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# MYCOGENIC NANOPARTICLE SYNTHESIS: EXPLORING ESSENTIAL COMPONENTS, OPTIMIZATION STRATEGIES, AND ADVANCED MULTI-SECTORAL INDUSTRIAL APPLICATIONS

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***Abstract***

Recent advances in nanobiotechnology have promoted the development of fungal-mediated nanoparticle synthesis as a sustainable alternative to conventional physical and chemical methods. This narrative review provides a comprehensive overview of fungi as biofactories for the synthesis of mycogenic nanoparticles, with emphasis on synthesis components, production conditions, and multi-sectoral application. A literature search was conducted using scientific databases to identify original open-access articles published between 2021 and 2026. After applying predefined inclusion and exclusion criteria, 30 studies were selected for qualitative analysis. Fungi provide an efficient platform for nanoparticle production because they secrete extracellular enzymes, proteins, polysaccharides, and secondary metabolites that function as natural reducing, capping, and stabilizing agents. The physicochemical properties of mycogenic nanoparticles are influenced by reaction parameters such as pH, temperature, precursor concentration, and cultivation conditions. The incorporation of natural biopolymers, including chitosan and carboxymethylcellulose, further improves nanoparticle stability and biological activity. Mycogenic nanoparticles have demonstrated broad potential in agriculture, food systems, environmental, and biomedicine through their antimicrobial, antifungal, antioxidant, anticancer, biofungicidal, wastewater treatment, and active food packaging application. However, several challenges remain, including limited knowledge of fungal synthesis mechanisms, large-scale production, and nanoparticle stability and biosafety. Future research should improve the understanding of fungal metabolism, optimize fermentation process, standardize synthesis methods, and evaluate safety through in vivo studies.

***Keywords:*** *Fungi; Fungal-mediated synthesis; Mycogenic nanoparticle; Nanobiotechnology; Fungal biotechnology*

## 1. INTRODUCTION

The merging of nanotechnology with the biological sciences has given rise to nanobiotechnology, an interdisciplinary field that employs biological systems, such as fungi, bacteria, and plant extracts, as biofactories for the sustainable design, synthesis,

and functionalization of nanomaterials (El-shanshoury et al., 2025). Within this field, biogenic synthesis has emerged as a sustainable approach that utilizes biological organisms or their biomolecules as natural reducing, capping, and stabilizing agents to produce nanoparticles (Chavan et al., 2026). Compared with conventional physical and chemical methods, biogenic synthesis provides a more sustainable alternative by reducing energy consumption, minimizing the use of hazardous chemicals, and limiting the generation of toxic by-product while producing nanoparticles with enhanced biocompatibility (El-Morsy et al., 2026; Selim et al., 2026).

Among the various biological systems explored for biogenic nanoparticle synthesis, fungi have emerged as one of the most promising platforms due to their unique physiological and biochemical characteristics, giving rise to fungal-mediated nanoparticles, commonly referred to as mycogenic nanoparticles. Fungi are recognized as superior biological factories because of their rapid growth, abundant biomass production, and exceptional ability to secrete extracellular enzymes and metabolites that mediate metal ion reduction and nanoparticle stabilization (Chavan et al., 2026; Selim et al., 2026). Their extensive mycelial networks provide a large surface area for efficient biosorption and accumulation of metal ions which enabling both intracellular and extracellular nanoparticle synthesis (El-shanshoury et al., 2025). Fungal systems offer several advantages over bacteria and plants, including higher nanoparticle yields, better control over particle size and morphology, and simpler downstream processing under standardized cultivation conditions (Mohammed et al., 2024).

As fungi have gained recognition as efficient nano-factories for the green production of nanoparticles, research has increasingly explored a variety of fungal-mediated synthesis strategies to enhance production efficiency and nanoparticle quality (Oliveira et al., 2025). The synthesis process is fundamentally driven by fungal biomolecules, including extracellular enzymes, proteins, polysaccharides, and other metabolites, which act as reducing and stabilizing agents during nanoparticle formation (Aboul et al., 2025). Nevertheless, substantial methodological diversity has been

reported in the literature, encompassing the choice of fungal species, biological materials such as fungal biomass or cell-free filtrates, metal precursor, and synthesis condition. Variations in parameters such as precursor concentration, pH, temperature, and incubation time significantly affect the physicochemical properties of the synthesized nanoparticles, including their size, morphology, crystallinity, stability, and biological performance. Therefore, this review aims to provide an overview of fungal-mediated nanoparticle synthesis approaches, their effects on nanoparticle characteristics, and their implications for the development and functional applications of mycogenic nanoparticles. Reviewing the currently available fungal-mediated synthesis approaches is crucial for understanding their influence on nanoparticle characteristics and for identifying robust strategies that support the development of multifunctional mycogenic nanoparticles.

