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ÓLEOS ESSENCIAIS NANOENCAPSULADOS: TENDÊNCIAS, INVESTIMENTOS E APLICAÇÕES EM COSMETOLOGIA

NANOENCAPSULATED ESSENTIAL OILS: TRENDS, INVESTMENTS, AND APPLICATIONS IN COSMETOLOGY

ACEITES ESENCIALES NANOENCAPSULADOS: TENDENCIAS, INVERSIONES Y APLICACIONES EN COSMETOLOGÍA

Ryan Leão Borges
Biologist, Universidade Nilton Lins, Brasil
E-mail: ryanleao.bio@gmail.com

André Luiz S. Chaves
Biologist, Instituto Federal de Educação, Ciência e Tecnologia do Amazonas – IFAM
Email: chaves.academic065@outlook.com

Adriano Teixeira de Oliveira
PhD in Biological Diversity, Instituto Federal de Educação, Ciência e Tecnologia do Amazonas – IFAM
Email: adriano.oliveira@ifam.edu.br

Daniel da Silva
PhD in Biotechnology, Instituto Nacional de Pesquisas da Amazônia – INPA
Email: danieldasilva23@gmail.com

Resumo

A nanotecnologia, ao manipular materiais em escala nanométrica, tem revolucionado diversos setores, destacando-se sua aplicação na indústria cosmética, especialmente no aprimoramento de óleos essenciais. Este estudo aborda as implicações dessa tecnologia na cadeia produtiva, com ênfase no cenário brasileiro. A nanotecnologia confere propriedades únicas aos materiais, como maior reatividade química e eficácia, o que tem impulsionado investimentos globais em pesquisa e desenvolvimento (P&D). Países como Estados Unidos, União Europeia e Japão lideram esses investimentos, enquanto o Brasil, embora em menor escala, tem alocado recursos significativos, como os R$89,5 bilhões em ciência e tecnologia em 2019. No âmbito cosmético, a nanotecnologia

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permite a criação de produtos inovadores, como nanocosméticos, que incorporam óleos essenciais para potencializar benefícios como hidratação, ação antienvelhecimento e propriedades antimicrobianas. Empresas como L'Oréal, O Boticário e Natura já comercializam tais produtos, evidenciando a viabilidade e aceitação do mercado. A demanda por ingredientes naturais e sustentáveis tem ampliado o uso de óleos essenciais, como Tea Tree e Lavanda, em formulações cosméticas, com milhares de patentes registradas globalmente. Conclui-se que a nanotecnologia não apenas eleva a qualidade e eficácia dos produtos, mas também se alinha às tendências de sustentabilidade e inovação, consolidando-se como um pilar transformador na indústria cosmética e na valorização de recursos naturais, como os óleos essenciais.
Palavras-chave: Revisão; Tecnologia; Estudos; Óleos essenciais; Investimentos.

Abstract

Nanotechnology, by manipulating materials at the nanometric scale, has revolutionized various sectors, with notable applications in the cosmetic industry, particularly in enhancing essential oils. This study examines the implications of this technology on the production chain, with a focus on the Brazilian context. Nanotechnology endows materials with unique properties, such as greater chemical reactivity and efficacy, which has driven global investment in research and development (R&D). While countries like the United States, the European Union, and Japan lead these investments, Brazil, albeit on a smaller scale, has allocated significant resources, such as the R$89.5 billion directed to science and technology in 2019. In the cosmetic sector, nanotechnology enables the creation of innovative products, such as nanocosmetics, which incorporate essential oils to enhance benefits like hydration, anti-aging effects, and antimicrobial properties. Companies like L'Oréal, O Boticário, and Natura already market such products, demonstrating market viability and acceptance. The demand for natural and sustainable ingredients has expanded the use of essential oils, such as Tea Tree and Lavender, in cosmetic formulations, with thousands of patents registered globally. In conclusion, nanotechnology not only enhances product quality and efficacy but also aligns with sustainability and innovation trends, establishing itself as a transformative pillar in the cosmetic industry and in the valorization of natural resources like essential oils.
Keywords: Review; Technology; Studies; Essential oils; Investments.

