

Review

Minimum viable products in precision fermentation: defining translational milestones for food biotechnology[☆]

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Deven Madhani¹ and Yong-Su Jin^{1,3,4,*}

Precision fermentation has emerged as a promising platform for producing food ingredients. However, only a limited number of precision fermentation-derived ingredients have reached commercial markets. The concept of the minimum viable product (MVP) provides a useful framework for accelerating the practical adoption. MVP in precision fermentation is a food ingredient that provides a clear value proposition for a defined target consumer and can be safely and economically produced by an engineered microorganism. We introduce the Precision Fermentation Ingredient Pyramid, which can categorize targets into three tiers based on production volume, market value, and functional roles. A pipeline integrates market needs, biological and regulatory feasibility, economic competitiveness, and scalability for MVP selection. Applying this framework, we highlight opportunities across ingredient classes, including single-cell protein, ovalbumin, and β -carotene. Finally, we highlight the importance of techno-economic analysis for precision fermentation, particularly in linking strain performance and downstream processing to process economics.

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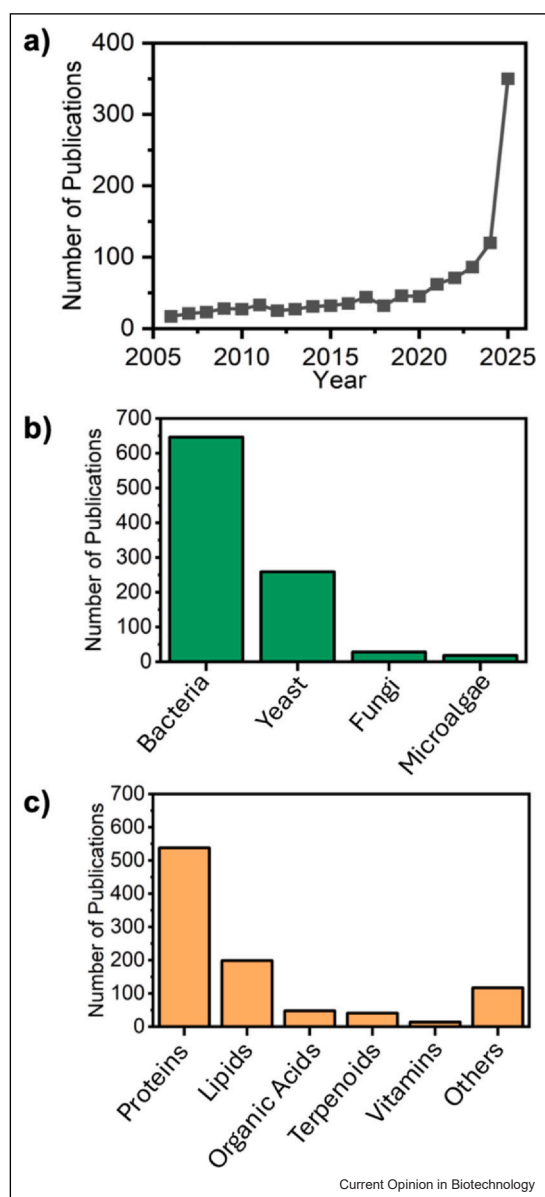
Introduction

Precision fermentation uses genetically engineered microorganisms to produce specific food ingredients by redirecting cellular metabolism through targeted genetic modification [1]. As a food-focused application of metabolic engineering and synthetic biology, it has gained increasing attention as a potential route toward more sustainable food production [2,3]. Reflecting this momentum, publications in the field have increased rapidly, nearly tripling in the past year alone (Figure 1a). Among reported targets over the past five years, proteins account for more than 50% of the molecules studied, and bacteria have been the most frequently used host microorganisms (Figure 1b,c).

Despite this rapid growth in research, the real-world impact of precision fermentation remains limited, with relatively few products reaching commercial markets [4]. Many studies fail to meet regulatory requirements or achieve competitive production costs for food applications. Moreover, most studies focus on specific technical aspects, such as strain engineering, rather than the full development pipeline, including scale-up, downstream processing,

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Figure 1



Publication trends in precision fermentation (a) Annual number of publications containing the term 'precision fermentation' (Topic search: TS = 'precision fermentation') in the Web of Science Core Collection from 2006 to 2025. **(b)** Distribution of publications (2020–2026) by host microorganism, based on Web of Science searches using the terms 'precision fermentation' and ('metabolic engineering' OR 'synthetic biology') AND 'food'. **(c)** Classification of publications by target ingredient class produced via microbial fermentation under the same criteria.

and market considerations [5]. Consequently, there is a critical need for translational research frameworks that connect strain engineering with market relevance.

