Bachelor’s Thesis

PRECISION FERMENTATION IN THE FOOD SYSTEM:

IS APPLIED PRECISION CELLULAR AGRICULTURE IN THE FOOD INDUSTRY A POTENTIAL DISRUPTIVE INNOVATION FOR THE FOOD SYSTEM?

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Abstract

The global food system faces a state of vulnerability, food insecurity, and possible crisis. In order to drive the transformation of the system to tackle the upcoming challenges, innovation might have a key role. This study investigates Precision Fermentation Agriculture (PCA) as a potential disruptive innovation in the food system. It highlights the vulnerability of the contemporary food system to external and internal pressures, with climate change exacerbating existing challenges. Agriculture and livestock farming contribute significantly to environmental degradation, impacting food security, especially in low-income countries. PCA offers an alternative to traditional livestock farming by producing proteins in large fermentation tanks, using minimal resources compared to conventional methods. While PCA has been lauded for its potential to transform the food system and ensure sustainability, existing literature often overlooks its disruptive potential. A case study of six relevant companies was conducted to assess their disruptive potential, revealing a blend of innovative technology, business models, and new-to-the-market products. PCA's superiority lies in its independence from external factors and its ability to address sustainability and ethical concerns. However, scaling up production and gaining consumer acceptance remain challenges. Further research is needed to explore the implications of PCA's disruptive process in the food industry, particularly in protein production and in consumer acceptance.

Keywords: Precision Fermentation, Precision Cellular Agriculture, Disruptive Innovation, Alternative Protein, Food Industry, Food System

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Abbreviations

CAGR…………………………………………………...…Compound Annual Growth Rate

CPG…………………………………………………………...Consumer Packaged Goods

EFSA…………………………………………………………European Food Safety Agency

ESG……………………………………………..Environmental, Social, Governmental

FAO……………………………….. Food and Agriculture Organization of the United Nations

GHG…………………………………………………………………Greenhouse Gases

GMO……………………………………………………Genetically Modified Organisms

GRAS……………………………………………………...Generally Recognized As Safe

IPCEI……………………………………...Important Project of Common European Interest

LI……………………………………………………………………...Lower Income

LMI……………………………………………………………...Lower Middle Income

PCA………………………………………………………...Precision Cellular Agriculture

SDG……………………………………………………. ….Sustainable Development Goals

UN………………………………………………………………………….United Nations

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Nomenclature Note

In this paper, I will use the term Precision Cellular Agriculture (PCA) to refer to the precision fermentation technology applied to derive traditionally animal-derived components without livestock (Mattick 2018, Stephens et al. 2018). This term was first coined in 2015 by the non-profit research institute New Harvest (Dupuis et al. 2022).

For consistency, I will later also apply this term in the conducted case study to refer to the companies Impossible Foods and Solar Foods, which produce traditionally soy-derived protein and the completely newly developed protein Solein® through precision fermentation.

The terms employed in the literature and in the business landscape for food ingredients and end products may vary. This paper will use the term PCA for all precision fermentation-related processes. For precision fermentation-related end products that are identical to an animal original in aspects such as taste, texture, nutritional value, and functionality, the term PCA-'name of the traditional product' will be used. For instance, in the case of the company Formo, their products will be referred to as PCA-cheese. For precision fermentation-related products that only mimic or replace a traditionally animal-derived product, the term PCA-substitute product will be employed.

1 Introduction

The food system in many ways can be considered one of the most significant systems of humankind and the root of our life on earth (UN 2024). As the source of all food, we rely on it more than on any other industry. However, given the recent evolution of our planet and species, it is undeniable that we have created several significant ecological problems by human activity which will have social and economic repercussions in all aspects of life on a global level, including our food system (IPCC 2022)

The way humans have organized agriculture, animal husbandry and fishery has profoundly shaped the environment, changed landscapes and damaged biodiversity and the climate (OECD 2024). According to the Food and Agriculture Organization of the United Nations (FAO), food systems are responsible for up to one third of the global anthropogenic emission of greenhouse gases (ghg) (Dury et al. 2019). Especially with respect to the organization of the food systems it is arguably statable that humanity is clearly operating beyond planetary boundaries (Dury et al. 2019).

It is estimated that ghg emissions from food systems between 2010 and 2050 will have increased by 80 to 92 per cent if neither technological changes nor mitigation measures are applied (Dury et al. 2019). However, the negative environmental effects highlighted also reveal that transforming production methods in a more sustainable way can have a large positive impact in combating climate change. By applying methods like recycling, creating biodiversity, capturing carbon and especially investigating in new innovations for climate mitigation, food systems have an important positive contribution to make in building a sustainable environment (OECD 2024).

There is an increased international consensus that transforming agrifood systems to increase their efficiency, inclusiveness, resilience, and sustainability is an essential comprehensive measure for realizing the 2030 agenda for sustainable development by the United Nations (UN) (FAO 2023). Therefore, in recent years, a more holistic concept of the ‘food system” has dominated debates amongst both scholars and policymakers (Ericksen, 2008). The new perspective integrates all the elements and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities (HLPE 2017).

In addition to the shift in the concept of the food system, there has also been a shift in consumers’ actions. Consumers in western countries for instance consume less meat out of environmental, ethical and health reasons (Vranken et al. 2014, Frank et al. 2017, Clark & Tilman 2007, Godfray 2018).

Considering all of the mentioned facts, it is evident that the food system is undergoing a profound transformation. To meet the newly emerging needs of the markets, players in the food system need to develop new technologies. One of the recently emerged promising technologies is the biosynthetic method of precision fermentation. It enables the production of traditionally animal-derived products without livestock by creating food ingredients that mimic their animal-derived examples precisely. All of this occurs within more environmentally friendly, resource-saving and stable conditions (Mattick 2018, Stephens et al. 2018). It can be argued that the technology is one of the most promising innovative technologies in the food system to date (Hassoun et al. 2022). Given the apparent solutions that the method gives to many of the rather urgent problems listed above, it is fair to examine its potential to have a disruptive impact in the food system.

This paper seeks to present the challenges faced by the conventional food system and examine precision fermentation as a promising solution. Existing literature to date covers various technical aspects such as fermentation process design, industrial food fermentation processes, positive technological and environmental impacts of precision fermentation-derived alternative proteins and current trends. However, there is still a gap in scientific literature when it comes to exploring what column journalists have been emphasizing for some time: the disruptive potential of the technology in the food and beverage sector as an alternative protein application.

The objective of this paper is to investigate the method's potential to create a sustainable impact on the food system and lay the groundwork for potential disruptive innovation models for players in the conventional- and alternative-protein sector. To comprehend the potential disruptive process of the food system through precision fermentation, a case study will be conducted. Six companies, that pose significant examples of the commercial landscape of the precision fermentation market, will be examined for their business models across 13 related categories. These categories consider both internal aspects of the companies as well as external implications for various stakeholders. Subsequently, the obtained results will be analyzed and connected to the theory of disruptive innovation.

The first chapter of this paper will present the results of the literature review, covering relevant information about the conventional food system, the precision cellular agriculture industry, and Christensen's concept of disruptive innovation. The following section will outline the methodology used in the case study of six pioneers in the precision cellular agriculture industry. Finally, the results of the case study will be presented and discussed concerning the method's potential as a disruptive innovation before drawing a final conclusion to the research question.

2 Theoretical Framework

2.1 The Conventional Food System

2.1.1 Definition

The Food System is a complex system that not only involves food production and distribution, but also a variety of other social-ecological interactions between humans and natural components (Allen & Prosperi 2016). The FAO defines it as follows: ‘The chains of market and non-market activities and actors connecting food production, aggregation, transportation and storage, processing and catering, distribution, preparation and consumption, waste and resources management as well as agro-input suppliers […] and the associated regulatory institutions and activities’ (Dury et al. 2019, p.16).

The food system not only plays the decisive role in the provision of food, but also has a significant influence on the economy, the environment, health and social justice (Tendall et al. 2015). The UN relates three of the Sustainable Development Goals (SDG) for the 2030 agenda closely to the food system, mentioning food security, nutrition and sustainable agriculture as keywords to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture (UN 2024).

The increasing importance of post-harvest, processing, and marketing activities is evident in their contribution to job and income creation, feeding non-farmers, influencing nutrition and health, impacting energy and resource consumption, contributing to loss and waste, and influencing biodiversity and pollution issues (Dury et al. 2019). This recognition has led to the expansion of the scope beyond agricultural production to cover entire food systems (Ericksen et al. 2009). With urbanization and the growth of market economies in rural areas, the significance of post-harvest activities has increased. These activities contribute to added value, job creation, and income generation in both rural and urban settings (Dury et al. 2019).

However, food systems do not cover all agricultural activities. Some of their products contribute to a broader bioeconomy (Dury et al. 2019).

Food security provided by the current food system is increasingly threatened. This is due to factors such as climate change, a growing world population, urbanization, and financial, political, or environmental shocks (Tendall et al., 2015). Particularly, livestock, as a protein source, is one of the most contaminating parts within the food system and thus a significant driver of climate change, posing a threat to the system (Poore & Nemecek, 2018). Therefore, PCA, as a substitutional way of producing livestock, is a promising solution for building resilience in the vulnerable food system.

2.1.2 Environmental, Social and Governmental Impact of the Conventional Food System

Amidst the mounting global concerns surrounding the sustainability and impact of the food system, this chapter delves into a comprehensive exploration of its environmental, social, and governmental implications.