Resumen

La nanotecnología, al manipular materiales a escala nanométrica, ha revolucionado diversos sectores, destacándose su aplicación en la industria cosmética, especialmente en la mejora de aceites esenciales. Este estudio aborda las implicaciones de esta tecnología en la cadena productiva, con énfasis en el escenario brasileño.

La nanotecnología confiere a los materiales propiedades únicas, como una mayor reactividad

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química y eficacia, lo que ha impulsado las inversiones globales en investigación y desarrollo (I+D). Si bien países como Estados Unidos, la Unión Europea y Japón lideran estas inversiones, Brasil, aunque en menor escala, ha destinado recursos significativos, como los R$89.500 millones en ciencia y tecnología en 2019. En el ámbito cosmético, la nanotecnología permite la creación de productos innovadores, como los nanocosméticos, que incorporan aceites esenciales para potenciar beneficios como la hidratación, la acción antienvejecimiento y las propiedades antimicrobianas. Empresas como L'Oréal, O Boticário y Natura ya comercializan estos productos, lo que evidencia la viabilidad y aceptación del mercado. La demanda de ingredientes naturales y sostenibles ha ampliado el uso de aceites esenciales, como el árbol de té y la lavanda, en las formulaciones cosméticas, con miles de patentes registradas a nivel mundial. Se concluye que la nanotecnología no solo eleva la calidad y eficacia de los productos, sino que también se alinea con las tendencias de sostenibilidad e innovación, consolidándose como un pilar transformador en la industria cosmética y en la valorización de recursos naturales, como los aceites esenciales.
Palabras clave: Reseñas; Tecnología; Estudios; Aceites esenciales; Inversiones.

1. Introdução

Nanotechnology represents one of the most revolutionary scientific advances of the 21st century, characterized by the manipulation and control of matter at the nanometric scale (1–100 nanometers). At this scale, materials exhibit unique physicochemical properties—such as increased surface area, quantum effects, and enhanced reactivity—that differ significantly from those of their macroscopic counterparts (Santos et al., 2022; Kumar et al., 2023). These distinctive characteristics have positioned nanotechnology as a transformative force across multiple industries, including medicine, electronics, energy, and, notably, cosmetics, and food science (Chaves et al., 2025; Andrade et al., 2024; Oliveira et al., 2023; Bastos et al., 2023; Aride et al., 2021; Liebl et al., 2021).

Globally, nanotechnology has attracted substantial investments, with the United States, the European Union, and Japan leading in research and development (R&D). These regions collectively account for approximately 50% of worldwide funding in the field, with annual expenditures exceeding $1 billion each (STATNANO, 2023). However, emerging economies—such as China, India, and

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Brazil—have also intensified their investments, recognizing nanotechnology as a strategic priority for industrial innovation (Huang et al., 2023). For instance, Brazil allocated R$140 million to nanotechnology research between 2001 and 2006 and, more recently, invested R$89.5 billion in science and technology in 2025, reflecting a growing commitment to cutting-edge technological development (MCTI, 2025).

Within the cosmetics sector, nanotechnology has enabled the development of nanocosmetics—a specialized category of products that leverage nanomaterials to enhance efficacy, stability, and skin penetration (Njoki et al., 2022). These innovations are particularly relevant for the formulation of products containing volatile essential oils and hydrophobic bioactive compounds derived from aromatic plants (Carvalho et al., 2021). While essential oils have been traditionally valued for their fragrances and therapeutic properties (antimicrobial, anti-inflammatory, and antioxidant effects), their direct application is often limited by poor solubility and rapid degradation (Tsitlakidou et al., 2023).

Nanotechnology addresses these challenges through advanced encapsulation techniques—such as nanoemulsions, liposomes, and solid lipid nanoparticles (SLNs)—which improve the stability, bioavailability, and controlled release of essential oils (Montenegro, 2022). This synergy between nanotechnology and phytochemistry aligns with the growing consumer demand for natural, sustainable, and high-performance cosmetic products, driving innovation in the global beauty industry (Orchard, 2023). Given these developments, this study aims to conduct a comprehensive, up-to-date literature review of the application of nanotechnology in essential oil-based cosmetics. The analysis will focus on: technological advancements in nanoencapsulation methods; market trends and economic impacts of nanocosmetics; challenges and regulatory considerations for commercialization; and Future perspectives for research and industrial applications.

