ISSN: 2455-8109

International Journal of Farmacia (IJF)

IJF |Vol.12 | Issue 3 | July–Sep-2026

www.ijfjournal.com

DOI : https://doi.org/10.61096/ijf.v12.iss3.2026 251-257

Carbon Quantum Dot – Based Drug Delivery Systems for Topical Antifungal Therapy: Recent Advances and Future Perspectives

Shalini Muruganantham[1], Pushpa Thangamani[2], Sathiyapriyan Murugesan[2], Sivasarma Sivasankar[2]

Sir Issac Newton College of Pharmacy, Nagapattinam, Tamil Nadu-611102, India.

Email: sathiyapriyan5002@gmail.com

Published on:

11.07.2026
Published by: Futuristic Publications

Abstract: Fungal infections affecting the skin represent a major global health concern, particularly in tropical and humid regions where environmental conditions favour fungal growth. Common pathogens such as *Candida albicans*, *Trichophyton rubrum*, and *Aspergillus fumigatus* are responsible for superficial and cutaneous infections, many of which are recurrent and difficult to treat. Conventional antifungal therapies, although widely available, suffer from limitations including poor skin penetration, low retention time, systemic side effects, and increasing resistance due to biofilm formation.

Recent advances in nanotechnology have introduced carbon quantum dots (CQDs) as promising nanocarriers for topical drug delivery. CQDs are ultra-small carbon-based nanoparticles (<10 nm) characterized by high surface functionality, excellent biocompatibility, photoluminescence, and intrinsic antimicrobial properties. Their ability to generate reactive oxygen species (ROS) and disrupt fungal cell membranes further enhances their therapeutic potential.

This review provides a comprehensive overview of CQD-based drug delivery systems for topical antifungal therapy, focusing on their synthesis, physicochemical properties, mechanisms of antifungal action, drug loading strategies, and incorporation into nanocarrier systems such as hydrogels and liposomes. Additionally, challenges related to toxicity, scalability, and regulatory approval are discussed. Overall, CQDs represent a promising platform for next-generation antifungal therapies, although further clinical studies are required for translation into practice.

Keywords: Carbon quantum dots, antifungal therapy, nanocarriers, topical drug delivery, biofilm inhibition, nanomedicine

1. INTRODUCTION

Fungal infections of the skin, commonly referred to as cutaneous mycoses, affect millions of individuals worldwide and represent a significant public health burden. These infections are particularly prevalent in regions characterized by high humidity, poor hygiene, and limited access to healthcare. Dermatophytes and yeasts such as *Candida albicans* and *Trichophyton rubrum* are among the most common causative organisms.

Although topical antifungal agents such as azoles, allylamines, and polyenes are widely used, their effectiveness is often compromised. One major limitation is the inability of drugs to penetrate the stratum corneum, the outermost barrier of the skin. This leads to reduced bioavailability at the site of infection and therapeutic failure.

Additionally, fungal resistance mechanisms, including efflux pumps, genetic mutations, and biofilm formation, significantly reduce treatment efficacy. Biofilms, in particular, provide a protective environment that limits drug penetration and enhances resistance.

To overcome these challenges, nanotechnology-based drug delivery systems have emerged as promising alternatives. Among these, carbon quantum dots (CQDs) have gained significant attention due to their unique physicochemical and biological properties.

2. OVERVIEW OF CARBON QUANTOM DOTS

2.1 Definition and Background

Carbon quantum dots are zero-dimensional carbon-based nanomaterials with sizes typically less than 10 nm. Unlike traditional quantum dots, CQDs do not contain heavy metals, making them safer for biomedical applications.

Since their discovery in 2004, CQDs have gained interest due to their optical properties, biocompatibility, and ease of synthesis.

2.2 Synthesis of CQDs

CQDs can be synthesized using two main approaches:

Top-Down Approach

This method involves breaking down larger carbon structures into nanoscale particles using techniques such as:

- Laser ablation
- Arc discharge
- Electrochemical oxidation

Although effective, these methods require high energy and complex equipment.

