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PRECISION FERMENTATION AND CULTURED PROTEINS: REDEFINING PROTEIN PRODUCTION AND NUTRITIONAL STRATEGIES IN MODERN PET FOOD SYSTEMS-MINI REVIEW

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The pet food sector is experiencing a profound scientific transition driven by increasing demand for nutritionally precise, environmentally sustainable, and ethically responsible protein sources. Traditional reliance on livestock-derived ingredients has raised concerns regarding resource inefficiency, environmental impact, raw material variability, and long-term sustainability. In response, advances in biotechnology, particularly precision fermentation and cultured protein technologies—have emerged as promising alternatives capable of transforming protein production for companion animal nutrition. Precision fermentation enables the microbial synthesis of animal-identical or functionally enhanced proteins with high consistency and safety, while cultured proteins are generated through the controlled growth of animal cells without conventional animal agriculture. This review critically examines the scientific foundations, nutritional quality, functional performance, sustainability implications, safety considerations, and regulatory challenges associated with these technologies. Current evidence suggests that both precision-fermented and cultured proteins can provide digestible, bioavailable, and nutritionally adequate protein sources for pet foods. However, knowledge gaps remain regarding long-term health outcomes, micronutrient optimization, and large-scale economic feasibility. Collectively, these emerging technologies represent a paradigm shift toward nutrition-by-design and offer a compelling pathway for the future of sustainable pet food systems.

Keywords: precision fermentation, cultured proteins, pet nutrition, sustainable protein, companion animals.

ДӘЛДІК ФЕРМЕНТАЦИЯ ЖӘНЕ ӨСІРІЛЕТІН АҚУЫЗДАР: ЗАМАНАУИ ҮЙ ЖАНУАРЛАРЫ ЖЕМ ЖҮЙЕЛЕРІНДЕ АҚУЫЗ ӨНДІРУ МЕН ҚОРЕКТЕНУ СТРАТЕГИЯЛАРЫН ҚАЙТА АЙҚЫНДАУ — ШАҒЫН ШОЛУ

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Үй жануарларына арналған жем өндіру секторы нутрициялық дәлдігі жоғары, экологиялық тұрғыдан тұрақты және этикалық жауапты ақуыз көздеріне деген сұраныстың артуына байланысты елеулі ғылыми өзгерістер кезеңін бастан кешіруде. Дәстүрлі мал шаруашылығы негізіндегі ингредиенттерге тәуелділік ресурстарды тиімсіз пайдалану, қоршаған ортаға әсер, шикізат сапасының құбылмалылығы және ұзақ мерзімді тұрақтылық мәселелерін туындатады. Осыған байланысты биотехнология саласындағы жетістіктер, әсіресе дәл ферментация және жасушалық өсіру арқылы алынатын ақуыз технологиялары, серіктес жануарлардың қоректенуіне арналған ақуыз өндірісін түбегейлі өзгертуге қабілетті балама шешімдер ретінде қарастырылуда. Дәлдік ферментация микроағзалардың көмегімен жануар тектес немесе функционалдық тұрғыдан жетілдірілген ақуыздарды жоғары тұрақтылық пен қауіпсіздік деңгейінде синтездеуге мүмкіндік береді. Ал өсірілетін ақуыздар дәстүрлі мал шаруашылығын қолданбай, жануар жасушаларын бақыланатын жағдайда өсіру арқылы өндіріледі. Бұл шолуда аталған технологиялардың ғылыми негіздері, тағамдық құндылығы, функционалдық тиімділігі, тұрақтылық аспектілері, қауіпсіздік мәселелері және нормативтік-құқықтық қиындықтары сыни тұрғыдан талданады. Қазіргі деректер дәл ферментация және жасушалық өсіру арқылы алынған ақуыздардың жоғары сіңімді, биожетімді және қоректік тұрғыдан жеткілікті бола алатынын көрсетеді. Дегенмен, ұзақ мерзімді денсаулық әсерлері, микронутриенттерді оңтайландыру және өндірісті ауқымды деңгейде экономикалық тиімді іске асыру

мәселелері бойынша зерттеу олқылықтары сақталуда. Жалпы алғанда, бұл технологиялар «жобаланған қоректену» тұжырымдамасына негізделген жаңа парадигмалық бағытты білдіреді және болашақтағы тұрақты үй жануарлары жем жүйелерін қалыптастырудың маңызды жолын ұсынады.

Негізгі сөздер: дәлдік ферментация, өсірілетін ақуыздар, үй жануарларының қоректенуі, тұрақты ақуыз, серіктес жануарлар.