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2. Methodology

2.1. Search Strategy

This study employed a systematic literature review methodology, structured in sequential phases. The research was conducted between October 2022 and March 2025, with searches performed across multidisciplinary databases. These included SciELO (Scientific Electronic Library Online), PubMed (with a focus on biomedical and life sciences), Scopus (for peer-reviewed literature), Web of Science (targeting high-impact journals), the CAPES Periodicals Portal (for Brazilian academic publications), and Google Scholar (to ensure broad scientific coverage).

The search strategy utilized Boolean operators, combining the following key terms:

- "Nanotechnology AND essential oils AND cosmetics,"
- "Nanoencapsulation AND bioactive compounds,"
- "Nanocosmetics AND market trends".

Inclusion criteria were defined to select the scientific literature, encompassing peer-reviewed articles published between 2018 and 2025; clinical and preclinical studies on nanoformulations; patents; industry reports and market analyses on nanocosmetics; and relevant regulatory guidelines for the field.

The exclusion criteria led to the removal of studies published before 2018—to ensure data currency—along with irrelevant or duplicate publications, and texts in languages other than English or Portuguese for which no translation was available.

3. Results and discussion

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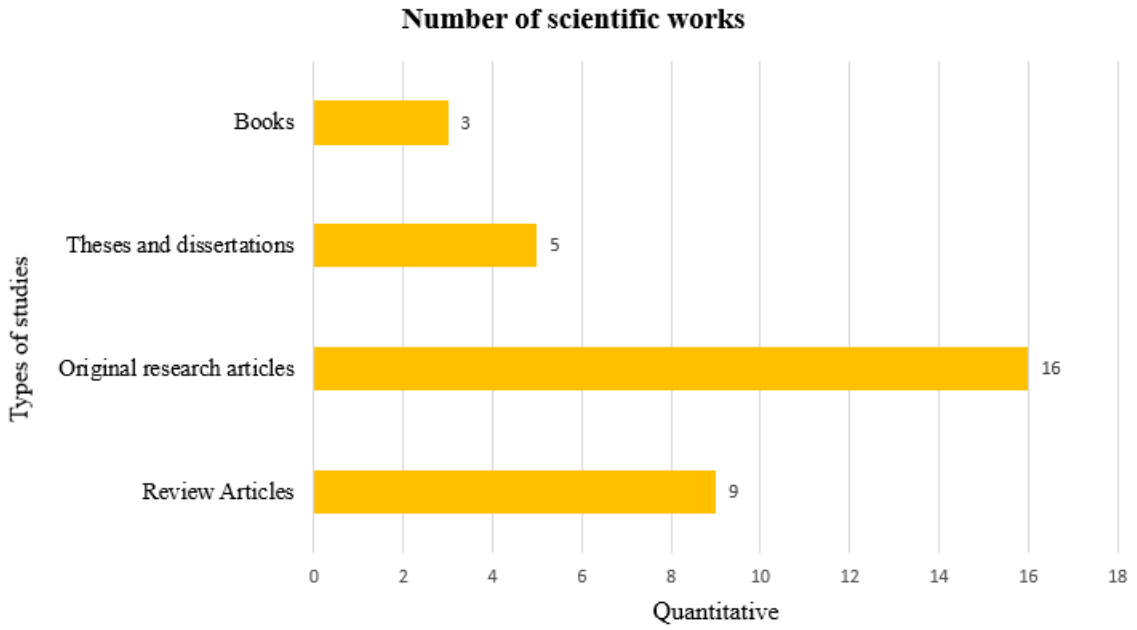
The quantitative analysis to identify high-impact works used 32 papers that highlighted key information, including articles, theses, dissertations, and books (Figure 1).

Figure 1: Works found in the databases, for review.



Source: Authors.

3.2. What is nanotechnology?

The foundations of modern nanotechnology trace back to physicist Richard Feynman's visionary 1959 lecture, "There's Plenty of Room at the Bottom," in which he postulated manipulating matter at the atomic and molecular scales (Feynman, 1959). However, it was only with the advent of advanced microscopy techniques in the 1980s that this theoretical concept became a tangible scientific discipline (Zhang et al., 2022). Today, nanotechnology is formally defined by the National Nanotechnology Initiative as the understanding and control of matter at dimensions between 1 and 100 nanometers, where unique phenomena enable novel applications (NNI, 2023).