## 2. RESEARCH METHOD

This narrative review provides a comprehensive overview of fungi as biological platforms for the synthesis of mycogenic nanoparticles and highlights their emerging multifunctional applications. A narrative review was considered appropriate because this topic spans several interconnected fields, including fungal biotechnology, green nanotechnology, materials science, and applied nanoscience. Relevant literature was systematically identified through comprehensive searches of major scientific databases, including ScienceDirect, SpringerNature Link, and Wiley Online Library. The review considered publications published between 2021 and 2026 that addressed fungal-mediated nanoparticle synthesis, mycogenic nanoparticles, green nanotechnology, fungal biotechnology, and their applications. Search queries combined terms such as “nanobiotechnology”, “fungi”, “biogenic”, “mycogenic”, and “food”. Boolean operators (AND, OR) were applied to refine the search, improve retrieval accuracy, and ensure comprehensive coverage of the literature (MacFarlane et al., 2022).

The retrieved publications were screened based on predefined inclusion and exclusion criteria. The inclusion criteria comprised original research and open access

article that focused on fungal-mediated synthesis of mycogenic nanoparticles and their potential applications. Studies involving filamentous fungi and yeast were considered eligible for inclusion. Studies were excluded if they primarily investigated plant-mediated nanoparticle synthesis, bacterial synthesis, microalgae-based synthesis, or the use of macro fungi. Review articles, conference abstracts, and book chapters were excluded regardless of their relevance to the topic. Publications that did not focus on inclusion criteria were also excluded. The final selection was based on title, abstract, and full-text screening to ensure that only eligible original research articles met the predefined inclusion criteria.

A total of 101 records were initially identified through the literature search. As no duplicate records were found, all articles proceeded to title and abstract screening. During this stage, 71 records were excluded because they focused on plant-mediated synthesis, bacterial synthesis, macro fungi, microalgae, review articles, or were not relevant to the objectives of this review. The remaining 30 articles were subsequently assessed through full-text evaluation and met the predefined inclusion criteria. Ultimately, 30 original research articles were included in the final qualitative synthesis. A summary of the literature search and study selection process is provided in Fig. 1.

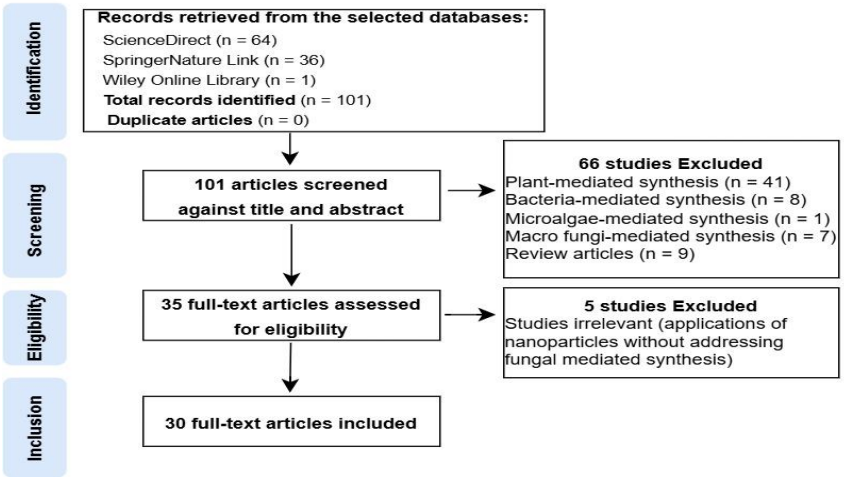



Fig. 1. Summary of the literature identification, screening, eligibility assessment, and study inclusion process employed in this narrative review.

