

Transdermal drug delivery: a bibliometric analysis of global trends and emerging device-assisted techniques

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(Accepted February 16, 2025)

Transdermal drug delivery has evolved from conventional topical formulations to advanced approaches designed to overcome the barrier function of the stratum corneum. This study provides a comprehensive bibliometric analysis of transdermal drug delivery research, with particular attention to emerging device-assisted techniques, including laser-assisted delivery and pneumatic needle-free injection systems. Bibliometric data were retrieved from the Web of Science using a systematic search strategy, yielding 15,865 publications between 1977 and 2025. The dataset was analyzed using VOSviewer to visualize recurring research themes, collaboration networks, and citation impact. The results demonstrate a marked growth in scientific output since the early 2000s, with original research articles representing the predominant publication type. The United States and China were the leading contributors to the field, while Ryan F. Donnelly (Queen's University Belfast) was identified as the most productive author. Among the most frequently studied transdermal drug delivery approaches were microneedles, iontophoresis, and lipid-based carriers, reflecting sustained interest in minimally invasive and formulation-driven strategies. Although laser-assisted techniques

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and needle-free injection were less represented in terms of publication volume, needle-free injection demonstrated a high citation impact. Laser-assisted drug delivery was less frequently represented in the dataset, likely reflecting its later emergence and methodological heterogeneity rather than a lack of scientific interest. Overall, transdermal drug delivery research is rapidly expanding across pharmacology, biomaterials science, and biomedical engineering, highlighting the interdisciplinary nature of innovation in this field.

KEY WORDS: transdermal drug delivery / skin / laser-assisted drug delivery / ablative laser / needle-free injection

Introduction

With advancements in pharmaceuticals enabling the treatment of many diseases, even those previously considered incurable, there is a growing need to make therapies more tolerable, safer, and faster to administer. Among various approaches, transdermal drug delivery represents a promising alternative, particularly as it may improve patient comfort and enable controlled drug release [Hoffman 2008, Pastore *et al.*, 2015].

Transdermal drug delivery offers an alternative to conventional administration routes such as oral, intravenous, transmucosal, and subcutaneous delivery. Although the field has developed rapidly over the past few decades, medication delivery through the skin has been recognized since ancient times. Historically, plant and animal extracts as well as minerals were applied topically in the form of powders, creams, pomades, and ointments to address dermatological and cosmetic indications [Pastore *et al.* 2015].

Transdermal delivery has gained notable attention in modern medicine, supported by several advantages. These include avoidance of first-pass metabolism and a reduction in gastrointestinal adverse effects, as well as the potential for improved bioavailability when a higher proportion of the active compound reaches systemic circulation. Furthermore, transdermal administration may provide sustained release, help maintain stable therapeutic drug levels, and reduce adverse effects associated with fluctuating concentrations [Hoffman 2008, Pastore *et al.* 2015].

A key obstacle to effective transdermal delivery is the stratum corneum, which functions as the primary barrier limiting penetration and protecting the body from microorganisms and water loss. The stratum corneum has been described as a two-compartment system consisting of corneocytes embedded in intercellular lipid bilayers, and the lipid composition plays a central role in regulating percutaneous transport [Elias *et al.* 1981]. Human skin consists of the epidermis, dermis, and subcutaneous tissue; the dermis contains blood vessels, nerve endings, and appendages, making it a key target when systemic exposure is desired [Kapoor *et al.* 2017].

