Revolution in cultivated proteins and emerging biotechnologies for sustainable food

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Abstract. Considering environmental, climate, economic and nutritional challenges, the food transformation's systems has become a global strategic priority. Additionally, owing to its natural resource's intensity, greenhouse gas emissions and dependence on vulnerable agricultural ecosystems, protein production, including those of animal origin, is identified as one of the main contributors to the overall human's food ecological footprint. Besides, plant proteins have been partially reduced this footprint, and their large-scale development faces technological, functional and environmental limitations related to extraction and industrial processing. Nevertheless, crop proteins, microbial proteins and fermentation products are emerging as new generation of protein solutions, based on controlled biotechnological processes and potentially separated from traditional agricultural constraints. These approaches are part of a protein transition, combining environmental sustainability, food security, industrial innovation and climate change's resilience. This article provides a comprehensive synthesis of the conceptual foundations, production technologies, and socio-economic constraints and environmental impacts combined with cultivated proteins and aims to reposition them as a structural pillar of alternative proteins, linked to sustainable agriculture, the circular bioeconomy and the emerging principles of industry 5.0 based on recent scientific literature.

Keywords: food ecological, food security, circular bioeconomy, Climate change, Agriculture productivity

1. Introduction

Global food systems are facing diverse constraints related to increasing global population, intensifying climate risks and limited natural resources, which limit the Sustainable Development Goals achievement (SDGs) [1,2]. In addition, traditional animal protein production is identified as a major contributor to greenhouse gas emissions, deforestation and water consumption, making it urgent diversifying protein sources has become necessary [3].

Vegetable proteins have long been considered as the main animal's proteins alternative. Nevertheless, their industrial transformation usually involves energy-intensive processes, especially to produce concentrates and isolates, and creates difficulties in terms of technological functionally and nutritional profile [4,5]. These limitations underline the need for range protein's solutions increasing.
With this, cultured proteins notably cultured meat, microbial proteins and fermentation products, appear as a strategic alternative protein's component [6-8]. This paper aims to analyse how cultivated proteins may be repositioned in sustainable protein transition pathways, through an integrated approach encompassing technological innovations and environmental impacts.

2. Cultivated proteins concept

Cultivated proteins include the full set of protein products obtained by controlled biotechnological processes, and include products from animal cell cultures, microbial biomasses and fermentation [6,9]. This encompassing notion makes it possible to go further than cultivated meat concept to induce a diversity of protein matrices.
Additionally, cultivated meat is based on the proliferation of differentiated animal cells within bioreactors, combined with edible scaffolding use and optimized culture media [10,11,12]. Meanwhile, microbial proteins, referred to as single-cell proteins, take advantage of microbe's ability such as filamentous fungi, bacteria and microalgae to convert various substrates into protein-rich biomass [6,8].
As for precision fermentation, it remains the third key category, allowing the targeted production to functional ingredients such as caseins, chymosin or egg proteins by genetically optimized microorganisms [7,8]. Despite of this, it doesn't replace plant proteins, but instead follow complementary approach, combining hybrid products with the use of plant materials as fermentation substrates [6].

3. Innovative approaches for cultivating proteins production

Cultivating proteins is based on advanced biotechnology techniques that aimed to produce proteins in a controlled, reproductible and potentially more sustainable way than conventional agriculture systems. These pathways differ in biological principles, technological requirements and industrial maturity's levels, meanwhile, converge towards a common goal which is to optimize resource efficiency while ensuring nutritional and functional properties adapted to food uses. An in-depth analysis of the main production routes, highlighting technological key building blocks, recent advances and current limitations are provided in this section.
Based on the ability to isolate, cultivate and differentiate animal cells in conjunction with controlled environments, cultivated meat production can be achieved. Overall, the used cells are stem cells or progenitor ones able to proliferate and differentiate into muscle and dispose tissues. Besides, a fundamental issue is the choice and stability of cell lines, as they determine productivity, health, and process reproducibility [10,11].
Culture media are one of the main technological challenges. Before, these have been based on foetal bovine serum use, which not fit with the sustainability objectives, ethics and economic viability.
For all this, significant advances have been made in serum-free media development, integrating recombinant growth factors, transport proteins and essential microbial fermentation produced nutrients [13,14]. However, these components remain costly and represents a substantial part of the production's total cost.
Another central element of cultured meat remains tissue engineering, in which what tissue requires is three-dimensional structuring using edible supports that enables cell adhesion, nutrient diffusion and cell spatial organization. Besides, plant-based biopolymers, polysaccharides and proteins are being studied to replicate the conventional meat's texture and mechanical properties [12,15]. To progress beyond the simple cellular biomass production, these developments are crucial for achieving consumers acceptable textured products.