Bottom-Up Approach

This method involves carbonization of small molecules such as citric acid or glucose using:

- Hydrothermal synthesis
- Microwave-assisted synthesis
- Pyrolysis

This approach allows better control over particle size and surface functionalization.

2.3 Physicochemical Properties

CQDs exhibit several important properties:

- **Small size:** Enables penetration through biological barriers
- **Photoluminescence:** Useful for imaging and diagnostics
- **Surface functionality:** Allows drug attachment
- **Biocompatibility:** Reduced toxicity compared to metal nanoparticles
- **Chemical stability:** Resistant to photo bleaching

3. PATHOLOGY OF FUNGAL INFECTIONS

3.1 Types of Infections

Fungal infections are categorized into:

- Superficial mycoses
- Cutaneous mycoses
- Subcutaneous mycoses

Cutaneous infections such as tinea and candidiasis are the most common and difficult to treat.

3.2 Skin Barrier Challenges

The stratum corneum acts as a major barrier to drug penetration. It restricts:

- Hydrophilic drug entry
- Diffusion of large molecules
- Drug retention at infection site

3.3 Biofilm Formation

Biofilms are structured microbial communities that:

- Reduce drug penetration
- Increase resistance
- Cause chronic infections

This highlights the need for advanced delivery systems.

4. ADVANTAGES OD CQD_S IN ANTIFUNGAL THERAPY

4.1 Enhanced Skin Penetration

Due to their nanoscale size, CQDs can penetrate deep into the skin layers and reach infection sites effectively.

4.2 Controlled Drug Release

CQDs allow sustained release of drugs, reducing dosing frequency and improving patient compliance.

4.3 Surface Functionalization

Functional groups enable:

- Targeted drug delivery
- Improved binding to fungal cells

4.4 Intrinsic Antifungal Activity

CQDs generate ROS, causing:

- Membrane damage
- Cellular disruption

4.5 Theranostic Applications

Their fluorescence enables:

- Real-time drug tracking
- Monitoring treatment response

5. ANTIFUNGAL MECHANISMS OF CQD_S

5.1 ROS Generation

Reactive oxygen species damage:

- Lipids
- Proteins
- DNA

This leads to fungal cell death.

5.2 Membrane Disruption

CQDs interact with fungal membranes, causing:

- Increased permeability
- Leakage of cellular contents
- Cell lysis

5.3 Intracellular Damage

CQDs interfere with:

- DNA replication
- Protein synthesis
- Mitochondrial function

5.4 Biofilm Disruption

CQDs penetrate biofilms and degrade their structure, enhancing drug effectiveness.

6. DRUG LOADING STARTEGIES

6.1 Physical Adsorption

- Simple and cost-effective
- Weak interactions may cause rapid release

6.2 Covalent Conjugation

- Strong bonding
- Controlled drug release
- Complex synthesis

6.3 Encapsulation

- High drug loading
- Sustained release
- Used in hydrogels and liposomes

6.4 Stimuli-Responsive Systems

Drug release triggered by:

- pH changes
- Light
- Temperature

7. SAFETY AND TOXICITY CONSETARATIONS

Although CQDs are generally biocompatible, concerns include:

- ROS-induced cytotoxicity
- Skin irritation
- Long-term accumulation
- Immune responses

Dose optimization and safety testing are essential.

8. CHALLENGES AND LIMITATIONS

8.1 Scale-Up Issues

- Difficulty in large-scale production
- Lack of standardization

8.2 Reproducibility

- Variation in synthesis affects performance

8.3 Stability

- Aggregation and degradation over time

8.4 Regulatory Barriers

- Lack of clear guidelines for nanomedicine

9. FUTURE PERSPECTIVES

9.1 Theranostic Systems

Combination of therapy and diagnostics for precision treatment.

9.2 Personalized Medicine

Customized formulations based on patient conditions.