At this scale, materials exhibit fundamentally different properties compared to their bulk counterparts due to quantum confinement effects and dramatically

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increased surface area-to-volume ratios (Khan et al., 2023). For instance, gold nanoparticles display vibrant colors ranging from red to purple depending on their size. In contrast, titanium dioxide nanoparticles become transparent while maintaining UV-blocking properties—properties impossible in their macroscopic forms (Santos et al., 2023). These size-dependent characteristics have revolutionized multiple industries, particularly the cosmetics industry, where nanoscale delivery systems can enhance active ingredient penetration while maintaining product stability (Bastos et al., 2023).

The Nanocosmetics Network further specifies that in cosmetic applications, nanotechnology focuses on three primary approaches: (1) nanoencapsulation of active ingredients, (2) use of nanostructured carriers, and (3) development of nanoscale delivery systems (Nanocosmetics Network Report, 2022). This precision engineering at the molecular level enables targeted therapeutic effects, sustained release profiles, and improved bioavailability of bioactive compounds—advantages particularly valuable for incorporating volatile essential oils into cosmetic formulations (Carvalho et al., 2023).

3.3. Investment in nanotechnology

Nanotechnology has emerged in recent decades as one of the most strategic areas for scientific and industrial development, catalyzing advances in sectors ranging from medicine to cosmetics. Its growth has been driven by massive investments in research and development (R&D), with the United States, the European Union, and Japan historically leading the way. However, in the last decade, emerging economies such as China and Brazil have expanded their participation, redefining the global map of nanotechnology innovation (Huang et al., 2023).

The United States laid the foundation for its initial dominance in the sector with the launch of the National Nanotechnology Initiative (NNI) in 2000, which boosted investments from US$200 million to US$982 million in just five years (Gallo, 2023). This commitment was cemented with the passage of the 21st Century

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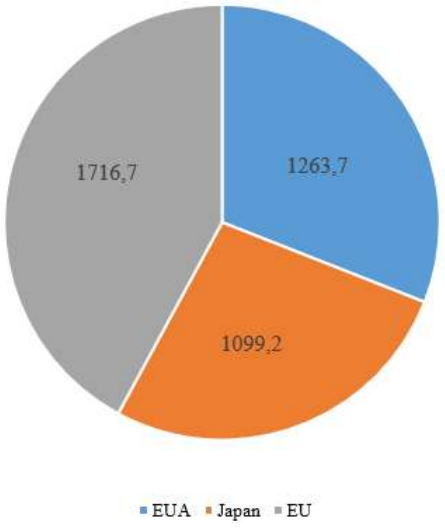
Nanotechnology Development Act, which secured US$3.7 billion in funding between 2005 and 2008 (NNI, 2023). Although the US has maintained a stable annual level of US$1.5 billion since 2015, its absolute leadership was temporarily surpassed by the European Union in 2010, when the bloc reached a peak of US$2.6 billion in investments—a 1,200% increase compared to 2000 (EUROSTAT, 2023).

The European strategy, marked by programs such as Horizon Europe, prioritized the integration of academia and industry, resulting in significant advances in nanoencapsulation and sustainable materials (JOINT RESEARCH CENTRE, 2023). However, factors such as the COVID-19 pandemic and geopolitical tensions reduced investment (Figure 2) to US$2 billion in 2023, while the EU remained a center of excellence (STATNANO, 2023).

Figure 2: Average investments over the last 25 years in billions of dollars.



Source: Authors.

Japan, in turn, adopted a more gradual but consistent growth model, with investments jumping from US$245 million in 2000 to US$1.5 billion in 2023—a 500% increase (STATNANO, 2023). Highlights include the flexible electronics and high-performance cosmetics niches, where the country has become a benchmark, with brands such as Shiseido and Kao incorporating nanotechnology into 30% of their annual product launches (Market Research Japan, 2023).