4. Precision fermentation for targeted functional proteins production

Relies on genetically optimized microorganisms, precision fermentation produces specific proteins with clearly defined functionalities. As opposed to microbial biomass, the objective remains to synthesize a target molecule such as caseins, whey proteins, chymosin or egg ones with a high level of purity rather than to produce a protein-rich cell mass [7,8].
Besides, the combination of high-performing microbial platforms and metabolic engineering strategies increases the yield and stability of produced proteins. Recent advances in recombinant growth factors production and serum proteins demonstrate precision fermentation 's potential to decrease the costs associated with cultured meat growing media [13].
Several advantages of precision fermentation, from an industrial perspective, include high reproducibility, tight process control, easy integration into infrastructure fermentation process. Nevertheless, genetically modified organisms related-regulatory issues, along with downstream purification costs remain major challenges to widespread adoption [7].

5. Microbial biomass production

The microbial proteins production, or single-cell proteins, is based on microbial culture able to convert efficiently carbon and nitrogen substrates into protein-rich biomass. This approach is characterized by high yields, short times production and high flexibility in terms of raw materials [6,8].

Among the most studied biological platforms, are filamentous fungi, bacteria, and microalgae. Their ability to recover agro-industrial co-products, is especially important, as it contributes to waste reduction and improves the overall food systems efficiency. This enhancement is fully aligned with both a circular economy and agricultural sustainability strategies [8]. Related to the nucleic acid composition of microbial mass, some constraints persist, which requires specific treatments to comply with food safety requirements, as well as proteins sensory and cultural acceptability [7,16].

6. Bioreactors and process digitalization

The bioreactor is the main bioprocessing unit for cultivated proteins production. Its engineering must satisfy complex requirements for mass, and heat transfer, pH, dissolved oxygen and nutrient flow control, as well as ensuring cultured cells viability and productivity [10,11]. Besides, industrial scale remains one of the most important challenges for cultivated proteins. Owing to physic-chemical gradients and diffusion limitations, laboratory level does not behave the same at large scale. To reduce energy consumption and improve crop homogeneity, recent studies demonstrate that bioreactor configuration, especially for cultured meat [10,15]. Moreover, integrating intelligent sensor and real-time monitoring systems, process digitalisation is key level for optimising production. These smart bioreactors enable precise critical parameters control, reduce losses and facilitate standardisation processes, in accordance with industry 5.0 principles [15].

7. Environmental impact and sustainability

According to life cycle analysis (LSAs), cultivated proteins have a significant potential to decrease land and water use compared to conventional animal proteins, although, depending on the energy sources and used substrates, the results show large variations [1,3,7]. Besides, energy consumption in bioreactors remains a major source of uncertainty for cultivated meat. Moreover, key strategies to improve the overall environmental performance of cultivated proteins include integrating agro-industrial co-products and coupling production with bioenergy pathways [6,8]. Additionally, to global food security, these proteins contribute through their high protein density, independence from climatic conditions, and local production potential [11, 17].

8. Major challenges

Despite their potential, cultivated proteins face many major challenges, such as production costs which remain high, especially due to growing media, recombinant growth factors and the investments needed to industrialize [6,10,13]. Moreover, driven by unnaturalness and health concerns perceptions, consumer acceptability remains a barrier [1,7]. Microbiological, allergenic and GMO related risks raise health safety issues that require draconian evaluation process [9,16]. Regardless of significant progress in some countries, novel food status and the international harmonization's lack are slowing down market entry [14,18].

9. Food systems integration and futures perspectives

The development of hybrid products combined with plant matrices and cultivated proteins is a key future scenario for integrating cultivated proteins, as well as targeting specific niches like functional ingredients or collective catering [6,7]. By coherent public policies, integrating comparative ACLs, safety standards and clear labelling schemes, their adoption will need to be supported [1,18]. Coupling with sustainable agriculture and industry 5.0 principles, including digitalisation, circularity and co-products valorisation, seems to be essential for large-scale adoption [8,15,19].

10. General conclusion

A major innovation with high potential to satisfy the contemporary challenges in sustainable food systems, cultivated proteins represent promising pathway. Nevertheless, systemic vision will be essential to their success, based on complementary approaches, transparency, equity and collective responsibility.

Cultivated proteins, rather than being major advance, can be seen as structuring element of a gradual transition towards more resilient, sustainable and inclusive food systems. Besides, scientific, industrial, political and social actors' ability to co-construct development trajectories in line with long-term sustainability objectives.

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