To overcome the barrier imposed by the stratum corneum, a wide range of enhancement strategies has been developed. Prausnitz and Langer proposed a commonly used classification of transdermal drug delivery systems into three generations based on their ability to cross the skin barrier [Prausnitz and Langer 2008] – Table 1. First-

Table 1. Generations of transdermal drug delivery systems with the latest advancements in drug delivery appliances. [Joshi *et al.* 2023, Banzhaf *et al.* 2016, Wang *et al.* 2020]

| 1st generation | 2nd generation | 3rd generation | Emerging drug delivery appliances |
|--|---|---|---|
| Topical applied formulations Patch technology | Chemical enhancement Iontophoresis Noncavitational Ultrasound | Electroporation Microdermabrasion Thermal ablation Cavitational ultrasound Microneedles | Triboelectric nanogenerator (TENG) Micro/nanocarriers- -assisted transdermal delivery Advanced devices with microneedles Pneumatic injection systems |

generation approaches primarily rely on passive delivery of lipophilic small-molecule drugs that can traverse the skin with minimal enhancement, including traditional patches and topical hormone preparations [Prausnitz and Langer 2008]. Second-generation methods temporarily increase permeability without significant tissue disruption and include chemical penetration enhancers as well as physical strategies such as iontophoresis and noncavitational ultrasound [Machet and Boucaud 2002, Dhote, 2012, Joshi *et al.* 2023]. Third-generation systems use targeted permeabilization to enable delivery of larger molecules, including proteins, nucleic acids, and vaccines, through approaches such as electroporation, microneedles, ultrasound-based methods, microdermabrasion, and laser-assisted techniques [Prausnitz, 2004, Pliquett and Weaver 2007, Gill *et al.* 2009, Zaleski-Larsen and Fabi 2016, Park *et al.* 2019].

Transdermal drug delivery research encompasses formulation-based, physically assisted, and procedure-based device-assisted approaches, reflecting interdisciplinary contributions from pharmacology, biomaterials science, and biomedical engineering [Prausnitz *et al.* 2004]. Notably, some procedure-based device-assisted approaches are less represented in terms of publication volume but may offer clinically meaningful advantages in dermatology and aesthetic medicine, where parameters such as delivery depth, safety, and patient comfort are critical [Janjua 2014, Hogan *et al.* 2015, Zaleski-Larsen and Fabi 2016, Rho *et al.* 2024].

The aim of this study was to perform a bibliometric analysis of transdermal drug delivery research indexed in Web of Science (1977-2025), mapping global trends, influential contributors, and thematic clusters, while providing a focused clinical interpretation of selected device-assisted approaches relevant to dermatology and aesthetic medicine.

Material and methods

A bibliometric analysis was conducted to identify key research trends, influential authors, and high-impact publications in the field of transdermal drug delivery. Bibliographic data were retrieved from the Web of Science (WoS) on January 16, 2025. The search strategy included the following terms: “transdermal drug delivery” OR “device-assisted drug delivery” OR “laser-assisted techniques” OR “pneumatic drug delivery”. No restrictions regarding document type, language, or publication

year were applied in order to capture the broadest possible research landscape. The initial query returned 15,865 records spanning the period from 1977 to 2025, and all retrieved records were included in the final analysis.

Web of Science was selected as the primary data source due to its standardized citation indexing, broad multidisciplinary coverage, and compatibility with bibliometric mapping and citation-based analyses. However, we acknowledge that using a single database may result in incomplete coverage of the literature compared with multi-database approaches (e.g., Scopus or PubMed).

The bibliographic data were exported from WoS in Plain Text format and analyzed using VOSviewer software (version 1.6.30; Van Eck and Waltman). Term mapping was performed based on terms extracted from titles and abstracts. To ensure map readability and to focus on recurring concepts, only terms appearing in at least 1% of the publications ($n = 159$) were included in the visualization. In addition, an author keyword map was generated using a minimum occurrence threshold of 0.1% of publications ($n = 16$), which allowed identification of the most consistently used keywords while avoiding over-fragmentation of the network. Apart from these threshold settings, VOSviewer parameters were kept at default values. In the visualized maps, node size represents the number of publications in which a term or keyword appears, while inter-node distance reflects the frequency of co-occurrence. The node color corresponds to the average citations per paper (CPP), where higher values indicate greater citation impact. The generated maps were exported and interpreted to summarize collaboration patterns and thematic clusters within transdermal drug delivery research.