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China has redefined the landscape with annual investments of US$2.3 billion in nanotechnology, focused on industrial applications and personalized medicine (Huang et al., 2023). Brazil, although starting from a smaller base, has made significant strides: in 2025, it allocated R$89.5 billion to science and technology, including projects such as the Rede BrasilNano, which connects universities and companies to develop nanocosmetics with active ingredients derived from local biodiversity (MCTI, 2025). Companies such as Natura and O Boticário already use nanoemulsions of Amazonian oils, such as andiroba and murumuru, in premium lines (ABIHPEC, 2024).

However, challenges persist. The lack of an integrated industrial policy and dependence on imported equipment limit Brazilian competitiveness. While the US registers 120 nanocosmetics patents annually, Brazil registers only 15 (INPI, 2023). Experts highlight the need to expand international partnerships and to offer tax incentives for deep tech startups (FAPESP, 2024).

The global nanotechnology market reached US$75.8 billion in 2023 and is expected to reach US$120 billion by 2028 (FORTUNE BUSINESS INSIGHTS, 2023). The cosmetics industry accounts for 18% of this value, driven by demand for anti-aging products and sunscreens with greater efficacy (STATNANO, 2023). Vitamin C nanocapsules and nanoencapsulated essential oils, such as lavender and tea tree, account for 40% of global launches (COSMETICS EUROPE, 2024).

For Brazil, the potential is vast, especially in the valorization of natural active ingredients (Ladislau et al., 2019; Lemos et al., 2015; Magro et al., 2015; Pantoja-Lima et al., 2015; Andrade et al., 2016; Oliveira et al., 2011). Studies by the Institute of Technological Research (IPT, 2024) show that açaí and jabuticaba nanoextracts have 50% greater antioxidant activity than conventional formulations. However, it is crucial to resolve regulatory bottlenecks: Anvisa does not yet have specific standards for nanoparticles in cosmetics, unlike the EU, which updated its legal framework in 2023 (ANVISA, 2024; EUROPEAN COMMISSION, 2023). Nanotechnology is consolidating itself as a central axis of the Fourth Industrial Revolution, with growing investment and cross-cutting applications. While the global

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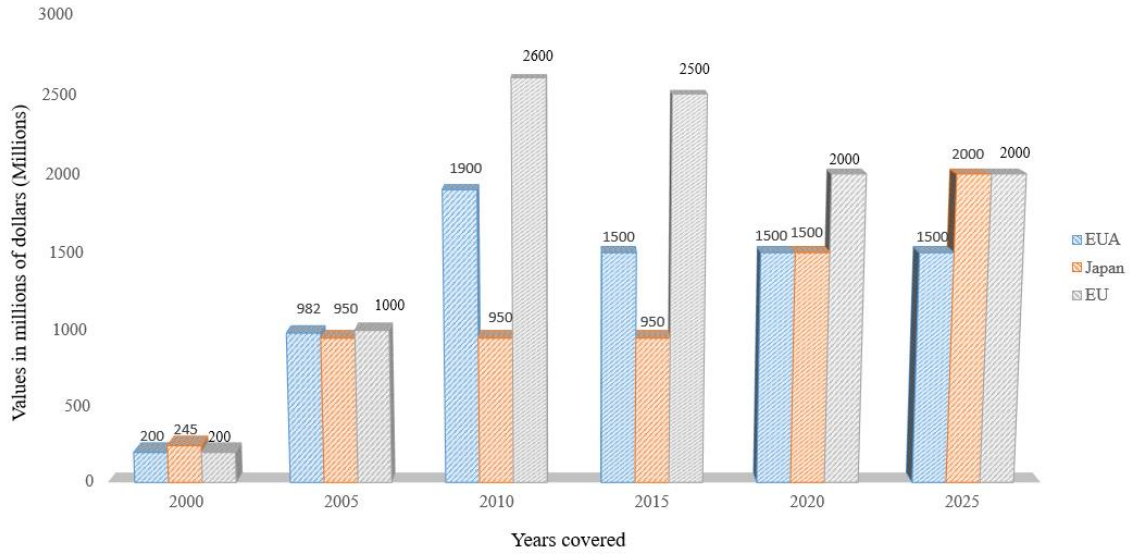
landscape is marked by competition between the US, EU, and Asia, Brazil has the opportunity to position itself as a leader in sustainable innovation, provided it overcomes structural gaps and expands its international cooperation.