One way to address this gap is to adopt the concept of the minimum viable product (MVP), defined as the

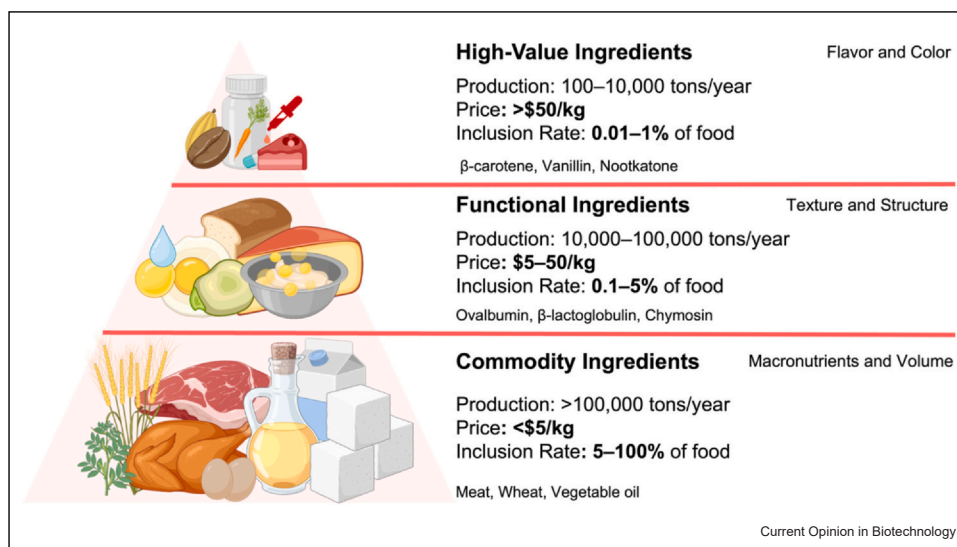
simplest functional product that demonstrates real-world value [6]. Prioritizing MVP development broadens evaluation beyond biological production capability to include marketability. While industrial biotechnology traditionally emphasizes improvements in titer, rate, and yield (TRY) [7], these metrics alone do not ensure commercial viability in the food industry, where regulatory approval, safety, and consumer acceptance are equally critical.

In this review, we present a systematic framework for identifying MVP for precision fermentation. MVP in precision fermentation is a food ingredient that provides a clear value proposition for a defined target consumer and can be safely and economically produced by an engineered microorganism. First, we introduce the Precision Fermentation Ingredient Pyramid, which categorizes potential MVPs by production volume, market price, and ingredient function to identify promising opportunities. Then, we propose a pipeline for MVP selection that integrates market needs, biological and regulatory feasibility, economics, and scalability. Finally, we apply this framework to representative case studies spanning three major food ingredient classes: single-cell protein as a commodity ingredient, ovalbumin as a functional ingredient, and β -carotene as a high-value ingredient. Together, these concepts provide a roadmap for defining translational milestones and accelerating the commercialization of precision fermentation-derived food ingredients.

Precision fermentation ingredient pyramid to prioritize minimum viable product targets

To support target selection, we propose the Precision Fermentation Ingredient Pyramid, which organizes potential MVPs by production volume and market price (Figure 2). At the base of the pyramid, commodity ingredients contribute to the majority of food mass and compete in low-price, high-volume markets represented by bulk proteins, fats, and carbohydrates. Competitiveness in this category requires mature technologies delivering high TRY with optimized downstream processing (DSP). The middle tier consists of functional ingredients providing structural properties and physicochemical stability. Here, the advantage is not necessarily lower cost per kilogram, but the ability to deliver a specific functionality not provided by bulk ingredients, enabling lower inclusion rates [8]. At the top of the pyramid are the highest value ingredients used at low inclusion rates but contributing significant value to the final product. These ingredients provide flavor, color, or bioactive effects, with value derived from potency and specificity rather than volume. In this category, precision fermentation enables the production of nature-identical or complex ingredients that are difficult, costly, or supply-limited through chemical synthesis or plant extraction. The price ranges presented in Figure 2 were derived

