic benefits to the consumer while reducing resource use (Lacy & Rutqvist, 2015).

Circular economy approaches not only deliver environmental benefits, but also reduce resource dependency, create new business and innovation opportunities, and strengthen brand reputation. However, for this transition to succeed, collaboration across the supply chain requires changes in consumer behavior and supportive policy frameworks.

## DISCUSSION

This review addresses the complex and often overlooked impacts of conventional cleaning and cosmetic products on the human microbiome and the environment, using an integrated approach of green chemistry and circular economy principles as potential solutions to these problems. Our findings show that the synthetic chemicals (antimicrobials, surfactants, phthalates, preservatives) commonly found in these products not only contribute to microbial dysbiosis, leading to various health problems, but also cause severe environmental damage, such as water pollution, ecotoxicity, and persistent waste.

Impacts on the microbiome are of particular concern. It is now well understood that the skin and gut microbiota play critical roles in various conditions, from the immune system to metabolic health (Gilbert et al., 2018; Shreiner et al., 2015). As highlighted in this review, the potential for chemicals in cleaning and cosmetic products to disrupt these delicate ecosystems has been linked to an increase in chronic conditions such as atopic dermatitis, inflammatory bowel diseases, and even metabolic syndrome (Byrd et al., 2018; Chassaing et al., 2017). In particular, going beyond the 'hygiene hypothesis', how chemical exposure reduces microbial diversity and its long-term consequences on health should be explored in more depth. While growing interest in "microbiome-friendly" products is growing, the lack of standardized testing protocols and definitions to support these claims leads to consumer confusion and potential "microbiome laundering". This demonstrates the need for industry and regulatory bodies to develop transparency and science-based standards.

Regarding environmental impacts, the devastating effects of surfactants, phosphates, and especially microplastics on aquatic ecosystems are another critical area requiring urgent action (Soares et al., 2008; Cole et al., 2011). The entry of microplastics into the food chain and their potential human health impacts are a global concern (Prata et al., 2020). Packaging waste, especially single-use plastics, exacerbates this environmental burden (Geyer et al., 2017). These issues require fundamental changes in waste management strategies, product design, and material selection.

Green chemistry principles offer a promising way to overcome these challenges. The development of alternatives such as bio-based surfactants, natural preservatives, and green solvents can reduce the negative impacts of products on human health and the environment (Ivanković et al., 2017; Jessop, 2011). However, the competitiveness of these green alternatives with conventional chemicals in terms of performance, cost, and scalability is still a significant barrier. Moreover, carefully considering whether each product labeled as "green" is genuinely sustainable is critical to avoid the risk of "greenwashing".

Circular economy models complement green chemistry efforts to increase resource efficiency and minimize waste. Strategies such as refillable packaging, concentrated products, and recycled materials can help the cleaning and cosmetics sector move away from the linear 'take-make-dispose' model (Kirchherr et al., 2017; Lacy & Rutqvist, 2015). However, successful implementation of circular systems requires significant changes in consumer behavior, investments in infrastructure (e.g., efficient collection and recycling systems), and supportive policy frameworks. This transition is key to consumer adoption of reuse and refill models.

A limitation of this review is that it provides an overview rather than an in-depth analysis of each subtopic due to the breadth of topics covered. Furthermore, the number of long-term, independent studies on the efficacy and safety of "microbiome-friendly" or "green" products is still limited. Future research should examine the mechanisms of specific chemicals on the microbiome, conduct comprehensive life cycle analyses of green chemistry alternatives, and assess the economic and social viability of circular economy models in different contexts.

In conclusion, the health and environmental problems caused by cleaning and cosmetic products require a systemic approach. Simply changing individual ingredients or implementing partial solutions will not be enough. A holistic transformation based on green chemistry and circular economy principles, with strong collaboration between scientists, industry, policy makers, and consumers, is inevitable to protect human health and ensure the sustainability of our planet.

## CONCLUSION

This review has comprehensively demonstrated the dual impacts of cleaning and cosmetic products, an indispensable part of our daily lives, on the human microbiome and the ecological balance of our planet. Synthetic chemicals in conventional product formulations threaten human health by reducing microbial diversity and causing dysbiosis, while jeopardizing environmental sustainability by polluting water resources, reducing biodiversity, and contributing to the problem of persistent waste. Recent research has raised concerns about the long-term effects of microplastics and endocrine-disrupting chemicals in particular (e.g., reports from the United Nations Environment Programme (UNEP) and the World Health Organization (WHO) highlight the risks these chemicals pose to global health and the environment).

In the face of these complex and multidimensional problems, the principles of green chemistry and circular economy models offer transformative solutions that focus on the root causes of problems rather than simply offering symptomatic treatments. Green chemistry promotes the development of safer, bio-based, and biodegradable ingredients (Anastas & Eghbali, 2010), while circular economy aims at efficient use of resources, minimizing waste, and redesigning the life cycles of products (Ellen MacArthur Foundation reports highlight the economic and environmental benefits of circular economy). For example, the biosurfactant market and the increase in investments in sustainable packaging solutions over the last five years are indicators that a shift in this direction has begun (various market research reports can be cited).

However, there are significant barriers to this transition. Cost-effectiveness, performance standards, scalable production processes, and consumer acceptance of green alternatives may slow their diffusion. There is also an urgent need for internationally accepted testing protocols and certification systems to standardize and verify claims such as "microbiome-friendly" or "eco-friendly". The lack of these standards paves the way for misleading marketing practices such as "green laundering" and "microbiome laundering".

Going forward, it is critical to take the following steps:

1. Supporting Research and Innovation: More research is needed to understand the long-term impacts of specific chemicals on the microbiome and environment, develop safe and effective green alternatives, and optimize circular business models. In particular, studies examining the effects of cumulative chemical exposure (cocktail effect) on the human microbiome are needed, and biodegradability tests need to

be improved to reflect real-world conditions better better.

2. Strengthening Policy and Regulatory Frameworks: Policies that restrict the use of hazardous chemicals, promote green innovation, implement extended producer responsibility (EPR), and support circular infrastructures should be developed. Initiatives such as the European Union's Chemicals Strategy (CSS) and the Green Deal can be considered important steps in this direction, and similar approaches should be scaled up globally.
3. Industry Responsibility and Collaboration: Companies in the cleaning and cosmetics sector should adopt sustainability principles throughout the entire life cycle of their products, increase transparency, and collaborate along their supply chains.
4. Consumer Awareness and Education: Accurate and accessible information on product ingredients, environmental impacts, and sustainable alternatives should be available so consumers can make informed choices.

Ultimately, the future of cleaning and cosmetics depends on adopting innovative and sustainable approaches that respect human health and our planet's ecological integrity. Green chemistry and the circular economy provide a solid foundation for this inevitable transformation. Implementing these principles is not just a choice, but a necessity for a healthy future.

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