Results

The bibliometric dataset included 15,865 publications on transdermal drug delivery indexed in Web of Science, spanning the period from 1977 to 2025. Overall, the analysis demonstrates a clear long-term increase in research output, with the most dynamic growth observed after 2000, indicating accelerated scientific interest in transdermal drug delivery technologies in the last two decades.

Geographical distribution and temporal trends

Year-by-year analysis of the five most research-active countries (the United States, China, India, South Korea, and England) demonstrates distinct growth patterns. The United States shows a sustained and relatively stable increase over time, maintaining its leading position across decades. In contrast, China exhibits the most rapid expansion in publication output, particularly after 2000, with a marked rise in research activity in recent years. China first surpassed the United States in annual publication output in 2019 and has maintained a sustained lead in subsequent years. India also demonstrates consistent growth, especially in the last two decades. South Korea and England contribute substantially to the literature, with visible increases in publication volume after 2000, although at a lower rate compared with China and India (Fig. 1).

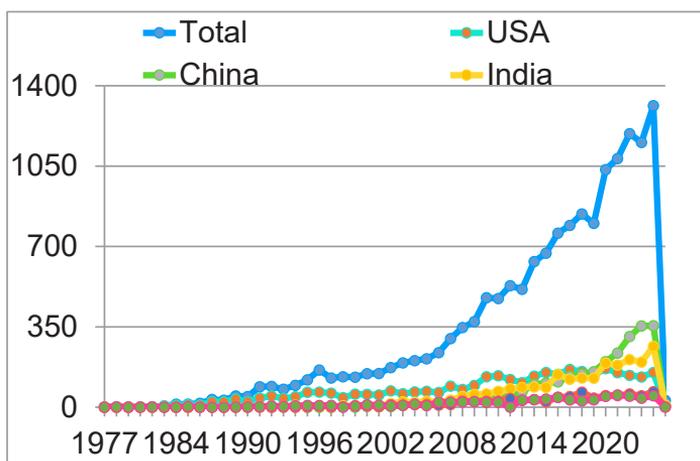


Fig.1. Total publication numbers for the entire dataset alongside the five most research-active countries.

Citation impact patterns further indicate that the highest citations per paper (CPP) values are observed for the United States, followed by England and South Korea. This suggests that countries with lower publication volume may still demonstrate strong research visibility and impact. Institutions contributing to high-impact output include Harvard University and the University of California System, which show high CPP values.

Journals and publication categories

Among the most prominent journals publishing transdermal drug delivery research, the *International Journal of Pharmaceutics*, *Journal of Controlled Release*, and *Journal of Drug*. The concentration of publications in these journals highlights the close links of transdermal drug delivery research with multiple scientific domains, underscoring its multidisciplinary character. In terms of citation impact, the *Journal of Controlled Release* demonstrated particularly high CPP values, indicating strong influence within the transdermal drug delivery domain.

Leading authors and institutions

The most prolific individual authors identified in the dataset include Ryan Donnelly, Richard H. Guy, Ajay K. Banga, Mark Prausnitz, and Samir Mitragotri. Notably, Samir Mitragotri and Mark Prausnitz demonstrate high citation-per-paper values, reflecting strong scientific influence in the field.

Institutional analysis revealed several affiliations with high publication output. However, it should be noted that bibliometric datasets may include affiliation entries that do not correspond to actual research institutions. Therefore, entries such as the Egyptian Knowledge Bank (EKB) - which represents a national research access

platform rather than a research institution - should be interpreted cautiously when assessing true institutional productivity.

The leading contributors by author, institution, country, journal, and research category are summarized in Table 2.