Figure 2



Precision fermentation ingredient pyramid. Conceptual framework categorizing food ingredients produced through precision fermentation based on production volume, market price, and functions in food formulation.

from a survey of representative ingredients within each category in the United States and are intended to provide a general reference rather than strict boundaries. An extended list of potential MVPs across categories is provided in [Table S1](#).

The pyramid captures the trade-off between market size and unit value. High-volume ingredients serve larger markets but compete in highly price-sensitive categories with tight margins. In contrast, lower-volume ingredients serve smaller markets but compete in higher-margin categories due to their specific functionalities. Moreover, there are substantial price differences between low-purity or synthetic products and high-purity or natural products. Accordingly, targeting the appropriate market niche is critical. Early success is more likely to come from prioritizing targets with clear value propositions, rather than competing directly with low-cost bulk ingredients.

A pipeline for precision fermentation minimum viable product selection

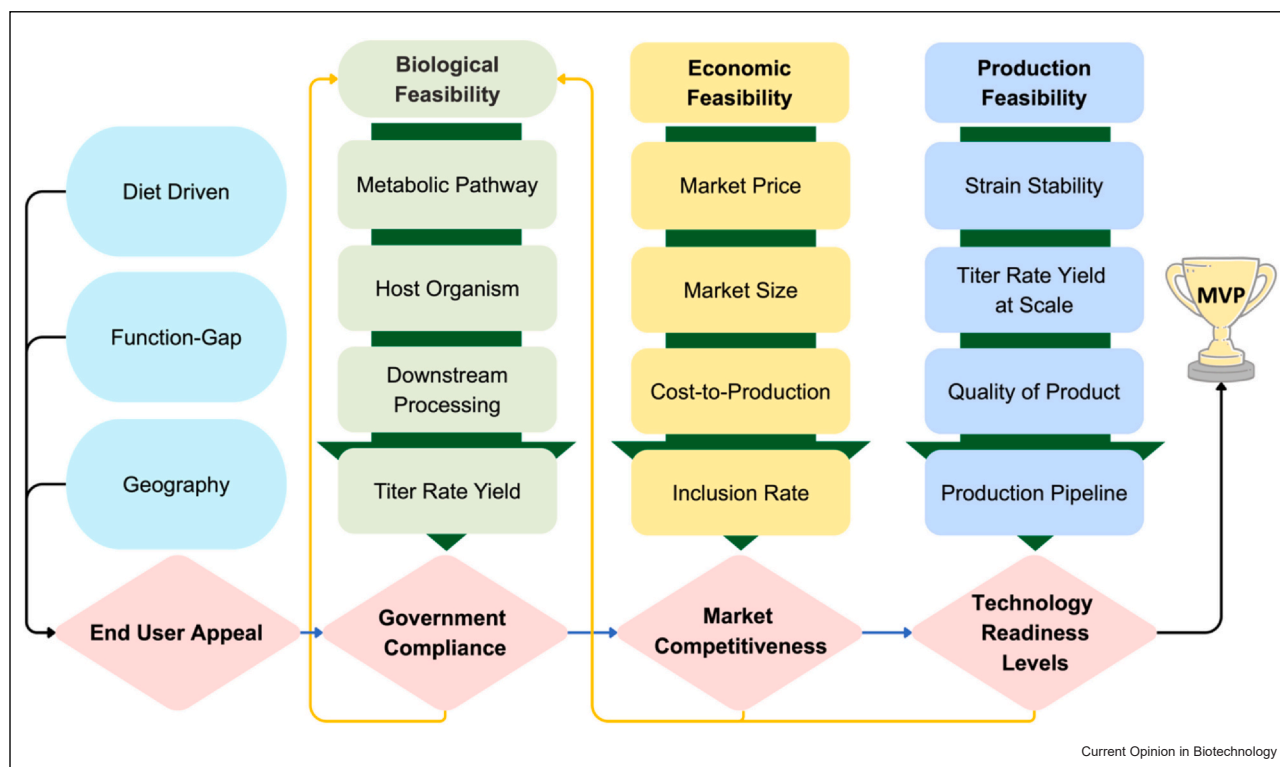
The proposed pipeline for precision fermentation MVP selection evaluates biological, economic, and production feasibility in a stepwise manner, beginning with the target consumer groups ([Figure 3](#)). Precision fermentation MVPs can address diverse societal and market needs. For example, individuals with dietary restrictions may benefit from ingredients produced through precision fermentation, such as vegetarian diets supplemented with long-chain polyunsaturated fatty acids [9]. Companies developing alternatives to conventional foods often rely on bulk plant ingredients to mimic