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## 3. RESULT AND DISCUSSION

### *3.1 Fungi as Biofactories*

The field of fungal-mediated nanotechnology uses a wide range of fungi, from common filamentous fungi such as *Aspergillus niger*, *Penicillium* spp., and *Fusarium oxysporum* to endophytic fungi isolated from different plant species, as summarized in Table 1. Endophytic fungi, including *Trichoderma virens*, *Clonostachys rosea*, *Sarocladium kiliense,* and *Amesia atrobrunnea* have attracted increasing attention because their diverse secondary metabolites can improve nanoparticle stability and biological activity. During nanoparticle synthesis, these fungi produce extracellular enzymes, proteins, and polysaccharides that naturally reduce metal ions and stabilize the resulting nanoparticles (Al-zahrani & Al-garni, 2023; Mohammed et al., 2024).

Table 1. Representative fungal species used in fungal-mediated nanoparticle synthesis, including synthesis components, synthesis conditions, and reported applications.

| Fungi | Synthesis Components | Synthesis Conditions | Applications | Ref. |
|---|---|---|---|---|
| *Amesia atro-brunnea* | Supernatant from the culture medium + Silver nitrate ($AgNO_3$) + Chitosan. | Variations in temperature, pH, molarity, and culture medium. | Antibacterial | (Al-zahrani & Al-garni, 2023) |
| *Aspergillus brasiliensis* | Supernatant from distilled water + $AgNO_3$ + CMC. | - | Antibacterial | (Oliveira et al., 2025) |
| *Aspergillus elegans* | Supernatant from distilled water and culture medium + $Fe_3O_4$ | Variations in culture media. | Bioremediation | (Muksy et al., 2024); (Mohammed et al., 2024) |
| *Aspergillus flavus* | Crude pectinase extract + Selenium (Se) | - | Antibacterial, Antifungal, Anticoagulant, Antioxidant | (Abdulmumini et al., 2025) |
| *Aspergillus flavus* | *A. flavus* on PDA medium + $Na_2SeO_3$ produces SeNP | - | Bioremediation | (Eltarahony et al., 2026) |
| *Aspergillus fumigatiaffinis* PP235788.1 | Supernatant from distilled water + $AgNO_3$ + a kombucha cellulose membrane. | Variations in $AgNO_3$ concentration, pH, and temperature | Antibacterial, Antifungal | (Aboul et al., 2025) |

| Fungi | Synthesis Components | Synthesis Conditions | Applications | Ref. |
|---|---|---|---|---|
| *Aspergillus fumigatus* KIBGE-IB33 | Supernatant from distilled water + $AgNO_3$ + Chitosan. | - | Antibacterial | (Raza et al., 2021) |
| *Aspergillus niger* | *A. niger* + $SiO_2$ | Cultivation Methods | Production of Silica Nanoparticles (SNPs) | (Hasanien et al., 2024) |
| *Aspergillus niger* TS16 | Supernatant from the culture medium + *Zinc oxide* (ZnO) | Variations in temperature, pH, supernatant concentration, reaction time, culture medium, and agitation time. | Antibacterial | (El-saadony et al., 2021) |
| *Aspergillus niger* AUMC 16028 | Supernatant from distilled water + *Iron oxide* ($Fe_2O_3$) | Optimizing the study using *Plackett-Burman Design* and *Box-Behnken Design*. | Bioremediation | (El-shanshoury et al., 2025) |
| *Aspergillus niger* IBCLP20 | Supernatant from the culture medium + silver nitrate ($AgNO_3$) | - | Antibacterial, Antifungal, Ecotoxicity, Salinity Stress Tolerance | (Assis et al., 2022); (Neto et al., 2026) |
| *Colletotrichum gloeosporioides* | Supernatant from distilled water + Silver nitrate ($AgNO_3$) | - | Antiproliferative Activity | (Gupta et al., 2024) |
| *Colonstachys rosea* | Cytoplasmic fraction of fungi + ZnO + MnO | Variations in *feeding strategy, feeding regime, feeding volume*. | Antibacterial, Antibiofilm | (Moslamy et al., 2024) |
| *Kluyveromyces marxianus* M59 | *Carboxymethylated* β-glucan + $SeO_2$ | - | Antibiofilm, Antioxidant | (Cinar-acar, 2025) |
| *Mucor circinelloides* | Supernatant from the culture medium + $CuSO_4$; Supernatant from distilled water + $CuSO_4$ | - | Fungicide | (Ahmed et al., 2026) |
| *Penicillium fimorum* | Supernatant from the culture medium + Silver nitrate ($AgNO_3$) | Variations in pH value | Antifungal, Antibiofilm, Antioxidant, Anticoagulant | (Barabadi et al., 2023) |
| *Penicillium oxalicum* | Supernatant from distilled water + $SiO_2$ | - | Bioremediation | (Elsayed et al., 2025) |
| *Phoma glomerata* | Supernatant from distilled water + CuO | - | Antifungal | (Ingle et al., 2023) |
| *Phoma herbarum* | Supernatant from distilled water + $AgNO_3$ | - | Bio-fungicide | (Bektas, 2025) |