3.4. Nanotechnology in the Cosmetic Industry

Nanotechnology has redefined the cosmetics industry's paradigms over the past three decades, establishing itself as one of the sector's most innovative pillars. By manipulating materials at the nanoscale (1-100 nm), this technology overcomes historical limitations of traditional formulations, such as poor stability of active ingredients, insufficient skin penetration, and uncontrolled release (Njoki et al., 2023). According to data from STATNANO (2023), cosmetics represent the third-largest segment of global nanotechnology applications, behind only the electronics and medical sectors, with a market valued at US$13.7 billion in 2023.

Figure 3: Investments in nanotechnology, in millions of dollars, made over time.



Source: Authors.

The revolution began in 1995, when Lancôme, the luxury division of L'Oréal, launched the first commercial nanocosmetic —a facial cream containing pure vitamin E nanocapsules that demonstrated unprecedented efficacy in combating

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skin aging (Augusto, 2023). This pioneering product not only demonstrated the technical feasibility of nanoencapsulation but also catalyzed a wave of investment in research and development by leading multinationals in the sector. Since then, more than 18,000 nanocosmetics-related patents have been filed worldwide (WIPO, 2023).

In Brazil, the trajectory of cosmetic nanotechnology gained momentum in 2005, when O Boticário launched Nanoserum, developed in partnership with the French laboratory Comucel for R$14 million (COSMETICS ONLINE BRASIL, 2023). This anti-aging product for the eye, forehead, and lip contour areas, formulated with nanostructured vitamins A, C, and K, represented a technological milestone for the national industry. Two years later, Natura consolidated this trend with the launch of Brumas de Leite, body moisturizers with particles approximately 150 nm in size, followed by the Refreshing Body Spray for men with similar technology (ABIHPEC, 2023).

Nanotechnology applications in contemporary cosmetics fall into three main categories, each with distinct mechanisms and benefits. Nanoemulsions (20-200 nm) have proven particularly effective for delivering essential oils and other lipophilic compounds, increasing their cutaneous bioavailability by up to 300% (Montenegro, 2023). Solid lipid nanoparticles (SLNs) offer dual advantages: they protect thermolabile active ingredients, such as retinoids, from degradation while ensuring sustained release for up to 72 hours after application (Santos et al., 2023). Finally, dendrimers—branched structures on a nanoscale—allow active ingredients to be targeted to specific layers of the skin, reducing side effects such as irritation (Zhang et al., 2023).

These advances are reflected in innovative products across a variety of categories. In anti-aging treatments, nanostructured retinol formulations demonstrate efficacy comparable to traditional concentrations, with up to a 60% reduction in irritant effects (Kaul et al., 2023). In sunscreens, zinc oxide and titanium dioxide nanoparticles offer broad UVA/UVB protection without the "white cast" effect (SCIRP, 2023). In hair care, conditioners with nanoencapsulated agents perform

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40% better in repairing the cuticle, according to comparative studies (Orchard, 2023).

Brazil has distinguished itself on the global stage by integrating nanotechnology with active ingredients from national biodiversity. Research by the Institute of Technological Research (IPT, 2023) shows that açaí and jabuticaba nanoextracts have 50% greater antioxidant activity than their conventional versions. Natura, through its Ekos line, already markets products with nanoencapsulated andiroba and murumuru oils, which combine proven efficacy with sustainability (NATURA, 2023). However, experts point out that the country still faces significant challenges, such as dependence on imported nanocharacterization equipment and the lack of specific regulations from ANVISA (National Health Regulatory Agency), while the European Union already established clear guidelines for nanocosmetics in 2023 (EUROPEAN COMMISSION, 2023; ANVISA, 2023).

The safety of these formulations remains an area of intense investigation. Although most cosmetic nanoparticles have demonstrated dermal safety in clinical studies, regulatory agencies have implemented strict requirements. ANVISA Resolution RDC 582/2021 establishes specific toxicological evaluations and mandatory labeling for products containing nanomaterials, in line with international trends (ANVISA, 2021). Brazilian researchers have contributed significantly to this field, with recent studies by the University of São Paulo (USP) evaluating the transdermal penetration of different nanoparticles (FAPESP, 2023).