structure and functionality [10], whereas precision fermentation-derived ingredients can provide more precise functionality and improved product quality. In addition, countries with geographic or agricultural constraints can leverage precision fermentation for more predictable and sustainable ingredient production, contributing to food security.

Following market identification, biological feasibility must be evaluated while considering regulatory frameworks. Production hosts should ideally have a long history of safe use in food production. During metabolic pathway design, it is important to determine whether the target ingredient can be produced using native metabolic pathways or requires heterologous genes. If heterologous genes are necessary, they should not originate from pathogenic organisms. Under these constraints, the biologically optimal TRY may not always be achievable.

Because regulatory frameworks vary across regions, biological feasibility should be evaluated on a region-by-region basis. In the United States, entities may voluntarily notify the Food and Drug Administration (FDA) regarding the Generally Recognized as Safe (GRAS) status for food ingredients produced via precision fermentation. The FDA then responds with ‘no questions’ letter regarding the submitted notice [11]. In Europe, by contrast, entities must obtain approval before placing a product on the market. The European Food Safety Authority (EFSA) evaluates the safety of a Novel Food, defined as a food that was not consumed to a significant degree in Europe before 1997 [12,13]. For example, EFSA concluded that 2-fucosyllactose (2-FL)

Figure 3



A pipeline for precision fermentation MVP selection. Framework for prioritizing precision fermentation targets by integrating biological feasibility, market competitiveness, and production feasibility.

produced by engineered *Escherichia coli* K-12 is “safe under the proposed conditions of use,” based on the manufacturing process, composition, and specifications. EFSA examined results, such as the bacterial reverse mutation test, the *in vitro* micronucleus test, and a 90-day oral toxicity study to conclude on the safety of 2-FL [14]. Other parts of the world, such as Canada, Australia/New Zealand, China, and Singapore, have comparable regulatory frameworks for novel foods and similarly evaluate safety based on toxicity and potential effects on human consumption [12].

The next stage evaluates economic feasibility and market competitiveness. Techno-economic analysis (TEA) evaluates the economic performance of emerging technologies by estimating production costs and the minimum selling price [5]. These analyses incorporate multiple variables, including feedstock cost, fermentation performance, and DSP. Effective TEA frameworks should offer a solution space that enables the exploration of multiple process scenarios under varying assumptions and input parameters. Platforms like Biorefinery Simulation and Techno-Economic Analysis Module (BioSTEAM) offer this flexibility and support sensitivity and uncertainty analyses [15]. In addition, TEA can help researchers

identify the parameters with the greatest influence on cost reduction and benchmark new processes against established production methods [16]. Doing so, TEA guides research and development priorities to close the gap between biological feasibility and economic viability.

Finally, production feasibility at scale must be assessed. As engineered strains often behave differently at an industrial scale, strain stability and TRY must be validated under industrial fermentation conditions [17,18]. Processes compatible with existing manufacturing infrastructure are advantageous, as they reduce capital investment [19,20]. If scale-up challenges persist, biological feasibility should be revisited. Technology Readiness Levels (TRL) are a standardized framework used to assess the maturity of a technology from early research to market deployment [21]. In biomanufacturing, TRL is typically demonstrated through validation in increasingly relevant environments, often progressing from lab-scale to pilot-scale and commercial-scale production [22]. Therefore, MVP targets with higher TRL are advantageous, as they provide evidence that the process can be manufactured at scale. To illustrate this framework, three food ingredients were evaluated through the proposed pipeline.