| Fungi | Synthesis Components | Synthesis Conditions | Applications | Ref. |
|---|---|---|---|---|
| *Sarocladium kiliense* | Supernatant from distilled water + ZnO + MgO | - | Anticancer, Antibacterial, Antibiofilm | (Selim et al., 2026) |
| *Talaromyces australis* | Pigments from the supernatant + $AgNO_3$ | - | Antibacterial, Antioxidant | (Chavan et al., 2026) |
| *Trichoderma asperellum* | Extracellular filtrate + ZnO | - | Fungicide | (El-Morsy et al., 2026) |
| *Trichoderma koningiopsis* | Supernatants and biomass via sonication + $Fe_2O_3$ | - | Plant Stress Tolerance | (Liaquat et al., 2025) |
| *Trichoderma longibrachiatum* | Supernatant from the culture medium + ZnO | - | Fungicide | (Ghareeb et al., 2024) |
| *Trichoderma reesei* | Supernatant from the culture medium + $AgNO_3$ | - | Antivirus COVID-19 | (Carraro et al., 2025) |
| *Trichoderma virens* | Extracellular filtrate + $TiO_2$+CuO+*graphene oxide* (GO) | - | Antibacterial, Bioremediation | (El-sayed & Baek, 2025) |
| *Trichoderma virens* strain EG92 | Extracellular filtrate + MnO | - | Antibacterial, Antifungal | (Moslamy et al., 2023) |

Despite these advantages, several challenges remain. Maintaining long-term nanoparticle stability and preventing aggregation are still difficult because changes in pH, temperature, or protein structure can affect particle stability. In addition, producing nanoparticles with consistent size and shape across different fungal species and production batches is essential for large-scale applications. Several strategies have been proposed to overcome these limitations (Moslamy et al., 2024). One approach is the use of genetically engineered fungi to improve metal tolerance and enhance nanoparticle production (Oliveira et al., 2025). Another promising strategy is the combination of fungal synthesis with kombucha SCOBY (a symbiotic culture of bacteria and yeast), where the bacterial cellulose network serves as a natural support for nanoparticle immobilization, resulting in stronger and more functional bionanocomposites (Aboul et al., 2025). Future research should focus on integrating these strategies to develop more robust, scalable, and commercially viable fungal-mediated nanoparticle production systems.

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*3.2 Components of Mycogenic Nanoparticle Synthesis*

As shown in Fig.2, the biological production of nanoparticles primarily relies on a biological platform, where researchers utilize either the harvested fungal biomass or the cell-free filtrate containing active secretions to mediate the reaction. To initiate the process, specific metal salts such as silver nitrate, zinc nitrate iron chlorides, or sodium silicate are added as precursors to the fungal extract (Assis et al., 2022). This entire transformation is driven by a diverse array of fungal biomolecules, particularly extracellular enzymes like nitrate reductase, which act as natural reducing agents (El-saadony et al., 2021).