ТОЧНАЯ ФЕРМЕНТАЦИЯ И КУЛЬТИВИРУЕМЫЕ БЕЛКИ: ПЕРЕОСМЫСЛЕНИЕ ПРОИЗВОДСТВА БЕЛКА И СТРАТЕГИЙ ПИТАНИЯ В СОВРЕМЕННЫХ СИСТЕМАХ КОРМОВ ДЛЯ ДОМАШНИХ ЖИВОТНЫХ — МИНИ-ОБЗОР

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Сектор кормов для домашних животных переживает значительную научную трансформацию, обусловленную растущим спросом на нутриционно точные, экологически устойчивые и этически ответственные источники белка. Традиционная зависимость от ингредиентов животного происхождения вызывает обеспокоенность в связи с неэффективным использованием ресурсов, воздействием на окружающую среду, вариабельностью сырья и долгосрочной устойчивостью производства. В ответ на эти вызовы достижения в области биотехнологии, в частности технологии точной ферментации и культивируемых белков, стали перспективными альтернативами, способными изменить производство белка для питания животных-компаньонов. Точная ферментация позволяет микроорганизмам синтезировать белки, идентичные животным или функционально улучшенные, с высокой степенью стабильности и безопасности. Культивируемые белки получают путем контролируемого выращивания животных клеток без использования традиционного животноводства. В данном обзоре критически рассматриваются научные основы, питательная ценность, функциональные характеристики, аспекты устойчивости, вопросы безопасности и регуляторные проблемы, связанные с этими технологиями. Современные данные свидетельствуют о том, что белки, полученные с помощью точной ферментации и клеточного культивирования, могут обеспечивать высокую перевариваемость, биодоступность и полноценность в составе кормов для домашних животных. Тем не менее сохраняются пробелы в знаниях относительно долгосрочного влияния на здоровье, оптимизации микронутриентов и экономической эффективности при масштабировании производства. В целом данные технологии представляют собой парадигмальный сдвиг к концепции «питание по дизайну» и открывают перспективный путь к формированию устойчивых систем производства кормов будущего.

Ключевые слова: точная ферментация; культивируемые белки; питание домашних животных; устойчивый белок; животные-компаньоны.

Introduction

Protein is the most essential and metabolically demanding nutrient in companion animal diets, serving as the primary source of amino acids required for muscle maintenance, immune function, enzymatic activity, and overall physiological homeostasis [1-3]. Dogs and cats, particularly obligate carnivores such as cats, have evolved dietary requirements that necessitate high-quality, highly digestible protein sources. For decades, the pet food industry has depended on animal-derived ingredients originating from livestock production systems [4, 5], including meat meals and animal byproducts. While these ingredients have historically provided adequate nutrition, their continued use is increasingly challenged by sustainability concerns, fluctuations in raw material availability, and growing scrutiny from consumers and regulators alike [5, 6].

The environmental burden associated with animal agriculture, including greenhouse gas emissions, land use, and water consumption, has prompted critical evaluation of protein sourcing across both human and animal food systems. Pet food production alone represents a substantial share of global animal protein utilization [7, 8], thereby amplifying the urgency for alternative approaches. Within this context, precision fermentation and cultured protein technologies have emerged not as incremental innovations, but as fundamentally new paradigms for protein production [9].

Unlike earlier pet food trends driven primarily by consumer perceptions such as grain-free or raw

diets these technologies are grounded in molecular biology, microbial engineering, and cellular agriculture. Their application allows unprecedented control over protein composition, functionality, and safety, positioning them as cornerstone innovations for next-generation pet nutrition [10, 11].

Materials and research methods

A systematic search of peer-reviewed literature was conducted using major scientific databases. The search focused on identifying studies related to the gut microbiome in companion animals, precision fermentation, and cultured proteins in pet food systems. Key search terms included "companion animal microbiome," "precision fermentation," "cultured proteins," "sustainable pet nutrition," and "functional dietary strategies".

Results and discussion

1. Scientific Foundations of Precision Fermentation

Precision fermentation refers to the use of genetically engineered microorganisms to produce specific target proteins through controlled fermentation processes [12-14]. By introducing genes encoding desired proteins into microbial hosts such as yeast or bacteria, it is possible to direct cellular metabolism toward the synthesis of proteins that are identical or functionally comparable to those found in animal tissues.

One of the most significant advantages of precision fermentation is its ability to produce proteins with consistent amino acid profiles, independent of external variables such as animal age, diet, or processing conditions [15-17]. This consistency addresses one of the longstanding challenges in pet food formulation batch-to-batch variability which can influence nutrient availability and product performance. Moreover, fermentation systems can be optimized to enhance the expression of limiting amino acids, thereby improving protein efficiency and reducing the need for post-formulation supplementation.

From a processing perspective, precision-fermented proteins often exhibit favorable functional properties, including improved solubility, emulsification capacity, and thermal stability [18,19]. These attributes are particularly relevant in extrusion-based pet food manufacturing, where protein behavior influences kibble expansion, texture, and palatability. As such, precision fermentation not only contributes to nutritional adequacy but also supports manufacturing efficiency and product quality [20].