To secure the growing demand for food and rising living standards, global water consumption has increased nearly sixfold over the past 100 years and continues to rise (Wada et al. 2016). The expansion of agriculture is the direct driver of almost 90 percent of deforestation (UN 2024). Between 2015 and 2019, at least 100 million hectares of healthy and productive land were degraded every year. Globally, one-fifth of the Earth's land area is degraded, an area nearly the size of India and the Russian Federation combined. Soil degradation drives species to extinction and exacerbates climate change. Lost forests mean the disappearance of livelihoods in rural communities, increased carbon emissions, diminished biodiversity, and land degradation (UN 2024).

Hence, this matter is integrated into the SDGs. Goal 15 aims to protect life on land. It aims to protect and restore terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss (UN 2024).

The food supply chain alone accounts for 26% of anthropogenic greenhouse gas emissions (Poore & Nemecek 2018). Food production causes about 32% of global terrestrial acidification and about 78% of eutrophication. These emissions can fundamentally alter the species composition of natural ecosystems and reduce biodiversity and ecological resilience (Poore & Nemecek 2018).

Around half of the world's habitable land is used for agriculture. Of this, 77% consists of crops for livestock for meat and dairy. Meanwhile, 52% of greenhouse gas emissions from food production come from livestock. However, livestock only contribute 18% to the global calorie supply and 37% to the global protein supply, thus significantly exceeding their relative weight of environmental impact (Poore & Nemecek 2018, cited in Ritchie & Poser 2019).

The ten most greenhouse gas-intensive protein sources are animal-derived. The production of the most intensive plant-based protein source, grain, emits only 64% of the least intensive animal-derived protein source, eggs. Compared to the most greenhouse gas-intensive protein source, beef, grain emits 5.4% of greenhouse gases (Poore & Nemecek 2018, cited in Ritchie 2020).

All of the aspects outlined above and more threaten the food chain. However, it's not just the quantity of production that's at risk but also its quality. A combination of higher temperatures and higher concentrations of CO2 reduces the mineral content, protein, and B vitamins in crops (Myers et al. 2014). This ultimately affects the nutrient content of food for people and thus their health.

While it has been acknowledged that food security represents a significant global concern, it is notably exacerbated in Low-Income (LI) and Lower Middle-Income (LMI) countries. Here, large parts of the population are entirely dependent on food trading. A study by Kinnunen et al. (2020) found that 26%-64% of the global population cannot fulfill their needs of specific crops within a distance of 1.000km. This part of the population is especially vulnerable to shocks in the food system or trading barriers.

Moreover, extreme food price volatility poses a severe threat to food and nutrition security, with expectations for its escalation in the foreseeable future (Dury et al. 2019).

Lastly, another influencing factor of the food system on human health is the increasing resistance to antibiotics and reserve antibiotics in livestock farming (Greenpeace 2021, Landers et al. 2012). If antibiotic use is not reduced, estimates by the World Bank predict 10 million deaths annually worldwide due to AMR by 2050 (The World Bank 2023).

In conclusion, the intricate examination of the environmental, social, and governmental dimensions of the food system underscores the imperative for concerted efforts towards fostering sustainability, equity, and resilience in the face of pressing global challenges.

2.1.3 The Future of the Food System

Based on the environmental, social and governmental impact of the food system outlined above, it results evident, that a transformation towards a more sustainable food system is necessary in order to further ensure food security (Allen & Prosperi 2016). One of the most used definitions of a sustainable food system refers to “the ability of a system to maintain productivity in spite of a major disturbance, such as caused by intensive stress or a large perturbation” (Conway 1985, p. 35). Stress and perturbation today are largely caused by climate variability and extreme events. Therefore, it results important to map the future of the food system to consider the most relevant factors that will affect the food system in the coming years. Based on an extensive literature review, six critical drivers of change and five significant challenges in the food system were identified.

2.1.3.1 Drivers Shaping Food Systems

In this chapter, the drivers are neither evaluated nor prioritized, which is why they are presented in alphabetical order.

Biophysical and environmental drivers: These drivers are influenced by the availability of natural resources, environmental pollution, and climate conditions. They predominantly impact food systems in terms of production, as the availability of essential resources such as water, land, and biodiversity play a crucial role in food production. The most important events are climate change and the scarcity of natural resources such as water and soil, partially caused by food production, and the shifting geography of food production sites (Dury et al. 2019, Allen & Prosperi 2016).

Demographic drivers: These factors encompass population growth, urbanization, migration, and population displacement. They significantly shape demand, affecting not only the quantity of required food but also the quality and variety of consumed food, along with the overall food environment (Dury et al. 2019).

Economic drivers: Economic drivers affect all aspects of food systems from production to demand. They include incomes, globalization and trade, prices and financial systems (Dury et al. 2019).

The income level for instance partially determines the predominantly used technologies in production, as these have a direct impact on the price of goods and therefore on purchasing power. Incomes however can also concern State revenues and therefore determine the investment, regulation and policies in the sector (Bené et al. 2019, Allen & Prosperi 2016).

Trade and globalization refer to the local, international and global network of incumbents of the sector. Especially in terms of marketplaces future innovations pose a lot of potential for innovation and transformation (Bené et al. 2019, Kearney 2010).

Prices and the Financial System both significantly influence the financial activity within the system. They determine not only cost and consumption but also the overall food security. Undoubtedly, climate variability and extremes are critical to food prices, availability and access but also economic and trade policies which promote responses such as lower food stocks and speculative investment strongly influence the food system (Ericksen et al. 2009).

Innovation and technology: Innovation, technology, and infrastructure play crucial roles in driving food systems. They impact both, the supply side, enhancing system productivity, and demand. Innovation and Technology strongly impact in agricultural and post-harvest activities as well as productivity of land and labor. The infrastructure´s impact is more concentrated in transport, water and energy supply, marketplaces, storage facilities harbors, slaughterhouses and communication networks (Dury et al. 2019).

Political drivers: These factors encompass governance, public policies, conflicts, and humanitarian crises, influencing numerous aspects within food systems. A severely dangerous driver for transformation in the food system is conflict and civil unrest. In an extreme scenario, as for instance experienced during the war in Ukraine (2022 – today), civil unrest that culminates in war cuts of food and ingredient accessibility and effects the global supply chain as a whole in food safety, accessibility and prices (Dury et al. 2019).

Socio-cultural drivers: Socio-cultural drivers are developments and changes in culture, religion, rituals, education, health, values and identity. For instance, in recent years a shift to more health, environmental and animal welfare awareness, primarily in western countries, has strongly influenced in consumption patterns, to which the competitors in the market can or cannot react (Vranken et al. 2014, Frank et al. 2017). On the other hand, civil unrest that culminates in war is a major threat to the food systems (Bené et al. 2019).

2.1.3.2 Challenges in the Food System

In this chapter, the challenges are neither evaluated nor prioritized, which is why they are presented in alphabetical order.

Addressing climate change and intensification of natural hazards: Climate change poses multiple concerns about food security and access. Damage and losses to production, the degradation of land, forests, water and other natural resources will affect food availability as well as nutritional outcomes (Campbell 2021, FAO 2017).

Ensuring a sustainable natural resource base: Until 2050 we face growing pressures on agricultural land, water, forests capture fisheries and biodiversity. Additionally to the increasing degradation of soils, new available land is not readily accessible. Therefore, increases in food demand will have to meet the increase of agricultural production in productivity and resource-use efficiency. Moreover, water scarcity will expose production systems to high environmental stress (Poore & Nemecek 2018).

Making food systems more efficient, inclusive and resilient to combat its vulnerability: the food system faces a need for dynamic pathways to balance the efficiency of modern food systems with equity (FAO 2017, Kinnunen et al. 2017). The Affordability of food is a crucial aspect of inclusivity within the system. The economic access to nutritious food that meets the basic needs poses a central challenge to maintain while transforming into a more productive and efficient system (Allen & Prosepri 2016).

Preventing transboundary and emerging agriculture and food system threats: Food systems are threatened by an alarming increase in transboundary animal and plant pests and diseases. Control of transboundary plant pests and diseases is crucial for reducing yield losses. Growing food demand through intensive animal production raises concerns about higher pollution, increased antibiotic use, and the potential for more serious epidemics of zoonotic diseases. The growing challenge of antimicrobial resistance, which affects the prevention and treatment of infections is also highlighted (FAO 2017, The World Bank 2023).

Sustainably improving agricultural productivity to meet increasing demand: The demand for agricultural products is projected to increase by 50 percent until 2050 (FAO 2017). While demand is undergoing significant structural change at the same time, the resources are becoming less and more intensely competed over. Therefore, a key challenge for the future is to produce more products more efficiently while preserving the environment and the planet (World Economic Forum 2023).

2.2 Precision Fermentation Technology

2.2.1 Definition

Precision fermentation is a technique used in modern synthetic biotechnology. It is used to produce specific synthetic ingredients for products from various industries (Pham 2018). The method has been a standard in the pharmaceutical industry for years, while it has only recently been increasingly used and recognized in the food industry and related science (Dupuis et al. 2022).

Precision fermentation is a specified derivation of fermentation. This includes traditional fermentation, biomass fermentation and precision fermentation (Teng et al. 2021). Fermentation as a pillar of modern industrial biotechnology is defined as a 'chemical transformation of any organic matter via microbial metabolism, mediated by myrial enzymes' (Chai et al. 2022, p.1). It is used in medical, water, environmental, energy, construction and, most recently, food industries (Chai et al. 2022).