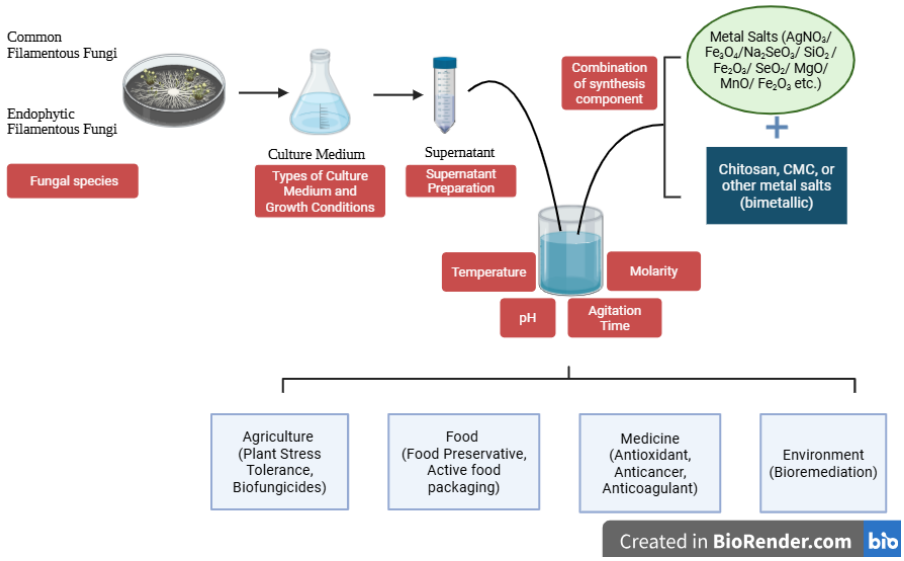



Fig. 2. The synthesis of mycogenic nanoparticles begins with the selection of an appropriate fungal species, followed by optimization of the culture medium, growth conditions, supernatant preparation, and synthesis components, with the critical factors at each stage indicated in the brown boxes. The physicochemical characteristics of the synthesized nanoparticles are further regulated by reaction parameters (brown boxes), thereby influencing their applications in agriculture, food, medicine, and environment (Created by the authors using BioRender.com based on the reviewed literature).

Beyond enzymes, various proteins and polysaccharides in the secretions play a vital role by wrapping around the formed particles to provide a natural capping layer that prevents clumping. Secondary metabolites like phenols and flavonoids further contribute to this stabilization while also enhancing the inherent biological activity of the resulting nanostructures (Muksy et al., 2024; Selim et al., 2026). While fungi have

been used to create many materials, silver (AgNPs) and zinc oxide (ZnONPs) remain the most popular choices due to their potent and well-documented antimicrobial effects. However, these fungal factories are capable of much more, including the synthesis of magnetic iron oxide, selenium, silica, and manganese oxide nanoparticles.

Despite the remarkable progress in fungal-mediated nanoparticle synthesis, several important challenges remain. One of the major limitations is the incomplete understanding of the biochemical mechanisms and metabolic pathways involved in fungal-mediated metal ion reduction. Although enzymes such as nitrate reductase and various secondary metabolites are known to play key roles, the underlying molecular processes have not yet been fully elucidated. Future studies should expand beyond commonly investigated metals and bimetallic nanocomposites which may offer enhanced or novel functionalities. At the same time, establishing standardized synthesis protocol is essential to minimize variations in nanoparticle size, morphology, and physicochemical properties (Dwivedi et al., 2026; El-shanshoury et al., 2025).

Another persistent challenge is maintaining long-term colloidal stability. Researchers are increasingly integrating natural biopolymers like chitosan and carboxymethylcellulose (CMC) as stabilizing agents to enhance functionality and prevent aggregation by forming an effective capping layer around biogenic nanoparticle. The use of chitosan in nanoparticles derived from fungi such as *A. atrobrunnea* or *A. fumigatus* has been shown to produce smaller particle sizes and provide synergetic antimicrobial effect that improves penetration into pathogens membranes (Al-zahrani & Al-garni, 2023; Raza et al., 2021).

Meanwhile, CMC acts as an effective stabilizing agent by binding to the nanoparticle surface through its carboxyl groups, creating electrostatic repulsion that keeps the particles well dispersed in colloidal systems. When incorporated into nanoparticles synthesized using *A. brasiliensis*, CMC has been shown to maintain colloidal stability while also improving resistance to UV exposure and allowing the nanoparticles to remain stable across a broader pH range (Oliveira et al., 2025).

Integrating natural biopolymers like chitosan and CMC serves as a vital step in refining mycogenic nanoparticle synthesis to ensure the safety, sustainability, and stability required for high-impact applications in medical treatments and food packaging.