2. Nutritional Quality and Digestive Utilization

Emerging in vivo and in vitro studies evaluating precision-fermented proteins in canine and feline diets indicate that these ingredients exhibit high digestibility and efficient nitrogen utilization. Apparent protein digestibility values reported for microbial-derived proteins are comparable to, and in some cases exceed, those of conventional poultry or meat meals. This enhanced digestibility may be attributed to the absence of connective tissue components and the uniform molecular structure of fermentation-derived proteins [21,22].

Additionally, fermentation-based protein production minimizes exposure to contaminants commonly associated with animal-derived ingredients, including pathogenic microorganisms, antibiotic residues, and heavy metals. This contributes to improved ingredient safety and may reduce variability in gastrointestinal responses among pets. Preliminary research also suggests that fermentation-derived proteins may positively influence gut microbiota composition, although mechanistic understanding of these effects remains limited and warrants further investigation [23].

3. Cultured Proteins and Cellular Agriculture

Cultured protein technology, also known as cell-based or cultivated protein production, involves the expansion of animal-derived cells under sterile, nutrient-controlled conditions. Through this approach, muscle cells are encouraged to proliferate and differentiate, forming tissue that closely resembles conventional animal muscle at the cellular level. Unlike precision fermentation, which focuses on isolated proteins, cultured protein retains cellular architecture, including myofibrillar proteins and intracellular micronutrients [24].

Nutritional analyses indicate that cultured muscle tissue closely matches traditional meat in essential amino acid composition and protein quality metrics. The presence of native muscle proteins and heme-associated iron may contribute to high palatability and bioavailability, attributes that are particularly important for feline nutrition [25, 26]. These characteristics suggest that cultured proteins may be well-suited for use in premium pet food formulations or as partial replacements for conventional meat ingredients.

From an industry perspective, pet food represents a strategic application for cultured proteins due to lower regulatory hurdles and greater flexibility in formulation compared with human food products. Blended formulations incorporating cultured protein alongside conventional or fermented ingredients may offer a pragmatic pathway for gradual adoption while addressing cost and scalability constraints [27-29].

4. Sustainability Implications and Environmental Benefits

Sustainability considerations are central to the development of both precision fermentation and

cultured protein technologies. Life-cycle assessments consistently demonstrate that these systems require substantially less land and water and generate fewer greenhouse gas emissions compared with traditional livestock production [30-32]. Precision fermentation, in particular, offers strong scalability potential and compatibility with renewable feedstocks, aligning with circular bioeconomy principles. Given the significant contribution of pet food production to global animal protein demand, widespread adoption of alternative protein technologies could meaningfully reduce the environmental footprint of companion animal nutrition. This is particularly relevant as pet ownership continues to rise globally, amplifying the cumulative impact of dietary choices [34, 35].

5. Safety, Regulatory Landscape, and Quality Assurance

Short- to medium-term feeding studies evaluating precision-fermented proteins indicate no adverse effects on growth performance, metabolic health markers, or gastrointestinal function in companion animals. However, long-term data encompassing reproductive performance, aging, and disease susceptibility remain limited [34-36]. Cultured proteins face additional regulatory complexity, as frameworks governing their classification, labeling, and safety assessment are still evolving across different jurisdictions. Robust safety evaluation protocols, transparent labeling practices, and standardized nutritional assessment methods will be essential to ensure consumer trust and regulatory acceptance. Furthermore, integration of these novel proteins into existing pet food standards will require collaboration among scientists, industry stakeholders, and regulatory agencies.

6. Challenges, Knowledge Gaps, and Research Priorities

Despite their promise, several challenges must be addressed before precision fermentation and cultured proteins can be fully integrated into mainstream pet nutrition. These include the need for long-term feeding trials, optimization of micronutrient composition, evaluation of oxidative stability during storage, and comprehensive assessment of interactions with the gut microbiome. Economic feasibility and scalability, particularly for cultured protein systems, remain critical barriers that must be overcome through technological innovation and infrastructure development.

Conclusions and Future Outlook

Precision fermentation and cultured protein technologies represent a fundamental shift in pet food science, enabling unprecedented control over protein composition, functionality, and sustainability. Rather than relying on traditional agricultural systems, these approaches support a transition toward nutrition-by-design, where dietary proteins are engineered to meet specific physiological and environmental objectives. As research advances and regulatory frameworks mature, these technologies are poised to play an increasingly central role in shaping the future of pet nutrition. Their integration with emerging tools such as artificial intelligence, metabolomics, and microbiome analysis may further enable personalized, health-focused dietary strategies for companion animals. In this context, precision fermentation and cultured proteins should be viewed not as niche innovations, but as foundational components of next-generation, sustainable pet food systems.

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