Potential commodity ingredient minimum viable product

Commodity food ingredients are challenging targets for precision fermentation due to low prices and thin margins. One strategy is to improve existing microbial production systems. Single-cell protein (SCP), defined as edible microbial biomass used as a food ingredient or protein source, represents an established process [23]. A notable example is mycoprotein produced by Quorn since 2002 [24]. *Fusarium venenatum*, a GRAS filamentous fungi, can accumulate protein to 45% of its dry biomass [25]. In industrial-scale 140 000 L fermenters, production rates can reach up to 350 kg of biomass/hour, and the product can be directly used in food formulations with minimal DSP [26]. The estimated production cost of biomass is \$3.55/kg, which is competitive against \$6.56/kg beef [27]. However, the current industrial process does not involve genetic modification [26].

This creates an opportunity for precision fermentation to enhance nutritional value, improve texture, reduce off-flavors, and tailor digestibility through genetic engineering without requiring major process redesign. Recent advances in *F. venenatum* support this approach, including neutral genomic integration sites [28], Cas9-based genome editing [29], and antibiotic-free endogenous markers [30]. Such modifications primarily affect product quality rather than the core fermentation process, increasing market value without disrupting the favorable economics of mycoprotein production [31,32].

Further opportunities exist to improve fermentation efficiency and economic competitiveness. Engineering strategies that alter cell wall composition [33] or reduce carbon loss through CO₂ evolution [34] may enhance biomass yield and sustainability. While current processes rely on glucose and ammonium [26], lower-cost feedstocks such as agricultural residues or food processing by-products could reduce production costs [35].

Other filamentous fungi may represent promising SCP platforms, particularly for solid-state or low-cost fermentation. In this context, *Aspergillus oryzae* [36] and *Neurospora intermedia* [37] are noteworthy alternatives, given recent advances in genetic engineering tools. Yeasts such as *Saccharomyces cerevisiae* also represent promising SCP platforms, supported by advances including improved essential amino acid content [38]. Overall, SCP illustrates how the commodity tier of the ingredient pyramid can be approached by upgrading a proven bioprocess into a high-value precision fermentation MVP.

Potential functional ingredients minimum viable product

Functional ingredients are attractive MVP targets because their value depends on performance in food formulations. Precision fermentation enables the production of specific functional proteins without relying on animal-derived sources, while outperforming plant-based substitutes.

Ovalbumin, the major protein in egg white, is widely used in the food industry for its foaming and gelling properties, which are important in applications such as baked goods. Traditionally, these functions are achieved by incorporating egg whites or egg protein isolates [39]. However, manufacturers developing animal-free products often rely on plant proteins to replicate these functionalities, which may not fully reproduce the functional properties of egg proteins and can introduce undesirable flavors or textures [40]. Therefore, precision fermentation provides a promising route to produce nature-identical functional proteins without relying on animal-derived ingredients.

The biological feasibility of ovalbumin production through precision fermentation has been demonstrated across multiple microbial hosts. Because recombinant protein production requires genetic engineering, regulatory considerations favor secreted protein production, which simplifies DSP. A study using *S. cerevisiae* reported extracellular ovalbumin titers of 8 mg/L, although most of the protein remained intracellular [41]. *Komagataella phaffii*, commonly used for secreted protein production, reached titers of 35 mg/L [42]. Industrial-scale production has also been demonstrated by The EVERY Company (GRAS Notice No. 1104). In this context, OPENPichia, a license-free *K. phaffii* strain and genetic engineering toolkit, can serve as a shared platform for academia and industry, accelerating recombinant protein development through increased collaboration [43]. Higher titers have been reported in *Trichoderma reesei*, producing 2 g/L of secreted ovalbumin. The recombinant protein showed comparable structural properties and greater foam stability than egg-derived ovalbumin [40]. Its production potential has been further supported by DSP strategies [44].

However, the limited availability of detailed TEA makes it difficult to reliably evaluate the commercial competitiveness of precision fermentation-derived ovalbumin. Consequently, advancing ovalbumin toward MVP will require greater emphasis on robust TEA and scale-up data to evaluate its economic viability.