*3.3 Variations in Fungal Nanoparticle Synthesis Conditions*

The properties of mycogenic nanoparticles can be controlled by adjusting the synthesis conditions. Temperature and pH affect fungal growth and the activity of enzymes that reduce metal ions, which influences the size and shape of the nanoparticles (Aboul et al., 2025; Al-zahrani & Al-garni, 2023; Barabadi et al., 2023). The concentration of metal salts is also important because high concentrations can increase nanoparticle formation but may also cause the particles to stick together. The type of culture medium, such as Mineral Salt Medium (MSM) or Czapek-Dox medium, affects the production of fungal compounds that help reduce metal ions and keep the nanoparticle stable (Aboul et al., 2025; Hasanien et al., 2024; Muksy et al., 2024). Other factors, including mixing speed, reaction time, and the amount of cell-free filtrate, also influence the quality, uniformity, and yield of the nanoparticles.

To identify the best synthesis conditions, many researchers now use statistical tools, including Plackett-Burman and Box-Behnken designs, to reduce the need for trial-and-error experiments (El-shanshoury et al., 2025). Once the process has been optimized at the laboratory scale, the next challenge is to produce nanoparticles on a larger scale by controlling fungal growth, aeration, and oxygen supply. Another approach to improve production is the use of fed-batch fermentation, where nutrients are added gradually during cultivation to increase nanoparticle yield (Moslamy et al., 2023). While, the use of low-cost agricultural waste, including orange peel and wheat bran, as culture substrates helps reduce production costs and makes the process more sustainable (Abdulmumini et al., 2025; Moslamy et al., 2023).

*3.4 Industrial Application of Mycogenic Nanoparticle*

Mycogenic nanoparticles have a wide range of applications in the biomedical, agricultural, environmental, and food sectors. These biologically synthesized

nanoparticles show strong antibacterial and antifungal activity against human pathogen such as *Staphylococcus aureus* and plant pathogens including *Fusarium* sp. They can also disrupt microbial biofilm, making them effective in preventing persistent infection. In the biomedical field, mycogenic silver and selenium nanoparticles exhibit antioxidant, anticoagulant, anticancer, and potential antiviral activities (Carraro et al., 2025; Selim et al., 2026). In environmental application, fungal-synthesized iron oxide and silica nanoparticles are used to remove toxic heavy metals and degrade synthetic dyes from wastewater (El-sayed & Baek, 2025; Eltarahony et al., 2026).

In agriculture, they improve plant tolerance to drought and salinity while acting as biofungicides and nematicides to control soil-borne pathogens. Their use in active food packaging has also attracted growing interest because they can help extend food shelf-life and improve food safety. Natural capping agents produced during fungal synthesis enhance nanoparticle stability and biocompatibility, thereby supporting their application in food-contact materials. In addition, the incorporation of kombucha SCOBY cellulose, chitosan, and CMC improves nanoparticle stability by reducing aggregation and enhances antimicrobial efficacy against food spoilage fungi, including *A. niger* and *F. oxysporum* (Aboul et al., 2025; Al-zahrani & Al-garni, 2023; Oliveira et al., 2025). Besides metal nanoparticles, fungi can also produce silica nanoparticles and carbon dots for bioimaging applications (Hasanien et al., 2024; Soares et al., 2026). In the future, carbon dots derived from fungal biomass may be explored as fluorescent sensing materials for detecting food spoilage and food adulteration through their unique fluorescent properties.

## 4. CONCLUSION AND SUGGESTION

### *4.1 Conclusion*

Fungal biological platforms provide a sustainable and cost-effective approach for nanoparticle synthesis by utilizing secreted enzymes, such as nitrate reductase, and other proteins as natural reducing and capping agents. The physical and chemical

properties of the synthesized nanoparticles can be controlled by adjusting reaction parameters, including pH, temperature, and precursor concentration. However, the development of standardized synthesis protocol is necessary to ensure consistent nanoparticle production for large-scale industrial application.

*4.2 Suggestion*

Future research should improve the understanding of fungal metabolic pathways, optimize large-scale production through advanced fermentation techniques, and evaluate the safety of mycogenic nanoparticles through comprehensive in vivo studies.

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