Table 2. Leading five contributors by author, institution, country, journal, and research category in transdermal drug delivery

| Item | Number of papers % of 15865 | Citation per paper (CPP) |
|---|--------------------------------|-----------------------------|
| Author | | |
| Donnelly, Ryan | 177 1.1 | 48.5 |
| Guy, Richard H. | 118 0.7 | 43 |
| Banga, Ajay K. | 114 0.7 | 29.3 |
| Prausnitz, Mark | 108 0.6 | 91.9 |
| Mitragotri, Samir | 83 0.5 | 113.4 |
| Affiliation | | |
| Egyptian knowledge Bank (EKB) ¹ | 712 4.5 | 30.9 |
| University of California System | 348 2.1 | 70.4 |
| Harvard Univeristy | 219 1.4 | 90.5 |
| Chinese Aademy of sciences | 213 1.3 | 43 |
| Cairo University | 211 1.3 | 31 |
| Journal | | |
| International Journal of Pharmaceutics | 1040 6.6 | 45.9 |
| Journal of Controlled Release | 570 3.6 | 72.6 |
| Journal of Drug Delivery Science and Technology | 490 3.1 | 15.8 |
| Journal of Pharmaceutical Sciences | 380 2.5 | 41.9 |
| Pharmaceutics | 353 2.4 | 28 |
| Country | | |
| USA | 3444 2.1 | 47.6 |
| China | 2566 1.6 | 27.1 |
| India | 2348 1.5 | 30.7 |
| South Korea | 790 0.5 | 33 |
| England | 752 0.5 | 42.6 |
| Reseach area | | |
| Pharmacology Pharmacy | 8603 54.2 | 36.3 |
| Chemistry | 3534 22.3 | 43.1 |
| Materials Science | 2075 13.1 | 33.2 |
| Science Technology Other Topics | 1603 10.1 | 37.8 |
| Engineering | 1474 9.3 | 30.5 |

¹The Egyptian Knowledge Bank (EKB) appeared among the most frequent affiliation strings; however, as it represents a national research access platform rather than a research institution, it was not considered in the institutional productivity ranking.

Research themes and technique prevalence

The analysis confirms that transdermal drug delivery research is highly interdisciplinary. Pharmacology and Pharmacy represented the largest share of publications, followed by Chemistry and Materials Science, emphasizing the integration of pharmaceutical research with materials engineering and biomedical technology development.

Table 3. Most frequently mentioned transdermal drug delivery techniques in titles and abstracts of research paper

| Technique | Number of Papers | Citations per Paper (CPP) |
|--------------------------------|------------------|---------------------------|
| Transdermal delivery | 1578 | 34.69 |
| Microneedles | 417 | 47.51 |
| Iontophoresis | 320 | 48.21 |
| Electroporation | 245 | 37.95 |
| Sonophoresis | 195 | 40.00 |
| Nanoparticles | 384 | 46.32 |
| Liposomes | 422 | 24.36 |
| Hydrogels | 129 | 35.15 |
| Patch | 248 | 29.85 |
| Permeation enhancers | 250 | 28.36 |
| Ablative laser | 52 | 20.98 |
| Fractional laser | 49 | 22.76 |
| Hollow microneedles | 114 | 49.19 |
| Dissolving microneedles | 85 | 21.29 |
| Solid microneedles | 77 | 42.87 |
| Chemical penetration enhancers | 91 | 33.54 |
| Thermal ablation | 66 | 39.71 |
| Needle-free injection | 112 | 55.86 |
| Ethosomes | 299 | 39.50 |
| Nanoemulsions | 243 | 45.19 |

When technique-related terminology was analyzed, microneedles (417 papers; CPP 47.51) emerged as one of the most frequently studied approaches, reflecting strong and sustained interest in minimally invasive delivery strategies. Other electrically assisted techniques such as iontophoresis (320 papers; CPP 48.21) and electroporation (245 papers; CPP 37.95) were also prominently represented. Sonophoresis (195 papers; CPP 40.00) appeared as another relevant theme, supporting continued interest in ultrasound-assisted permeabilization strategies. The most frequently mentioned techniques identified in titles and abstracts are summarized in Table 3. A term map generated from titles and abstracts illustrates the co-occurrence structure of key concepts (Fig. 2), while a complementary keyword-based map further highlights thematic clustering and citation impact (Fig. 3).