Potential high-value Ingredients minimum viable product

Precision fermentation offers an attractive route for producing high-value food ingredients that are traditionally obtained through plant extraction or chemical synthesis. Compared with these conventional approaches, biological production can provide advantages in sustainability, scalability, and stereochemical specificity. Chemical synthesis may generate unwanted stereoisomers and often requires environmentally intensive processes. Plant extraction can also be inefficient and resource-intensive. For example, 50 kg of carrots are required to obtain only 2 g of β -carotene [45]. These limitations make certain high-value ingredients particularly suitable targets for precision fermentation.

β -carotene is used as a natural food colorant and antioxidant in food formulations [46]. *Dunaliella salina*, a GRAS microalga, can accumulate β -carotene up to 10% of dry cell weight (DCW) under natural sunlight with minimal resources, but β -carotene titers remain low (0.2 mg/L) because of slow growth [47,48]. In contrast, engineered yeast platforms require controlled fermentation and defined feedstocks, such as glucose, but can achieve substantially higher titers. In *S. cerevisiae*, titers of 772.8 mg/L have been reported [49]. Further improvements have been achieved using the oleaginous yeast *Yarrowia lipolytica*, which provides high precursor flux toward isoprenoid biosynthesis and has enabled titers of 39.5 g/L, corresponding to nearly 50% of DCW [50]. Notably, oxygen availability has been identified as a key factor for stable β -carotene production in *Y. lipolytica*, underscoring its importance during scale-up [51]. In addition, streamlined DSP strategies for carotenoid recovery have been demonstrated in the native carotenoid-producing yeast *Phaffia rhodozyma* (syn. *Xanthophyllomyces dendrorhous*) [52]. Together, these studies demonstrate the strong biological feasibility for microbial β -carotene production.

However, economic feasibility remains insufficiently studied. There is one TEA based on *P. rhodozyma* that estimated β -carotene production costs at \$1559/g, based on a single fixed point at a low yield (67.9 μ g/g DCW) and expensive medium components such as glucose, peptone, and yeast extract [53]. Given the substantially higher TRY values now being reported, a TEA model that allows variation in key inputs is needed to reevaluate economic feasibility. For example, replacing these conventional medium components with low-cost feedstocks, such as molasses and fish-processing by-products, can reduce media costs by 70% [54]. Although β -carotene is a compelling MVP target for precision fermentation, the limited available TEA studies hinder accurate prediction of its market competitiveness.

Conclusion and prospect

In this review, we introduced the Precision Fermentation Ingredient Pyramid as a framework for categorizing potential target ingredients and proposed a systematic pipeline for identifying MVPs suitable for precision fermentation. This framework integrates biological feasibility within regulatory constraints, economic feasibility evaluated through market competitiveness, and production feasibility at scale. In addition, we emphasize the importance of identifying target consumer populations and application contexts when selecting MVPs, ensuring that technological development is aligned with real market needs. Applying this framework, we highlighted SCP, ovalbumin, and β -carotene as representatives of the ingredient families spanning commodity ingredients to high-value ingredients.

These case studies highlight a critical need in the development of robust TEA models tailored to precision fermentation. Many studies demonstrate biological feasibility but lack rigorous economic evaluation, limiting assessment of commercial potential. Greater academic engagement in TEA modeling, along with consensus on key assumptions and benchmarking standards, will be essential for guiding translational research and enabling more realistic evaluation of precision fermentation opportunities.

More broadly, adopting an MVP-oriented strategy may shift how precision fermentation research is conducted. Rather than prioritizing incremental improvements in individual engineering steps, the field may benefit from defining translational targets early in the development process and aligning biological design with market realities. Integrating strain engineering, process development, and techno-economic modeling within a unified framework will be essential for transforming precision fermentation from a promising technology into a scalable platform for sustainable food production.

CRedit authorship contribution statement

Hyunjoon Oh: Conceptualization, Writing – original draft, Writing – review & editing. **Suk-Chae Jung:** Writing – review & editing. **Sungjun Kim:** Writing – review & editing. **Deven Madhani:** Writing – review & editing. **Yong-Su Jin:** Conceptualization, Supervision, Writing – review & editing.

Data Availability

No data were used for the research described in the article.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.copbio.2026.103515.

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Papers of particular interest, published within the period of review, have been highlighted as:

- of special interest
- of outstanding interest

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