The term precision fermentation is more generally covered by the term cellular agriculture, or more specifically, precision cellular agriculture (PCA) (Dupuis et al. 2022). A term first coined in 2015 by the non-profit research institute New Harvest (Dupuis et al. 2022). It is specifically defined as the production of traditionally animal-derived components without livestock (Mattick 2018, Stephens et al. 2018).

PCA can be described as an optimized fermentation process using specifically designed microbial hosts as ´cell factories` to produce high value functional food ingredients with high yields and purity. Said ingredients, such as enzymes, lipids, protein, carbohydrates, vitamins, flavoring, colorants, antioxidants, and preservatives, typically project higher yields, purity and a lower environmental footprint compared to their conventional methods of production like agriculture, animal husbandry, foraging, bulk extraction or organic synthesis. According to Chai et al., the 'industrial-scale fermentation of food-related products using native microbial producers is hardly novel" (Chai et al. 2022, p.1). However, precision fermentation is practically synonymous with metabolic engineering, a method which involves genetic manipulation of microbial chassis (Chai et al. 2022).

The method primarily uses bacteria, yeasts or filamentous funghi (Chai et al. 2022). It can exactly mimic the composition of their counterparties extracted from traditional methods (Augustin et al. 2023). The method´s projected relevance in the future food system, which is being discussed in chapter 2.2.4 'Markets" is therefore justified by the functionality of the

PCA-derived food ingredients. The exact functionality and utilization of each host will be discussed in chapter 2.2.3 ‘2.2.3 Application of PCA-Derived Protein as a Food Ingredient’.

2.2.2 Production of Food Ingredients

As this thesis will focus on the economic aspects and analyze the potential of PCA as a disruptive innovation, the biochemical production process of food ingredients will only be dealt with superficially.

Although the production of food ingredients follows a general pattern, it differs in detail depending on the host used and the desired end ingredient. In general, the process follows the following five steps: ‘(1) identification and optimization of the gene expressing the protein of interest, (2) incorporation of the gene into a DNA molecule […], (3) uptake of the (DNA molecule) […] by the cellular host, which consequently becomes ‘transformed”, (4) initiation of targeted gene expression in the transformed cell, and (5) secretion and harvesting of the gene product (i.e., the protein of interest) (Dupuis et al. 2022, p.887). After the successful transformation of the cellular host, the expression machinery, namely the promoter and the secretion signal, are the most important parameters for a high yield (Dupuis et al. 2022).

One of the advantages of the usage of the technique in the food industry is that the PCA-derived food ingredients do not have to be as purified as required in the pharmaceutical industry (Augustin et al. 2023). Likewise, only microorganisms that are labelled as safe or non-harmful are used (Chai et al. 2022).

Biologists as well as economists see tremendous potential in the method. Due to recent advances in so called ‘omics” tools, it is possible to develop products that exactly fit the desired characteristics and ensure a very precise fermentation process (Teng et al. 2022). This implies the possibility of exactly mimicking the composition and functionality of food products which to date can only be produced in the less ecologically friendly, traditional ways (Augustin et al. 2023).

In terms of the commercial production of PCA-derived food ingredients, most companies use fungal expression hosts (Dupuis et al. 2022). Fungi are (micro)organisms with strong environmental adaptability. This makes them suitable microbial hosts for PCA. They have a natural tendency to accumulate high levels of commercially valuable food compounds, making them conveniently efficient hosts for industrial-scale production of their products. (Chai et al. 2022).

2.2.3 Application of PCA-Derived Protein as a Food Ingredient

Many of the companies that are performing commercial production of PCA-derived food ingredients are expressing dairy-associated proteins like the two primary classes of milk protein, whey or casein fractions (Dupuis et al. 2022). Said proteins, such as whey (β-Lactoglobulin) are already applied as an ingredient in ice cream, cream cheese and protein powder (Dupuis et al. 2022). Meanwhile Caseins are the core component of cheese and sports supplements (Dupuis et al. 2022). Recombinant milk proteins are also applicable as egg replacers (Augustin et al. 2023).

Another relevant liquid food protein is egg protein, which for a large part consists of total egg white protein (Dupuis et al. 2022). Recombinant egg white production systems can primarily find use in bakery and beverage applications (Dupuis et al. 2022). They have been of great interest especially due to their functional characteristics like foaming, emulsifying and thickening (Dupuis et al. 2022).

Structural or muscle associated proteins are especially relevant for the elaboration of meat substitutes (Dupuis et al. 2022). Collagen for instance is found in bones, skin, muscles, blood vessels, tendons and cartilage of mammals (Wang et al. 2022). Another highly relevant protein for the production of meat substitutes is soy protein (leghemoglobin). It is a metalloprotein, natively originating from the soybean, that shows similarities to animal hemoglobin and is therefore suitable to mimic the flavor and color of animal hemoglobin (Dupuis et al. 2022). Finally, recombinant non-animal heme proteins are used to provide the color and flavor to meat analogues (Augustin et al. 2023).

All of the mentioned proteins allow to convey the flavors and colors associated with meat while not using any animal-derived resources (Dupuis et al. 2022).

2.2.4 Markets

In the past, products produced by synthetic biology have mainly been used in the health sector and only rarely in the agricultural sector (Augustin et al. 2023). In recent years, however, the method has approached the market for food and beverage products.

In 2022, there have been registered 70 biomass fermentation companies and 62 precision fermentation companies with business models dedicated to produce functional ingredients for protein-based meat, dairy, egg and seafood alternatives (Bushnell et al. a) 2022). At least 100 additional companies have a business line in alternative protein fermentation including major food companies such as Nestlé, Unilever and Bel Group (Bushnell et al. a) 2022).

Hassoun et al. (2022) describe the PCA method as an emerging food trend in the fourth industrial revolution (Hassoun et al. 2022). This statement is confirmed by the predicted growth of the market. In 2021, the global market size for synthetic biology in food and beverage, agriculture and consumer goods were valued at USD 1.3 billion (Bloomberg 2023). Until 2031, it is projected to reach USD 34.9 billion (Bloomberg 2023). This represents a compound annual growth rate (CAGR) of 40.5% (Bloomberg 2023). The figures vary slightly depending on the source.

Investment in the industry is significant. According to the Good Food Institute (Bushnell et al. 2022), around USD 1.69 billion was invested in fermentation companies in 2021. Well-established players in the industry like DSM, DuPont und JBS are indeed investing in the new technology.

In terms of government funding, Europe funneled 155 million $ into PCA research. The Netherlands only made a 65 million $ investment in the completion of protein facilities. The United States, in comparison, supported PCA research at federal levels in a minor way (Bushnell et al. a) 2022).

The increasing attention and appeal of the technology attracts investment and eventually leads to reduced prices of biosynthetic technologies (BCG 2021). This further facilitates the development of sustainable value chains based on precision fermentation and benefits the further growth of the market (BCG 2021).

The cost for PCA has been falling exponentially (Augustin et al. 2023). By 2023-2025 the average cost of precision fermentation derived protein is expected to be $10/kg (Tubb & Seba 2019 cited by Augustin et al. 2023). This would represent for the first time a competitive price point and could help the approach to the market for food products (Tubb & Seba 2019 cited by Augustin et al. 2023).

The drivers of the market for food ingredients are diverse. They can be caused externally by consumers or environmental influences or internally by players within the market such as investors and stakeholders. Drivers caused externally by consumers include (1) changing food habits, shifting consumer preferences and tastes while increasing the number of vegetarians and vegans and the acceptability of their respective lifestyles (Frost & Sullivan 2018 cited by Augustin et al. 2023, Bloomberg 2023), (2) increasing demand for high quality food (Frost & Sullivan 2018) and (3) increasing consumer concerns about animal welfare in animal husbandry as well as the impacts of the food system in the environment and personal health

(Bloomberg 2023). Drivers caused externally by environmental influences include (1) a rising global protein demand due to over population (Bloomberg 2023), (2) increasingly overloaded areas and soils that negatively affect crop yields (Dury et al. 2019) and (3) climate change, which also negatively affects crop yields in the form of extreme weather events (Dury et al. 2019).

Drivers caused internally by market participants include (1) increased innovation and investment in fermentation companies (Bloomberg 2023) as well as (2) increasing scrutiny on ESG (Environmental, Social and Governmental) aspects especially in the start-up scene (Bloomberg 2023). The empirically proven relation between ESG and financial performance (Friede et al. 2015) is an important aspect regarding the attractiveness of start-ups for investment funds which are of great importance for any young company (Bloomberg 2023).

To date, the large emerging markets in alternative animal protein have primarily been served by plant-based alternatives (Augustin et al. 2023). The fermentation approach is therefore not yet widely established. However, it is possible to estimate in which areas of the market the fermentation method will develop most strongly. Based on application, the meat substitute-segment is predicted to develop at the quickest rate until 2031 while the dairy substitute-segment became the global leader in 2021 (Bloomberg 2023). Based on microorganisms, the bacteria segment is expected to develop at the quickest rate in the following years (Bloomberg 2023).