Lipid-based formulation approaches were widely represented, including liposomes (422 papers; CPP 24.36) and nanoemulsions (243 papers; CPP 45.19), consistent with the ongoing development of carriers designed to enhance stability and permeation. Hydrogels (129 papers; CPP 35.15) and patches (248 papers; CPP 29.85) also accounted for a substantial share of research activity, highlighting sustained interest in controlled release formulations.

Although laser-assisted drug delivery (LADD) approaches were less frequent in the dataset (ablative laser: 52 papers; CPP 20.98; fractional laser: 49 papers; CPP 22.76), they represent a clinically relevant device-assisted subgroup within transdermal delivery research. Because LADD studies are heterogeneous in terms of laser platforms and exposure patterns, an overview of commonly reported laser modalities is provided

to support clinical interpretation (Tab. 4). Needle-free injection (112 papers; CPP 55.86) demonstrated the highest citation impact among the analyzed techniques, indicating meaningful scientific attention despite a smaller publication volume.

Table 4. Laser used with LADD [Zaleski-Larsen 2016, Kim *et al.* 2020]

| Laser | Wavelength | Drug Permeation Mode |
|---|------------|----------------------|
| CO2 | 10600 | ASR, aFP |
| Er:Yag | 2940 | ASR,aFP |
| P.L.E.A.S.E diode pumped Er:YAG | 2940 | aFP |
| 1,927-nm diode | 1927 | nFP |
| Thulium | 1927 | nFP |
| Erbium-doped | 1550 | nFP |
| Neodymiumdoped yttrium aluminum garnet (Nd:YAG Q-switched Quasi-long) | 1064 | NDR |
| Q-switched Ruby | 694 | NDR |
| Argon-fluoride excimer (ArF) | 193 | NDR |
| Picosecond alexandrite | 1755 | NDR |
| Long-pulsed dye laser | 595 | NDR |
| Erbium glass (Er:Glass) | 1550 | nFP |

ASR - ablative skin resurfacing NDR - non-ablative skin remodeling AFP - ablative fractional photothermolysis nFP - non-ablative fractional photothermolysis.

VOSviewer term mapping

Term mapping based on titles and abstracts revealed several recurring thematic clusters in transdermal drug delivery research, reflecting strong associations between drug delivery technologies, formulation strategies, and clinical applications (Fig. 2). The most prominent nodes were related to microneedles, iontophoresis, nanoparticles, liposomes, and permeation enhancement, consistent with the quantitative technique prevalence analysis.

A complementary keyword-based visualization further highlighted frequently recurring concepts and their co-occurrence relationships (Fig. 3). Together, these maps support the conclusion that transdermal drug delivery research is characterized by strong interdisciplinary overlap and sustained focus on minimally invasive and enhancement-based strategies.

Discussion

This bibliometric analysis of transdermal drug delivery research (1977-2025) provides a structured overview of long-term publication trends, dominant research themes, and influential contributors across nearly five decades. The sustained increase in scientific output, particularly since the early 2000s, reflects growing interest in alternative drug delivery routes that aim to improve tolerability, patient adherence, and therapeutic precision [Hoffman 2008, Pastore *et al.* 2015]. The diversity of research topics identified confirms that transdermal drug delivery has evolved into a

distinctly interdisciplinary field, integrating pharmacology, biomaterials science, and biomedical engineering rather than remaining a formulation-driven niche [Prausnitz *et al.* 2004].