9.3 AI-Based Optimization

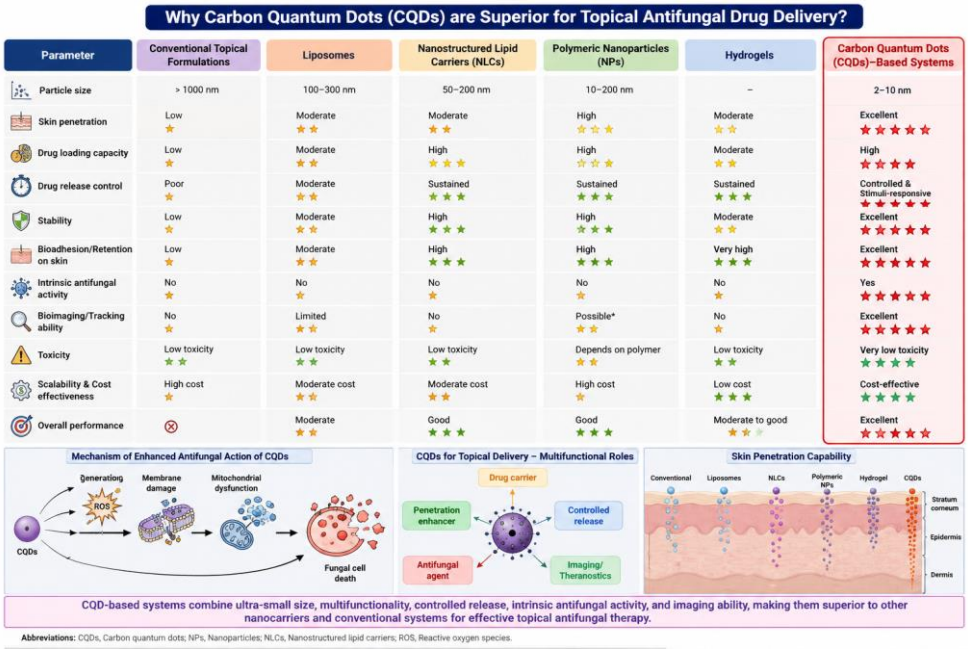
Use of AI to design efficient formulations.

9.4 Smart Drug Delivery Systems

Multi-stimuli responsive systems for targeted therapy.

9.5 Green Synthesis

Use of eco-friendly methods to improve safety and sustainability.



10. CONCLUSION

Carbon quantum dots represent a revolutionary advancement in topical antifungal therapy. Their unique properties, including enhanced skin penetration, controlled drug release, and intrinsic antifungal activity, make them highly effective compared to conventional treatments.

Despite promising results, challenges related to safety, scalability, and regulatory approval must be addressed before clinical translation. Continued research and interdisciplinary collaboration will be crucial in unlocking the full potential of CQD-based drug delivery systems.

11. REFERENCES

A. General Fungal Infections & Clinical Background

1. Brown, G. D., Denning, D. W., & Levitz, S. M. (2012). Tackling human fungal infections. *Science, 336*(6082), 647. https://doi.org/10.1126/science.1222236
2. Bongomin, F., Gago, S., Oladele, R. O., & Denning, D. W. (2017). Global burden of fungal diseases. *Journal of Fungi, 3*(4), 57. https://doi.org/10.3390/jof3040057
3. Havlickova, B., Czaika, V. A., & Friedrich, M. (2008). Epidemiological trends in skin mycoses worldwide. *Mycoses, 51*(Suppl. 4), 2–15. https://doi.org/10.1111/j.1439-0507.2008.01606.x
4. Gupta, A. K., & Cooper, E. A. (2008). Update in antifungal therapy of dermatophytosis. *Mycopathologia, 166*(5–6), 353–367. https://doi.org/10.1007/s11046-008-9109-0
5. Perlin, D. S. (2015). Echinocandin resistance in *Candida*. *Journal of Infectious Diseases, 212*(Suppl. 6), S612–S617. https://doi.org/10.1093/infdis/jiv353

6. Rodrigues, M. L., Nosanchuk, J. D., & Casadevall, A. (2020). Fungal diseases as neglected pathogens: A wake-up call to public health officials. *PLoS Neglected Tropical Diseases, 14*(6), e0008249. https://doi.org/10.1371/journal.pntd.0008249