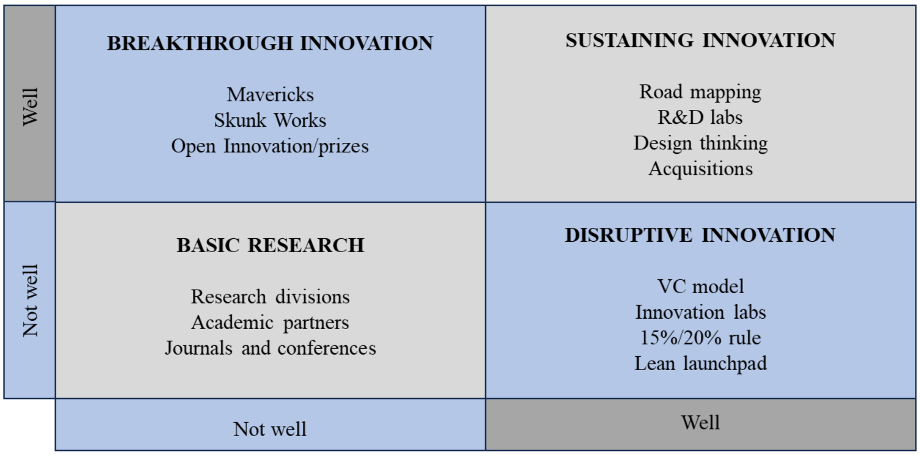
2.3 Innovation Models

2.3.1 Comprehensive Overview

In this dissertation, the analytical emphasis will be on disruptive innovation. The following chapter is included to provide completeness to the thesis and, therefore, is only briefly addressed.

In his article published in the Harvard Business Review in 2023, Greg Satell describes 4 types of innovation, illustrated in the Innovation Matrix (Satell 2023) (Figure 1).

Figure 1. THE INNOVATION MATRIX (Greg Satell 2017)



Own illustration based on Greg Satell (2017)

Sustaining Innovation is the type of innovation that seeks to improve an already well-defined domain. There is a clear vision regarding the existing problem and the required skill set for the solution of the problem (Satell 2023). Effective strategies are strategic road mapping, traditional R&D labs, mergers & acquisitions and design thinking methods (Satell 2023).

Breakthrough Innovations evolve from exploring unconventional skill domains and solution approaches to well-defined problems that are exceedingly hard to solve. Open innovation strategy can be a highly effective strategy in this regard (Satell 2023). Often times the posed problems have unexpectedly easy solutions that have a certain paradigm to them (Satell 2023).

Basic Research is a type of innovation that is highly reliant on financial resources to invest in basic investigation and labs (Satell 2023). This poses a barrier especially for young and small companies (Satell 2023).

Disruptive Innovation is the fourth and last type of innovation presented by Satell and is described in detail in the following chapter 2.3.2 ‘Disruptive Innovation’.

2.3.2 Disruptive Innovation

The term ‘disruptive innovation’ was first coined by Christensen in 1997 (Christensen 1997). It characterizes the phenomenon of an innovation that, due to its novelty and initial uniqueness, alters the success attributes of a market to such an extent that it disrupts established and successful companies, ultimately leading to their downfall (Christensen 1997). The phenomenon emerges in different types of markets (Christensen 1997). Notably, it does not only affect companies that are already in an unstable position. Christensen identifies a common aspect in these cases, highlighting that the affected entities are often well-established market leaders known for their own innovation and execution capabilities (Christensen 1997).

2.3.2.1 Categories and Characteristics

Christensen originally associates disruptive innovation primarily with technology (Christensen 1997). Later, Markides will argue that disruptive innovations should be categorized not only into disruptive technologies but also into disruptive business models and radical new-to-the-market product innovations (Markides 2006).

- Disruption through technology innovation

  There are no established criteria provided to clearly define what qualifies as a disruptive technology. (Danneels 2004). It is also not certain whether a technology itself can be considered inherently disruptive or whether the ‘disruptiveness’ of a technology is related to the company it concerns (Erwin 2004). According to Christensen (Christensen et al. 2000 cited by Danneels 2004) the internet for instance is simultaneously disruptive towards some and sustaining towards other companies.

  The point at which a technology qualifies as a disruptive technology is uncertain (Erwin 2004). Specifically, there is no clear definition regarding whether a technology should only be classified as disruptive when it displaces established market incumbents reliant on previous technologies, or if this criterion is not fully applicable (Erwin 2004).

- Disruption through business model innovation

  Markides defines a business model innovation as the ‘discovery of a fundamentally different business in an existing business” (Markides 2006, p.20). This implies that they do not define an entirely new product or service but redefine what an existing product or service is, how its value is created and what value it provides to the customer.

Therefore, disruptive business models (1) attract customers that are different from those that established firms focus on and (2) require different value-chains from the ones established companies provide. The latter is additionally conflicting with respect to the existing value-chain of the incumbent companies. Therefore, those initially have only little incentive to adopt the innovative business model (Markides 2006). One of the most famous and impactful examples of innovation in business model of the recent years is Amazon in bookselling (Markides 2006).

- Disruption through product innovation

Markides narrows down the second further specification of disruptive innovation to radical- new-to-the-world product innovations (Markides 2006). These are characterized by the absolute novelty of the products or services. The Apple iPhone is an excellent example of a product innovation.

To consumers, product innovations are disruptive because they create value in a way that disturbs the prevailing consumer habits and behaviors in a significant way (Markides 2006). For producers, they are disruptive because they undermine competences and complementary assets upon which existing competitors have built success (Markides 2006).

Radical product innovations are rarely driven by demand (Markides 2006). Instead, they are the result of a supply-push process (Markides & Geroski 2005). Markets that emerge from such processes share the following characteristics (Klepper & Simons 2000 cited by Markides 2006, Utterback 1994 cited by Markides 2006):

(1) Despite enormous technological and product uncertainty the new markets attract a significant number of new entrants. This happens well before the markets start to grow.

(2) Product variety surges to very high levels

(3) The markets experience a sharp and sudden shakeout leading to the death of most early pioneers. This associated with the emergence of a dominant design in the market. It is a signal of the beginning of growth in the market.

(4) The markets take a long time to unfold. The structure of new markets remains remarkably fluid throughout the early years. The number of entries and exits from the

market is significantly higher than the number of actually operational companies. (Klepper & Simons 2000 cited by Markides 2006, Utterback 1994 cited by Markides 2006).

A frequently occurring phenomenon is that early pioneers only very rarely dominate the market later on (Markides 2006). Product innovations initially serve niche markets. The early pioneers are rarely the ones who scale up the market from a niche market to a mass market. Often the late entrant captures the market even when their product is not as good as the product of the early pioneers. The role of pioneers is often played by start-ups who pool the expertise. The role of the later entrants is often assumed by larger players who have sufficient capital and capacity to scale up the niche market to the mass market (Markides 2006).

2.3.2.2 Disruption Process

One of Christensen's key findings is that disruptive technologies eventually grow to dominate and therefore disrupt the market (Christensen 1997). Disruption is described as a process not an event (Christensen et al. 2013), which in some cases can take decades to penetrate an industry. However, in the case of a truly disruptive technology, success is guaranteed (Markides 2006).

Disruptive business models, on the other hand, display a different behavior. They usually grow relatively quickly and take over a certain percentage of the market, but in most cases fail to take over the market as a whole (Markides 2006) The established and disruptive innovative business models can coexist in the same market (Christensen et al. 2013).

In order to recognize why an innovative business model has a disruptive effect on the market, it is important to note that new markets have different key success factors to the old market (Markides 2006). Therefore, different combinations of customized activities and concepts such as the value chain, internal processes, structures and culture are needed to be competitive (Markides 2006).

Due to their complexity, the extensive and far-reaching changes are often incompatible with other ways of doing business. This is due to various conflicts and trade-offs that result from the attempt to combine them (Markides 2006).

According to Porter, a company trying to compete in two positions simultaneously risks paying a straddling cost and degrading the value of its existing activities (Porter 1996).

As the innovative business models are sufficient in the old attributes established by the market, but better than the established players in the newly discovered attributes, the new business models are increasingly taking market share from the established incumbents. This growth reaches a climax at which it attracts the attention of the established players, forcing them to react (Markides 2006).

This creates a dilemma for the established players. The two different ways of doing business are fundamentally different. Their business model is becoming obsolete, a total adoption of the new business model is expensive, radical and uncertain, and a coexistence of both models harbors internal conflicts.

Hence, these new innovative business models are referred to as *disruptive to the established firm* (Markides 2006).

3 Methodology

After having examined the theoretical framework of conventional agriculture considering aspects such as definition, future, and environmental impact, as well as exploring precision fermentation in terms of definition, production, application, and markets, the transition towards the central focus of this research is now following—the case study. As mentioned in the introduction, the case study concentrates on the analysis of business models of leading companies, representative of the industry. Subsequently, a qualitative evaluation will be conducted to determine whether the considered types of business models have the potential to disrupt the food industry and to comprehend this process of disruption. Finally, the initial question of investigation 'Is Applied Precision Cellular Agriculture In The Food Industry A Potential Disruptive Innovation For The Food System?' shall be answered.

The choice of a qualitative case study as a research method for this bachelor thesis presents several compelling arguments. The exploratory aim of the investigation is to explore a new, and therefore contemporary, phenomenon (Yin 2009) in the realm of PCA companies and formulate a hypothesis regarding their disruptive potential. The application of a holistic approach allows for the consideration of various aspects of the examined companies, aiming to achieve a comprehensive understanding of the activities of PCA companies (Eisenhardt 1989). The complexity of the research subject necessitates an in-depth analysis to gain a detailed understanding of the peculiarities of PCA companies and their differences. This is crucial for fully comprehending the potential process of disruption (Eisenhardt 1989). The qualitative case study also facilitates embedding the research within the context of the current state of the food industry (Yin 2009). This ensures that the research findings relate to the real conditions of the industry. Furthermore, the qualitative method supports the goal of later establishing a theory-practice connection by applying the theory of disruptive innovation to concrete practical examples. This contributes to gaining insights that are not only theoretically sound but also relevant in practice (Eisenhardt 1989).