A key finding of the present analysis is the predominance of formulation-based and physically assisted transdermal delivery strategies, including microneedles, iontophoresis, and lipid-based carrier systems. Microneedles, in particular, have been extensively investigated as minimally invasive platforms that enhance skin permeability while maintaining favorable patient acceptability and broad applicability across drug classes [Prausnitz 2004, Waghule *et al.* 2019]. Electrically assisted methods such as iontophoresis and electroporation remain widely studied due to their capacity to facilitate the delivery of charged or hydrophilic molecules and their relatively high degree of methodological standardization [Banga *et al.* 1999, Dhote 2012]. Lipid-based carriers, including liposomes and nanoemulsions, continue to attract substantial attention as versatile formulation strategies capable of improving drug stability, penetration, and local skin targeting [Huang *et al.* 2024].

Geographical analysis revealed that the United States and China are the leading contributors to the transdermal drug delivery literature. The United States demonstrates a sustained and stable publication output over several decades, whereas China shows a rapid increase in publication volume beginning in the mid-2000s, with particularly pronounced growth in recent years. This shift indicates a redistribution of research activity and increasing research capacity beyond traditionally dominant regions. These findings reflect the increasingly globalized nature of transdermal drug delivery research and the expansion of research activity across multiple regions.

Although LADD and pneumatic needle-free injection systems are less represented in terms of publication volume, their position within the bibliometric landscape warrants careful interpretation. The relatively smaller number of publications associated with LADD likely reflects, at least in part, the later emergence of these techniques compared with formulation-based and physically assisted approaches. While methods such as iontophoresis and lipid-based delivery have been studied for several decades, laser-assisted approaches entered broader experimental and clinical investigation more recently, particularly following the widespread adoption of fractional laser technologies after 2010 [Zaleski-Larsen and Fabi 2016] - Table 5.

In addition to relative novelty, the procedural nature of LADD introduces higher technical, cost-related, and regulatory barriers that may slow the accumulation of large, methodologically comparable datasets. LADD requires specialized equipment and operator expertise, and published studies often differ substantially in terms of laser type, wavelength, fluence, density, and treatment protocols. This heterogeneity complicates standardization and limits direct comparison across studies, which may contribute to a slower expansion of the bibliometric footprint compared with more easily scalable approaches such as microneedles or formulation-based systems [Ibrahim *et al.* 2017, Wenande *et al.* 2017].

Table 5. Applications of LADD based on Zaleski-Larsen *et al.* review based on Medline and Muskat *et al.* review referring to LADD use in the treatment of scars, rhytids, and melasma based on PubMed. [Zaleski-Larsen 2016, Kim *et al.* 2020]

| Drug | Effect |
|---|--|
| 5-aminolaevulinic acid (5-ALA) | Local photosensitizing action in the treatment of actinic keratosis, Bowen disease, superficial basal cell carcinoma; Hyperthropic scars/keloid clinical improvement |
| 5-aminolevulinate (MAL) | Local photosensitizing action in the treatment of actinic keratosis, Bowen disease, superficial basal cell carcinoma |
| Methotrexate | Topical application in the treatment of psoriasis |
| Imiquimod | Treatment of superficial skin cancers, actinic keratoses, genital warts, and molluscum |
| 5-Fluorouracil | Enhanced topical permeation in treatment of AK and Bowen disease in murine model; Hyperthropic scars/keloid clinical improvement |
| Timolol | Treatment of deep infantile hemangiomas |
| Triamcinolone acetonide, bimatoprost, tretinoin, pimecrolimus | Improvement of the hypopigmented scars appearance |
| Poly-L-lactic acid | Improvement of the atrophic scars appearance |
| Analgesics | Topical lidocaine and opioids application |
| Minoxidil and diphencyprone | Promotion of the hair regrowth |
| Vitamin C | Application of vitamin C as a collagen synthesis cofactor and an antioxidant in murine model |
| Small interfering RNA | the administration of RNA interference intended for the treatment of genetic-based diseases in murine model |
| Vaccine | Skin vaccine application in animal model |
| Allergen-specific immunotherapy | Attemption to desensitize to the allergen with a consideration of usage of Th1 promoting immnunomodulator on the murine model |
| Bone marrow transplantation | Attemption to deliver stem cells through the skin in murine model to preserve them from damage while administered intravenously |
| Corticosteroids | Hyperthropic scars/keloid clinical improvement |
| 5-FU/verapamil | Hyperthropic scars/keloid clinical improvement |
| Vitamin C ± growth factors | Hyperthropic scars/keloid clinical improvement |
| Exosomes | Atrophic scars clinical improvement |
| PRP | Atrophic scars clinical improvement |
| Stem cells | Atrophic scars clinical improvement |
| Prostaglandin analogs | Hipopigmented scars clinical improvement |