B. Carbon Quantum Dots – Fundamentals

1. Baker, S. N., & Baker, G. A. (2010). Luminescent carbon nanodots: Emergent nanolights. *Angewandte Chemie International Edition, 49*(38), 6726–6744. https://doi.org/10.1002/anie.200906623
2. Lim, S. Y., Shen, W., & Gao, Z. (2015). Carbon quantum dots and their applications. *Chemical Society Reviews, 44*(1), 362–381. https://doi.org/10.1039/C4CS00269E
3. Li, H., Kang, Z., Liu, Y., & Lee, S. T. (2012). Carbon nanodots: Synthesis, properties and applications. *Journal of Materials Chemistry, 22*(46), 24230–24253. https://doi.org/10.1039/C2JM34690G
4. Hola, K., Zhang, Y., Wang, Y., Giannelis, E. P., Zboril, R., & Rogach, A. L. (2014). Carbon dots—Emerging light emitters for bioimaging, cancer therapy and optoelectronics. *Nano Today, 9*(5), 590–603. https://doi.org/10.1016/j.nantod.2014.09.004
5. Wang, Y., & Hu, A. (2014). Carbon quantum dots: Synthesis, properties and applications. *Journal of Materials Chemistry C, 2*(34), 6921–6939. https://doi.org/10.1039/C4TC00988F
6. Sun, Y. P., Zhou, B., Lin, Y., et al. (2006). Quantum-sized carbon dots for bright and colorful photoluminescence. *Journal of the American Chemical Society, 128*(24), 7756–7757. https://doi.org/10.1021/ja062677d

C. CQD Synthesis & Properties

1. Dong, Y., Pang, H., Yang, H. B., et al. (2013). Carbon-based dots co-doped with nitrogen and sulfur for high quantum yield and excitation-independent emission. *Angewandte Chemie, 125*(30), 7954–7958.
2. Zhu, S., Song, Y., Zhao, X., Shao, J., Zhang, J., & Yang, B. (2015). The photoluminescence mechanism in carbon dots. *Nano Research, 8*(2), 355–381. https://doi.org/10.1007/s12274-014-0644-3
3. Cayuela, A., Soriano, M. L., Carrillo-Carrión, C., & Valcárcel, M. (2016). Semiconductor and carbon-based fluorescent nanodots: The need for consistency. *Chemical Communications, 52*(7), 1311–1326. https://doi.org/10.1039/C5CC08201A

D. Skin Barrier & Pathophysiology

1. Elias, P. M. (2005). Stratum corneum defensive functions: An integrated view. *Journal of Investigative Dermatology, 125*(2), 183–200. https://doi.org/10.1111/j.0022-202X.2005.23668.x
2. Barry, B. W. (2001). Novel mechanisms and devices to enable successful transdermal drug delivery. *International Journal of Pharmaceutics, 230*(1–2), 1–9. https://doi.org/10.1016/S0378-5173(01)00874-1
3. Bouwstra, J. A., & Ponec, M. (2006). The skin barrier in healthy and diseased state. *Advanced Drug Delivery Reviews, 58*(7), 797–800.

E. Nanotechnology in Antifungal Therapy

1. Gupta, M., & Vyas, S. P. (2012). Nanocarrier-based drug delivery system for antifungal therapy. *Critical Reviews in Therapeutic Drug Carrier Systems, 29*(6), 547–596.
2. Rai, M., Ingle, A. P., Pandit, R., et al. (2018). Nanotechnology-based antifungal therapy. *Biotechnology Advances, 36*(3), 834–847.
3. Pelgrift, R. Y., & Friedman, A. J. (2013). Nanotechnology as a therapeutic tool to combat microbial resistance. *Advanced Drug Delivery Reviews, 65*(13–14), 1803–1815.

F. CQDs in Antimicrobial Applications

1. Meziani, M. J., Dong, X., Zhu, L., et al. (2016). Visible-light-activated bactericidal functions of carbon dots. *ACS Applied Materials & Interfaces, 8*(17), 10761–10766.

2. Li, Y., Liu, Y., Fu, Y., et al. (2019). Carbon dots: A new type of antibacterial agent. *ACS Nano, 13*(4), 4270–4278.
3. Yao, B., Huang, H., Liu, Y., & Kang, Z. (2019). Carbon dots for antibacterial applications. *ACS Applied Bio Materials, 2*(6), 2261–2273.