The upcoming sections will scrutinize the selection process of the chosen companies, followed by an exploration of the data collection and compilation methodology. Subsequently, in the subchapter 'Analysis and Study of the Information', the specific criteria used to examine the previously selected companies in the case study will be introduced and substantiated.

3.1 Selection of the Companies Under Study

In the year 2022, the count of companies specifically dedicated to PCA for alternative proteins stood at 62 (Bushnell et al. a) 2022). This information is extracted from the annual report of the Good Food Institute. The Good Food Institute is a non-profit think tank dedicated to supporting the alternative protein industry. They are a member of the Precision Fermentation Alliance, founded in 2023, and provide a current overview of the commercial, investment, policy, and scientific landscape in the fermentation industry for alternative protein production in their annual report (The Good Food Institute 2024, Bushnell et al. a) 2022). For this case study, six of the 62 companies featured in the report were selected. According to Eisenhardt (1989) it is crucial for the selected companies to find themselves in extreme and polar situations, in which processes of interest are transparently observable. Therefore, the criteria applied to choose companies relevant to the objectives of this work included representativeness within the overall commercial landscape, technological approach, innovation level, and degree of commercialization. These criteria will be further justified in the following sections.

- Relevance of the Selected Companies within the Overall Commercial Landscape

  The process of selecting companies for this study is designed to mirror the commercial landscape, ensuring a comprehensive representation across diverse industry segments.

  The categorization of industry segments can be based on the types of alternative proteins produced, encompassing whey and casein protein, egg white, heme protein, enzymes and others. Further segmentation can be applied based on specific application areas, including meat and seafood alternatives, dairy alternatives, egg alternatives, and other categories.

  Within the industry, the segment of Dairy alternative protein emerges as the largest (Bloomberg 2023), justifying the inclusion of two companies that focus on both B2B and B2C models. The meat segment is predicted to grow at the largest growth rate in the upcoming years (Bloomberg 2023), which is why for the meat segment likewise two companies have been selected. This dual focus ensures a comprehensive understanding of the market dynamics.

  Geographically, the chosen companies originate from Europe and the USA, identified as core markets (Bushnell et al. a) 2022, p.21). Examining the development of business models surrounding precision fermentation within the expansive and diverse contexts of the European Union and the United States is deemed more appropriate than limiting the analysis to a single country, which could introduce bias. Furthermore, considering the mature and highly consolidated nature of the food industry (Reardon and Timmer 2012), the potential disruptive impacts of precision fermentation companies are expected to be equally comprehended across all participating markets.

- Technological Approach

The predominant approach in all companies in the industry is consistently centered around PCA. However, diverse key resources are employed within this framework. The approach of this case study is to include all technological approaches of importance.

- Innovation Level

The chosen companies, viewed from a technical perspective, emerge as pioneers within their specific industry segments. Their early market entry, coupled with advanced product development, has enabled them to cultivate robust networks of investors, partners, and customers (Bushnell et al. a) 2022). Notably, their pioneering status extends to the technical realm, setting them apart through the distinctiveness of their products.

The overarching objective of this selection is to integrate well-established and advanced solutions, along with innovative approaches, into the subsequent discussion. This approach ensures a comprehensive examination of both established practices and emerging trends within the context of the chosen companies' pioneering roles.

- Degree of Commercialization

The final step in the selection process involves filtering the previously identified companies based on their level of commercialization. Ideally, a higher degree of commercialization allows for a more nuanced evaluation of the market impact and customer implications. Nevertheless, given the nascent stage of the industry, not all companies of interest in this case study can achieve high levels of commercialization. Consequently, the selected companies showcase diverse degrees of commercialization, reflecting the current landscape of the precision fermentation sector (Bushnell et al. 2019).

3.2 Data Collection and Compilation of Information

Table 1 provides an overview of the selected companies. Collectively, they represent some of the most significant pioneers in the market, both in terms of size and technological innovation, as well as geography of the markets.

Impossible Foods, Perfect Day and The Every Company represent the US market. They are the largest companies. This is due to the faster issuance of necessary certificates and permits such as GRAS (Generally Recognized As Safe) in the USA. These three companies are also the most widely commercialized, meaning they have launched the most products to the market. They cover the three main segments of the market: dairy, eggs, and meat. It should be noted that Impossible Foods, the oldest company, is the only one producing plant protein through precision fermentation and thus not duplicating traditionally animal-derived protein.

The animal counterpart to the plant heme protein produced by Impossible Foods is produced by the Belgian company Paleo. They are the youngest company and thus the least commercialized. However, they have one of the most elaborated heme protein portfolios in the market. They stand out from other companies as they also produce myoglobin from mice, rats, and rabbits for the pet food market.

Formo represents the only European B2C PCA company in the selection. They are based in Berlin, Germany. With self-produced dairy proteins such as whey and casein, they produce animal-free dairy cheese using traditional methods. They are not yet on the market but plan to launch their first animal-free dairy cream cheese in 2024, the ‘Frischhain’, named after a district in Berlin.

The most unique company in terms of technology and processes is the Finnish company Solar Foods. They produce a specially developed protein called Solein®. The process differs significantly from the processes used by competitors due to the required resources. Solar Foods' specialty is that they produce protein almost exclusively from air and energy. From the air, necessary elements such as hydrogen, oxygen, and carbon are extracted through electrolysis, which are later enriched with a few other nutrients and then fermented in tanks into Solein®. This method even has the potential for CO2-negative production.

Table 1. Selected Companies

	Perfect Day	Formo	Impossible Foods	Paleo	The EVERY Company	Solar Foods
Segment	Dairy	Dairy	Meat	Meat and fish	Eggs	Others
Protein Produced	ProFerm (whey protein)	Casein, whey	Plant heme protein	Animal heme protein (myoglobin)	Egg protein	Solein® (new protein)
HQ	USA	Germany	USA	Belgium	USA	Finland
Founding Year	2014	2019	2011	2020	2014	217
Year of First Launch	2019	TBC	2016	TBC	2020	2023
Size by Employees	>330	>80	700	>30	>90	>35
Channels	B2B	B2C	predominantly B2C, also B2B	B2B	B2B	B2B
Website	Perfect Day	Formo	Impossible Foods	Paleo	The EVERY Company	Solar Foods

own illustration (2024)

Once the companies were selected, all the collected information has been gathered from different data sources, as recommended by literature (Eisenhardt 1989). Data collection sources have been their respective websites, press releases and publicly available interviews as well as industry reports.

Regarding the timeframe, the most recent information available to the public has been employed, predominantly corresponding to the year 2022 and 2023. This is justified by the youth and dynamism of the market, where developments are ongoing. Considering the novelty of all advancements in the sector, it is not deemed appropriate to address any information older than that which has been utilized.

3.3 Analysis and Study of the Information

The analysis of the examined companies was conducted exclusively on a qualitative basis following an abductive approach (Yin 2009). In order to analyze the business models of the selected companies and their potential to disruption in a comparable manner, they were examined based on 13 standardized criteria. These criteria are based on the analysis of the different aspects that are relevant to the exploration of the companies' business models, products and technologies, as these are the three possible sources, of which disruptive innovation can erupt, as presented in chapter 2.3.2. Furthermore, a criterion of examination is the environmental impact of the companies' business practices. This is due to the crucial role of the environmental impact of conventional practices in the food system and its significance for the drivers of change in the food system as presented in chapter 2.1.2 and 2.1.3. Alongside these criteria based on literature review, throughout the analysis process the possibility of including other relevant elements emerging to address the research question has remained open. Together, both analytical approaches yielded the results presented.

The criteria finally applied are the following:

- Micro description including name, headquarters, type(s) of protein produced, and segment of operation based on application area
- Mission
- Main Innovation Driver

  The main innovation driver serves to understand the motivation of the companies and aids to distinguish them from the main transformation drivers of conventional agriculture described in chapter 2.1.3.2 of this paper.

- Product Portfolio

  Information about the product portfolios is essential to comprehend their business model as they form the basis for the value proposition.

- Customer Segments

  Understanding the customer segments allows to draw conclusions about the future of a business models.

- Protein Application

Protein application determines which kind of disruptive process is in the scope of possibility of the company.

- Environmental Impact

One of the major weaknesses of conventional agriculture, and thus one of the key drivers of innovation and transformation within the sector, is the significantly detrimental impact of agriculture on the environment. It is therefore essential to examine the environmental impact of the companies to subsequently compare it to that of conventional agriculture.

- Key Resources

Key resources are important to understand potential dependencies. Resources significantly contribute to the volatility or stability of a business model and, therefore, play a central role.

- Value Proposition

The value proposition is the heart of every business model and ultimately determines whether the company, with its business model, meets a need in the market or not. In this category, the various approaches of the considered companies to value creation are examined, compared, and evaluated.

- Dependencies

Dependencies determine the risk or stability of a business model.

- Barriers

Companies dedicated to PCA, aiming to disrupt an existing and stable market, must contend with the market entry barriers of this sector. The magnitude of these barriers can ultimately determine the success or failure of the business models in the entered market.

- Investments, Key Partners and Scale-Up

The examination of investments in the considered companies, their key partners, and plans for scaling up production is an exploration of crucial stakeholders in these companies. This allows insight into which business partners or competitors are already involved in the economic activities of the considered young companies.

The research and development of PCA-derived food ingredients are largely driven by startups. This involves a significant reliance on partnerships, strategic alliances, and investors to obtain the financial means for optimization and scale-up, especially since most of the considered companies may not be market-ready and, consequently, not profit-generating at the time of the study.