Needle-free pneumatic injection systems demonstrate a distinct bibliometric pattern characterized by a lower publication volume but relatively high citation impact. This observation suggests that needle-free injection may represent a focused, high-interest niche rather than a marginal technology. These systems have been explored for decades as alternatives to conventional needles and have gained renewed attention due to their potential to improve patient comfort and facilitate intradermal delivery of biologically active compounds [Mitragotri 2013, Hogan *et al.* 2015]. Recent dermatological applications, including the intradermal delivery of biostimulatory agents for atrophic acne scars, further support the clinical relevance of this approach despite its smaller representation in the literature [Rho *et al.* 2024].

An important implication of the present findings is that publication volume alone does not necessarily reflect clinical relevance or translational potential. Formulation-

based and physically assisted approaches dominate the literature due to their broad feasibility, lower procedural barriers, and long-standing presence in research. In contrast, procedure-based device-assisted techniques may address specific clinical needs - such as controlled depth targeting or localized delivery- that are not adequately met by formulation strategies alone. Consequently, underrepresentation in bibliometric terms should not be interpreted as limited clinical value.

This study has several limitations. First, the analysis was restricted to the Web of Science, and relevant publications indexed exclusively in other databases may not have been captured. Second, bibliometric outcomes are dependent on search strategy and terminology, and studies employing alternative descriptors may be underrepresented. Third, citation-based indicators are influenced by publication age and journal prominence, which may favor older or more established technologies. Finally, VOSviewer-based mapping provides descriptive insights into research structure but does not replace in-depth quantitative or clinical effectiveness analyses.

Despite these limitations, the present bibliometric study offers a coherent overview of the historical development and current structure of transdermal drug delivery research. By distinguishing between formulation-based, physically assisted, and procedure-based device-assisted approaches, it highlights both dominant research directions and emerging areas of clinical interest. These findings may inform future research priorities, particularly in the context of device-assisted transdermal delivery strategies that require further standardization, comparative evaluation, and translation into well-defined clinical protocols.

Conclusions

This bibliometric analysis of 15,865 publications (1977-2025) demonstrates sustained and rapidly increasing global interest in transdermal drug delivery, particularly since the early 2000s. The United States and China emerged as the leading contributors to research output, while several highly productive and influential authors and institutions have shaped the development of the field. The most frequently studied approaches included microneedles, iontophoresis, and lipid-based carriers, confirming that minimally invasive and formulation-driven strategies remain central to transdermal delivery research. At the same time, device-assisted techniques such as LADD and pneumatic needle-free injection - although less represented by publication volume - may reflect clinically meaningful emerging directions due to their potential for depth-controlled delivery, improved patient comfort, and applicability in dermatology and aesthetic medicine. Future research should prioritize standardized reporting of device parameters and clinical endpoints, direct comparative studies across delivery modalities, and translation-focused trials that assess efficacy, safety, and patient-centered outcomes. This study is limited by the use of a single bibliographic database (Web of Science), potential keyword and indexing bias, and the descriptive nature of citation-based indicators. Nevertheless, the findings provide a structured overview of

historical development, global research dynamics, and underexplored opportunities in transdermal drug delivery innovations, and may support future research prioritization and informed development of device-assisted transdermal delivery strategies.

Conflict of interest: The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors used ChatGPT to assist with linguistic refinement. All content was subsequently reviewed and edited by the authors, who assume full responsibility for the final version of the work.

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