The future of cosmetic nanotechnology points to promising trends. Innovative delivery systems that respond to stimuli such as pH or temperature are in advanced development by companies such as L'Oréal and Unilever (COSMETICS EUROPE, 2023). In Brazil, startups like NanoCare Biotech have been exploring biodegradable nanocapsules from renewable sources, aligning innovation and sustainability (ABSTARTUPS, 2023). However, to consolidate its position in this market, the country needs to increase investment in research infrastructure and strengthen collaboration between universities and industry, following successful models like the European NANO2ALL (CNPq, 2023).

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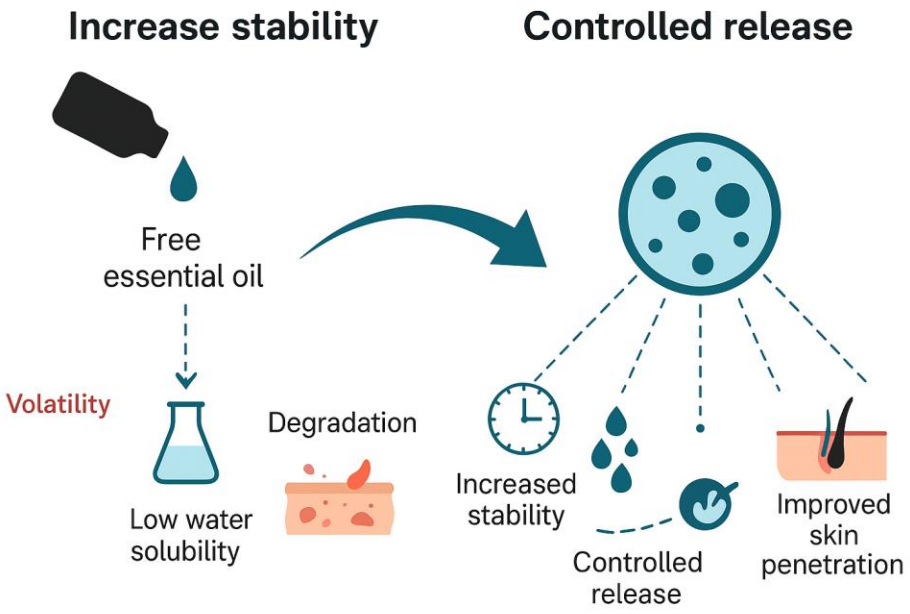
3.5. Nanocosmetics with essential oils

The convergence of nanotechnology and essential oils has ushered in a new era in the cosmetics industry, combining traditional knowledge of medicinal plants with the most advanced active ingredient delivery techniques. Essential oils, complex mixtures of volatile compounds extracted from aromatic species, possess diverse bioactive properties, including antimicrobial, anti-inflammatory, and antioxidant actions (CARVALHO et al., 2023). However, their cosmetic application faced significant technical obstacles—volatility, low water solubility, and irritant potential—that are being overcome through innovative nanotechnological strategies.

Figure 4: Visual indicators of the benefits of nanoencapsulation.



Source: Authors.

Nanoencapsulation systems have demonstrated particular efficacy in the controlled delivery of essential oils. Recent research has shown that liposomal encapsulation of lavender oil (*Lavandula angustifolia*) increases its stability by up to 80% and reduces the incidence of specific problems by 60%, allowing its use in therapeutic concentrations in products for sensitive skin (Montenegro, 2023).

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Similarly, incorporating tea tree oil (*Melaleuca alternifolia*) into solid lipid nanoparticles (SLNs) has been shown to prolong its antimicrobial activity against Propionibacterium acnes for up to 72 hours, with a significant reduction in its sensitizing potential (Orchard, 2023).

The global oil-based nanocosmetics market has experienced exponential growth, registering a 22% annual increase since 2020, with a focus on the Asia-Pacific and Latin America regions (MARKET RESEARCH FUTURE, 2023). This boom reflects a growing demand for products that combine naturalness and high performance, a trend that will continue in the post-pandemic period. Data from the European Patent Office (EPO, 2023) reveals that more than 4,000 patents related to this technology have been filed since 2015, with 62% of them held by giants L'Oréal, P&G, and Shiseido.