- Level of Commercialization

  This category serves to ascertain the commercial activity of the companies. As all companies are in an early stage, the developments in this regard are particularly diverse and crucial.

- Non-GMO (Genetically Modified Organisms)

  GMO is a crucial criterion for maintaining approvals from food authorities in different countries (FDA 2023, EFSA a) 2023).

- Price Parity

  Lastly, a crucial criterion for the adoption of a new product in a mature market is price parity with the animal-derived counterparts to the products of PCA startups. Here, price comparisons with comparable conventional products were conducted where price information was available.

  According to the above defined criteria, relevant information was gathered, interpreted, and contextualized in relation to the overall landscape of the food industry and the potential of business models centered around PCA.

4 Results Obtained by the Study of the PCA Business Models

As part of the elaboration of this case study, the detailed results of the six examined companies will not be presented in detail. The comprehensive and detailed results of each individual company can be found in appendix 1.

This section will focus on descriptively presenting the results in their entirety and highlighting specific features. The criteria presented are divided into two groups: (1) criteria with internal implications and (2) criteria with additional external implications involving various stakeholders. Since the criteria belonging to the first group are more descriptive, they will be presented first. Subsequently, the criteria belonging to the second group will be addressed.

4.1 Criteria with Internal Implications on the Business Model

The chosen companies represent relevant examples of the overall commercial landscape in the market.

Within the market, 31% of all PCA companies are located in the United States, 40% are located in Europe. In the conducted case study, 50% of the selected companies were founded and have their headquarters located in the United States, the other 50% originates from Europe.

All of the market segments regarding the operation based on the type of alternative protein produced and application area are represented in the selection. Perfect Day and Formo focus on the dairy segment, Paleo and Impossible Food on the meat and fish segment and The Every Company specializes in egg protein. The market segment *Others* is represented by Solar Foods and refers to a non-specified application area. This is justified by the fact that the protein Solein® developed by Solar Foods is not a duplicate of an animal-derived protein but rather a newly developed protein.

The selection prioritizes market leaders and pioneers to ensure a comprehensive analysis. Covering all segments based on application area provides a holistic view of the industry. Notably, the decision to choose two representatives for each of the dairy and meat segments is justified by their significant share in the market (Bloomberg 2023, Bushnell et al. a) 2022).

Main Innovation Driver

The study shows a strong alignment of the main innovation drivers among the companies. All companies solely cite ethical concerns regarding processes in conventional agriculture as the main innovation driver. These processes are strongly criticized in all companies.

Five out of six companies identify ethical concerns regarding the sustainability of the conventional system as the decisive driver. Only Paleo cites ethical concerns about animal welfare in animal husbandry as the main driver of their mission.

However, in general, reasons related to sustainability, risk mitigation of the food chain, animal welfare, and other ethical concerns are decisive for the founding and mission of the companies under consideration.

Mission

Different mission statements from the selected companies are the following:

- *'we want to massively reduce the impact of protein consumption on our home (planet earth) and those we share it with.' (Formo)*
- *'build a more equitable, resilient, and diverse food system for all of us.' (Perfect Day)*
- *' to make our global food system truly sustainable' (Impossible Foods)*
- *'we want to make meat and fish, but not kill animals to do it.' (Paleo)*
- *'unlock powerful proteins designed for the future of every human, every animal, everywhere.' (The Every Company)*
- *'disconnecting food production from agriculture to produce the world's most sustainable protein. Protein that will never run out.' (Solar Foods)*

The missions of the selected companies are generally aligned. The following values are the values extracted from the missions of the companies ranked by frequency of mention:

1. Sustainability
2. Resilience of the food system
3. Justice, veganism, protein performance

Product Portfolio

The offered products include pure protein for processing in (substitute) products by commercial customers (4/6 companies), functional ready-to-use protein substitute (1/6 companies), ready-to-consume food and beverages (2/6 companies), and animal-free animal-identical enzymes (1/6 companies).

Only the US-american companies have been able to launch products for broad sale by themselves or partnering up with other brands or groups. The most famous products launched by Perfect Day so far have been the PCA milk from Perfect Day X Nestlé called *Cowabunga* launched in 2022, the *nurishh* PCA-cream cheese from Perfect Day X BelGroup launched in 2022 and the PCA whey protein powder *whey fwrd* from Perfect Day X MyProtein US also launched in 2022.

As for Impossible Foods, their most known product launch is the *Impossible Burger* made from *Impossible Beef* launched in 2016 as the first of its kind. Since then, they have launched a variety of other plant-based meet alternatives including pork and chicken products.

The Every Company is the first and only company in the market to launch PCA-pepsin. Moreover, they offer their protein in bakery- and alternative meat solutions as well as a booster in supplements.

The European countries are not as far commercialized. Solar Food has launched a PCA-protein boosted chocolate bar as a pilot product in Singapore. Formo and Paleo have not yet launched any products to the market as of march 2024.

Protein Application

The application of the PCA-derived proteins by the selected companies varies in six areas, which are ranked below according to their frequency of mention:

1. Application as a nutritional supplement in non-substitutional products (4 companies: Solar Foods, Paleo, The Every Company, Perfect Day)
2.
    - Application as an ingredient for dairy substitute products (2 companies: Perfect Day, Formo)
    - Application as an ingredient for meat and fish (chicken/beef/pork/tuna) substitute products (3 companies: Impossible Foods, Paleo, The Every Company)
    - Application as an ingredient for egg substitute products (2 companies: The Every Company, Perfect Day)
    - Application as an ingredient exclusively for ready-to-consume products by the producing company (2 companies: Formo, Impossible Foods)

Non-GMO

Six out of seven companies produce GMO-free protein.

One company (Impossible Foods) is not GMO-free.

4.2 Criteria with Additional External Implications of the Business Model Involving Stakeholders

Channels and Customer Segments

Six out of seven companies sell their products exclusively to businesses.

One company (Formo) has not yet published any information about channels since their cheeses are not yet available in the market.

Figure 2. Customer Segments

Consumer Segments		
B2B	Producing clients	Food manufacturers incorporating dairy, meat, fish and egg
		Dairy, meat, and fish substitute manufacturers
		Food and beverage manufacturers unrelated to animal-derived ingredients that seek to nutritionally boost their products
		Plant-based food and beverage manufacturers
		Plant-based substitutional product manufacturers
	Wholesale & retail	Supermarkets
		Restaurants
		Online delivery providers
B2C	Consumers of meat, fish and dairy products who seek to reduce their consumption due to ethical or health related considerations	
	Consumers of plant-based meat, fish and dairy substitutes	
	Nutritionally aware consumers of non-animal related foods and beverages	

own illustration (2024)

Regarding consumer segments, a detailed elaboration of the various customer segments addressed by the companies observed in the case study is shown in Figure 2.

Key Resources

Since all selected companies share similar processes, the key resources of are very much aligned.

The most important physical resources are machinery and fermentation tanks of the mostly pilot production facilities as well as ingredients for alternative protein fermentation. Those are composed mainly by multicellular microflora/microorganisms, water, sugar, nutrients, yeast and predominantly renewable energy.

The second key resource that is as well shared by all selected companies is the intellectual resource of the know-how of all fermentation related processes.

Only Solar Foods differs in the key resources for the fermentation process, as they solely require air and energy. Only a few nutrients such as phosphorus and calcium need to be added in addition to the mentioned two resources. The required microorganisms and water are obtained from the air through electrolysis. Their claim 'food out of thin air' emphasizes this uniqueness.

Environmental Impact

The environmental impact of precision fermentation derived alternative protein in ghg emissions, water-, land- and energy use is in every case a fraction of the resource necessity of the same protein derived of animal husbandry or conventional agriculture.

Table 2 below shows the exact values in comparison to the corresponding animal- or plant-derived protein from conventional animal husbandry and agriculture.

Additionally, it should be noted that in the case of Solar Foods even a CO_2 negative production of Solein® is possible.

Table 2. Environmental Impact of the Selected Companies

Values compared to the corresponding animal-derived protein from conventional animal husbandry

	Dairy	**Beef**	**Plants**
Water	1% - 10%	0,16%-8%	1%
Land use	<1%	0,5%-4%	5%
Emission of ghg	3%-6%	0,5%-9%	20%
Energy use	40%		

own illustration (2024)

Value Proposition

The value propositions of PCA-derived alternative proteins and the products that incorporate them are highly versatile. Depending on the protein and product, they may vary and specialize. Below, the general value propositions proven to be applicable to all companies are presented. They are classified into categories Nutritional Advantage, Functional Performance, Production Advancements, Market Expansion, Pioneering and Innovation, Experience, and Sustainability. Each category additionally outlines customer segments targeted by the respective proposition. As previously mentioned, consumer segments are distinguished between producing clients, wholesale and retail clients, and end consumers.

- Nutritional Advantages of Precision Fermentation-Derived Proteins
  (customer segments: all):
  PCA-derived whey, casein, egg white, and heme proteins exhibit nutritional superiority compared to animal-derived proteins. This superiority stems from the absence of antibiotics, hormones, and cholesterol. Additionally, these proteins are rich in Branched-Chain Amino Acids (BCAAs), further contributing to their nutritional value.
- Functional Performance
  (customer segments: producing clients, end consumers):
  PCA-derived whey, casein, egg white, and heme proteins exhibit superior taste and texture compared to plant-based alternative proteins available in the market. Heme protein specifically imparts a savory and 'meaty' flavor (Paleo). In terms of texture and functionality, certain proteins, as the egg white protein by The Every Company, demonstrate clear blending capabilities in solutions.
- Production Advancements
  (customer segments: producing clients, wholesale, and retail clients):
  PCA-derived proteins and related ready-to-consume products offer a more stable and less risk-prone supply chain, attributed to their independence from weather conditions. Their pricing is also more stable due to their non-dependency on external factors. Solar Foods for instance states in their mission statement that Solein® is a protein 'that never ends' (Solar Foods) and thereby emphasizes the substantial reduction of risk in the Solein® supply chain.
- Market Expansion
  (consumer segments: producing clients, wholesale, and retail clients):
  The marketing of PCA-related products provides companies with the opportunity to expand their customer base and incorporate ESG considerations into their strategies. Additionally, there are extensive possibilities for local production of alternative protein, leading to a possible future reduction in the sourcing distances. Furthermore, PCA-derived protein holds the potential to not only achieve cost competitiveness but also potentially surpass the cost efficiency of animal- or plant-derived protein, especially following a scale-up in production.
- Pioneering and Innovation

(consumer segments: producing clients)
The selected companies are pioneers in several fields and possess the best expertise in the industry, such as the application of heme protein in plant-based substitutional products by Impossible Foods as the first in the market or the development of animal-free pepsin identical to pig-derived pepsin by The Every Company.

- Experience
  (consumer segments: end consumer):
  The value propositions of PCA-derived substitutional products extend beyond the product itself. They offer consumers the experience of enjoying animal-free dairy with identical taste and texture to animal-derived dairy, as well as the experience of consuming animal-free meat that is similar in taste and texture to animal-derived meat while being perceived as healthier. This of course is not the fact for Impossible Foods, who do use plant protein as their protein source.
- Sustainability
  (consumer segments: all):
  PCA-derived protein and related products use only a fraction of the resources compared to conventional farming and production. Therefore, they are far more sustainable, as detailed above in the Environmental Impact category.

Dependencies

Three critical dependencies arise for all selected companies. These include energy availability and energy price development, large-scale investments for scale-up, and consumer acceptance.

Energy is a crucial resource in the actual fermentation process. This entails significant dependence, both on its availability and its price. All examined companies are still in the early stages before a major scale-up of production, which is why the prices of alternative proteins are not yet competitive. Moving these into a competitive framework is one of the major challenges for all young PCA companies to establish themselves in the market. However, as the energy price is highly volatile, it plays a central role in the success of future market penetration.

As mentioned above, price parity is a crucial criterion for precision fermentation startups to establish themselves in the market. In chapter 2.3.4 of this paper, it has already been outlined that the market, as well as fundamental research and development for PCA-derived alternative proteins and food ingredients, is significantly driven by startups (Augustin et al. 2023). For the construction of production facilities and infrastructure to scale up the production of alternative proteins by startups, companies in the sector are heavily dependent on large-scale investments.

Lastly, the acceptance of the producing and retail customers, as well as end consumers, is, of course, crucial. Since the application of the technology in the food sector is entirely new, and customers have had no prior exposure to alternative precision fermentation derived protein, it is challenging to predict the level of acceptance. Anticipating and assessing the expected customer acceptance of the new proteins thus represents a limitation of this study.

However, the opportunity to mention a study conducted by Formo in collaboration with the University of Bath should not be overlooked. Five thousand individuals in Germany, Brazil, India, the UK, and the USA were surveyed regarding their willingness to try and buy animal-free PCA-derived cheese (Zollmann & Bryant 2021). The results indicate that over 78% of the surveyed participants would be willing to try animal-free PCA-derived dairy cheese, with over 70% willing to buy it. These percentages are significantly higher than previous research on meat alternatives has assumed. Consumers also found PCA-derived cheese to be more tasty than plant-based cheese alternatives. Furthermore, the research has found that among dietary aspects, vegetarian, vegan, and especially flexitarian respondents were most willing to buy PCA-derived cheese (Zollmann & Bryant 2021). Of course, this research also points out a potential conflict of interest for the authors. Zollmann is an employee of Formo at the time of conducting the study, and Bryant is the Director of Social Science at the Cellular Agriculture Society, which aims to promote cellular agriculture at the University of Bath. Therefore, the study is not factually generalizable to the sector or other similar products, but it may provide an indication of potential consumer acceptance.

Barriers

The market entry barriers are consistent among the examined companies and can be categorized as client education, obtaining regulatory approvals in crucial markets, and achieving economies of scale.

As highlighted earlier, gaining acceptance for the products from diverse customer segments is crucial for market penetration. Given that PCA-derived protein, both in its raw form and as finished products, is an entirely new concept in the market, educating all customers about its presence and subsequently communicating its value proposition is essential. This not only functions as a barrier to market entry but also incurs substantial costs.

Securing regulatory approvals is a fundamental requirement for entering any market. In the U.S. market, achieving GRAS status (Generally Recognized As Safe) is imperative for food additives (FDA 2023). In the EU and UK, obtaining approval from the EFSA (European Food Safety Authority) for novel food, additives, and non-GMO enzymes poses a substantial challenge (EFSA a) 2023). Following this, a potentially prolonged process ensues involving the European Commission and EU members, determining whether to authorize the product and establishing its conditions of use (EFSA b) 2023).

Finally, the established market participants' economies of scale present a substantial obstacle to market entry, given their ability to reduce prices to a competitive level through extensive production optimization processes (Ikerd 2023).

Investments, Key Partners and Scale-Up

The start-ups have attracted significant investments, ranging from tens of millions to $2 billion for Impossible Foods.

The three American companies have formed partnerships with major players in the traditional food industry. Nestle, Bel Group, Amazon Fresh, Amazon Buy Now, Ingredion, and AB InBev have either invested in or collaborated with American precision fermentation pioneers.

Solar Foods has been selected for the IPCEI program by the European Commission under its hydrogen core initiative, securing EU funding to expand its hydrogen fermentation facility.

Additional investors and partners are outlined in appendix two.

Of note is the establishment of the Precision Fermentation Alliance, a global industry coalition comprising leaders in precision fermentation and think tanks, established in 2023 (Precision Fermentation Alliance 2024).

Level of Commercialization

Three of the companies analyzed in the case study have already ventured into markets, introducing pilot products, conducting partner launches, or distributing their own products. All three of these companies are based in the United States. In contrast, none of the European companies have established a strong presence in any market. Solar Foods, the Finnish company, stands out by conducting a pilot partner launch in the Singaporean market.

The sole European market that has been penetrated to date is the UK. Impossible Food provides supplies to restaurants in the UK. However, direct supply to retailers or producers with products or food ingredients has not been established. This limitation is attributed to the absence of regulatory approval.

Price Parity

Detailed pricing information is exclusively available for consumer prices of companies already present in the market. The case study conducted price comparisons for Perfect Day and Impossible Foods, both of which are American companies and conventional brand and store-brand products found in Kroger[1] stores.

The findings reveal that precision fermentation-derived products were close to and over 200% the price of their conventionally produced counterparts in all cases. In a comparison with conventionally produced branded products, precision fermentation-derived items were 46%-116% more expensive in three out of four cases. Only the BelGroup X Perfect Day crem cheese nurishh was more expensive than the similar branded cream cheese by Laughing Cow. The results of the price comparisons including links to the products on the respective websites can be found in Table 3.

Table 3. Price Comparison

	Product type	Precision fermentation derived product	Conventional brand product	% pf/brand	Conventional Kroger store brand product	% pf/store brand
Perfect Day	Whey Potein Powder	39,80$/lb	27,27$/lb	**146%**	19,17$/lb	**208%**
	Cream cheese	0,69$/oz	0,79$/oz	**87%**	0,25$/oz	**276%**
Impossible Foods	Ground beef	0,75$/oz	0,56$/oz	**150%**	0,4$/oz	**188%**
	Chicken Patties	0,67/oz	0,31$/oz	**216%**	0,25$/oz	**268%**

own illustration (2024)

[1] Kroger is a food and drug retailer in the United States with a market share of 10% in the United States in 2017, second only to Walmart (Yahoo Finance 2024, Statista 2017)

5 Discussion

The case study results have been introduced and will now be employed to address the question: ‘Is Applied Precision Cellular Agriculture In The Food Industry A Potential Disruptive Innovation For The Food System?’ Therefore the characteristics associated with disruptive movements as described in the literature by Christensen and Markides will be analyzed, assessing the extent to which these features align with the companies and business models investigated in the case study.

In Chapter 2.3.2, it was proposed to analyze disruptive innovation through a contemporary approach that involves three categories. These categories encompass the disruptive technology originally defined by Christensen, disruptive business models, and, lastly, radical new-to-the-market product innovations (Markides 2006, Erwin 2004).
The conducted case study has highlighted the diversity of business models around precision fermentation-derived protein and enzymes, along with their product and value propositions. As a result, categorizing the disruptiveness of precision fermentation in food applications into one of the established types of innovations proves challenging. It is more appropriate to perceive the diversity of possibilities as a synthesis of various types of innovations collectively. Thus, it is recommended to link the specific types of innovations to the scrutinized business models and subsequently formulate a comprehensive conclusion by considering all aspects together.

5.1 PCA as a Disruptive Technology

Christensen does not provide specific criteria for defining a technology as disruptive (Danneels 2004). The fermentation method, as discussed in the introduction, has a long history spanning centuries. The method is traditionally employed on an industrial scale in the food industry for products like wine, beer, cheese, yogurt, and sourdough. Likewise, the technology underpinning PCA has an extensive history in various industries, notably the pharmaceutical sector. However, PCA has emerged as a groundbreaking innovation in the food sector only in the last four to five years. Especially the elaboration of PCA-derived protein as a 1-1 substitute to animal-derived protein is only recently emerging. The leading companies Perfect Day and The Every Company launched their first products in 2019 and 2020, which is when other companies only have been founded.