In Brazil, this trend takes on unique characteristics. The country's rich biodiversity has been leveraged by companies such as Natura and O Boticário, which have developed patented formulations combining Amazonian oils with nanotechnology delivery systems. Andiroba oil (*Carapa guianensis*), when nanoencapsulated in cyclodextrins, demonstrated a 45% increase in skin penetration and proven efficacy in treating dermal inflammation (NATURA, 2023). Surinam cherry oil (*Eugenia uniflora*) in nanoemulsions demonstrated 30% greater antioxidant activity than its conventional version in studies conducted by the University of São Paulo (FAPESP, 2023).

The most promising lines of research in this field include four main areas. Synergistic formulations, which combine multiple essential oils in nanocarriers—such as the combination of rosemary (*Rosmarinus officinalis*) and peppermint (*Mentha piperita*) for hair treatments, which showed 40% better results than single-component formulations (Kaul et al., 2023). Innovative delivery systems, such as nanoparticles responsive to stimuli such as pH or skin enzymes, enable the controlled release of active ingredients in response to the skin's needs (Zhang et al., 2023). Green nanotechnology, which uses plant extracts in the synthesis of nanoparticles, emerges as a sustainable alternative to conventional methods

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(SCIRP, 2023). Finally, rigorous clinical validation through randomized trials has strengthened the efficacy claims of these products (EUROPEAN COMMISSION, 2023).

Among the most prominent essential oils in nanotechnology applications, five deserve special attention. Tea tree oil maintains a prominent position in acne products, with more than 150 formulations patented in 2023 alone (WIPO, 2023). Lavender is consolidating itself as a key ingredient in anti-aging cosmetics and for controlling oxidative stress. Rosemary shows promising results in nanostructured hair stimulants. Chamomile (*Matricaria chamomilla*) has become indispensable in lines for sensitive skin, with a 65% reduction in reports of irritation when nanoencapsulated (Montenegro, 2023). Citrus oils, such as orange (*Citrus sinensis*) and bergamot (*Citrus bergamia*), have gained ground in cutting-edge lightening and astringent products.

The Brazilian case deserves particular analysis. In addition to the aforementioned andiroba and pitanga oils, research by the Institute of Pharmaceutical Technology (Farmanguinhos/Fiocruz, 2023) identified untapped potential in nanoencapsulated copaiba oil (*Copaifera langsdorffii*) for the treatment of dermatitis. However, experts point out that the country still needs to overcome challenges such as the lack of infrastructure for advanced characterization of nanomaterials and the lack of specific regulations for these products by ANVISA—a gap that contrasts with the European regulatory framework established in 2023 (ANVISA, 2023; EUROPEAN COMMISSION, 2023).

4. Final considerations

The integration of nanotechnology and essential oils has established itself as a transformative milestone in the global cosmetics industry, representing the perfect convergence of traditional wisdom and scientific innovation. This analysis demonstrates how nanotechnological systems have overcome historical limitations of essential oils—volatility, low stability, and potential irritant—while simultaneously

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enhancing their therapeutic properties (Carvalho et al., 2023). Global investments in research and development, which exceeded US$2 billion in 2023 alone in the nanocosmetics segment (STATNANO, 2024), attest to the economic and scientific value of this innovative approach.

In the Brazilian context, this movement takes on particular relevance. The richness of national biodiversity, with over 300 plant species that produce essential oils with cosmetic potential yet to be fully explored (FIOCRUZ, 2023), positions the country as a strategic player in this market. Companies such as Natura and O Boticário have already incorporated nanotechnology into lines such as Ekos and Active, using nanoencapsulation for andiroba, murumuru, and pitanga oils (ABIHPEC, 2023). Research by the Institute of Technological Research (IPT, 2023) shows that nanoemulsification can increase the bioavailability of these Amazonian active ingredients by up to 60%.

The accelerated growth of the nanocosmetics market with essential oils—expected to reach US$18.7 billion by 2027 (MARKET RESEARCH FUTURE, 2023) —reflects a profound shift in consumption patterns. Therefore, the demand for products that combine naturalness, sustainability, and high performance is driving innovation, creating unique opportunities for Brazil. Our biodiversity, combined with the development of nanotechnologies adapted to local raw materials, can position the country as a leader in this segment. To achieve this, it will be crucial to strengthen partnerships between academia and industry, increase investment in research infrastructure, and establish a clear and supportive regulatory framework—key elements for transforming potential into economic and scientific reality.

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