It remains uncertain whether a technology can inherently be considered disruptive or if its disruptiveness is contingent on the specific company involved (Erwin 2004).

Hence, it is plausible that the technology behind PCA may not inherently be classified as disruptive. Nevertheless, in its new application within the food sector, serving as an alternative protein or food additive for nutritional enhancement, it could potentially exert a disruptive influence.

5.2 PCA as a Disruptive Business Model

Markides defines business model innovation as the ‘discovery of a fundamentally different business in an existing business’ (Markides 2006, p.20). This implies a redefinition of what an existing product or service is, how its value is created, and what value it provides to the customer, rather than introducing an entirely new product or service.

The examination of the companies in the case study reveals only two instances where existing products are reinvented through the implementation of PCA in the supply chain: (1) the production of dairy substitute products and (2) the production of meat and fish substitute products. Distinguishing between them is reasonable, as dairy substitute products are significantly more similar to their animal counterparts compared to meat and fish substitute products. This similarity is attributed to proteins like whey and casein, simplifying the imitation of cow's milk compared to, for instance, a piece of meat.

Illustrated through examples like Formo's PCA-cheese and Perfect Day x Nestlé's ‘Cowabunga’ PCA-milk, these cases involve a redefinition of how value is created and what value is proposed. Similar to conventionally produced milk and cheese, alternatives from Formo and Perfect Day x Nestlé offer familiar value propositions such as taste, texture, and functionality. Additionally, they introduce value propositions like health benefits due to the absence of cholesterol, antibiotics, and hormones, along with a significantly reduced environmental impact and lower risk in the supply chain.

This represents the innovation in the business model, challenging not only manufacturers of animal-derived counterparts but also providers of plant-based dairy substitute products. PCA-derived products excel over plant-based alternatives not only in the mentioned value propositions but also in nutritional superiority and performance in taste, texture, and functionality.

This same principle applies to PCA-derived meat and seafood substitutes. While not being one-to-one substitutes for actual meat and fish due to differences in processing, they can be considered one-to-one substitutes for plant-based alternatives. Although they represent the same type of product fulfilling the same market need, the two substitute product types differ significantly in their supply chain and value proposition, similar to the differentiation described in the case of dairy substitute products.

The Impossible Beef by Impossible Foods, for instance, is plant-based like other existing beef alternatives, but distinguishes itself significantly in production through PCA, thus offering a much less risky and more easily scalable supply chain. As a result, Impossible Foods' products are less susceptible to supply shocks and price volatility of plant protein. In the case of Paleo, the innovation is similar to Nestlé's Perfect Day's Cowabunga and Formo's PCA-derived cheese. The proteins as ingredients in substitute products not only outperform plant-based substitutes in terms of supply chain, but also in taste, texture, and functionality. Additionally, Paleo offers a significantly greater variety by providing various heme proteins similar to pork, beef, tuna, lamb, and chicken, which contrasts with plant-based products typically based on soy, wheat, or pea protein.

Markides furthermore outlines two additional features alongside the redefinition of an existing product: (1) disruptive business models attract customers different from those targeted by established firms, and (2) they necessitate different value chains than those provided by established companies (Markides 2006).

The first aspect, attracting different customers than established firms, applies only to some extent. The targeted customers vary based on purchasing intent and the product category. PCA-derived food ingredients address diverse subsegments within the food industry. For instance, in the market for existing dairy, meat, and fish substitute products, those incorporating PCA-derived food ingredients predominantly attract customers who choose vegan and vegetarian products due to ethical and moral convictions. Considering the added value of improved performance, nutrients, and sustainability, the potential for disruption in this sector can be deemed quite high. This statement is further supported by the study conducted by Formo and the University of Bath mentioned in chapter 4.2. They conclude that surveyed participants following a vegetarian, vegan, and particularly flexitarian diet are most likely to be willing to try and purchase PCA-derived cheese (Zollmann & Bryant, 2021).

Examining another subsegment, the market for actual dairy, meat, and fish products, the shared customer base primarily comprises individuals who purchase these products – in pure or processed form – exclusively for their nutritional value or functionality. These customers may also turn to PCA-substitutes due to their consistent nutritional content and functionality. Thus, the potential for absolute disruption leading to the decline of established players in this subsegment may not be considered high. However, it is plausible that PCA-substitute products could coexist and capture a significant market share.

The case study highlights that the application of PCA-derived food ingredients extends beyond the production of substitute products. Four out of the six examined companies state that their alternative proteins and enzymes can be applied as food additives in various foods and beverages. Especially The Every Company serves this sector by offering their egg white protein that blends clearly in beverages. Also, Perfect Day has entered the sector by partnering up with MyProtein to launch a PCA-derived whey protein powder calles Whey FWRD in 2022. In this food additive sector, the largest addressed customer group comprises producing clients seeking nutritional enhancement for their products. In this case, customers of animal- and plant-derived food additives align one-to-one with customers of PCA-derived food additives, presenting significant competition potential. The potential disruptive impact of fermentation technology in this context is argued to be largely determined by the scale-up and price development of fermentation alternatives.

Concerning Markides' second feature, the transformation of the supply chain through innovative business models, it can be observed that the supply chain, along with its sustainability and risk factors, undergoes significant changes, as highlighted by all the companies examined in the case study. This makes the manufacturers and customers of PCA companies far less prone to price volatility and supply shocks.

5.3 PCA as a Disruptive Product Innovation

Radical new-to-the-market products represent innovations that did not exist in their current form before their development. In the conducted case study, three such cases emerged: (1) PCA-derived whey, casein, and muscle heme protein myoglobin, (2) functional PCA-derived egg substitute, and (3) PCA-derived Pepsin.

These products introduce pure substances into the market, suitable for processing by various companies as ingredients or food additives. The ‘radical newness’ of these products lies in their distinctive nutritional values, functionality, and, significantly, their impact on the supply chain. The difference between the pure protein and enzyme substances as radical new-to-the-market products and the meat, fish, and dairy substitute products is very small yet crucial. The former are seen as new-to-the-market products because the PCA-derived animal-imitating proteins and enzymes did not previously exist in the market. However, substitute products in general already existed, although plant-based. The latter are therefore classified as business model innovation since they do not differ in product or market need but solely in value proposition, ingredient list, and supply chain.

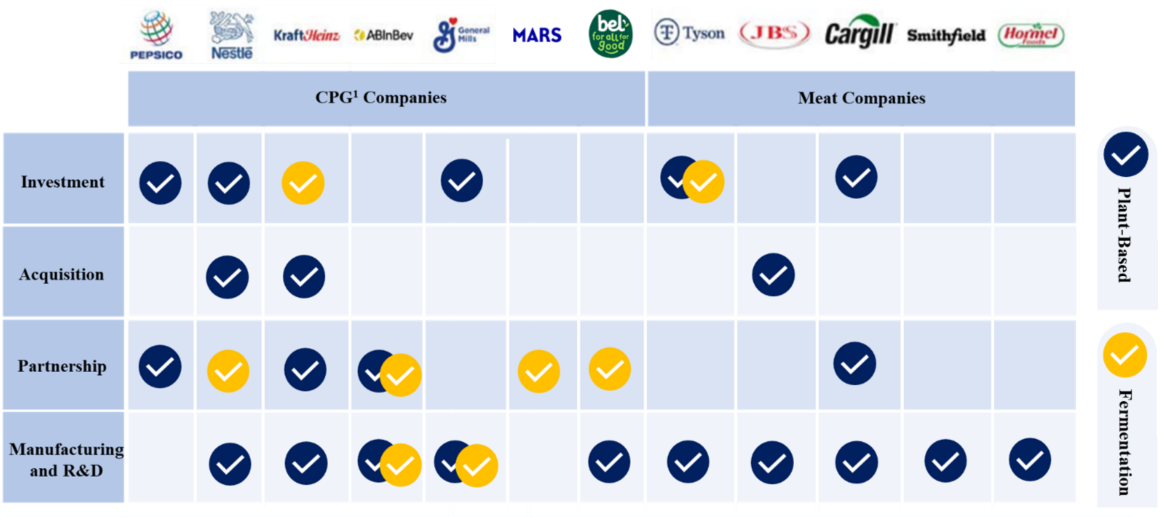
The unique value propositions align with those described in the section on business model substitute products, encompassing nutritional excellence, functionality, taste, texture, sustainability, and risk reduction in the supply chain.

What sets radical product innovations apart is their infrequent drive by demand (Markides 2006). Instead, they often result from a supply-push process (Markides & Geroski 2005). In a PCA context, this theory underscores a crucial aspect and main driver of the innovation - addressing human-induced climate change and environmental degradation.

The conducted case study ultimately identifies a primary innovation driver for all companies: the prevention of soil destruction and contribution to human-induced climate change through conventional agricultural practices. This driver is prominently mentioned in the mission statements of all of the analyzed companie, as for instance in Impossible Foods’ mission statement *'to make our global food system truly sustainable'*. This driver also fuels the transformation of conventional agriculture as outlined in chapter 2.1.3. (Bené et al. 2019). It is noteworthy that these drivers are not defined solely by the industry’s considerations for climate, environment, and biodiversity. They encompass the heightened risks within food supply chains associated with these issues. As emphasized in the introduction, the food system holds immense significance for humanity. We depend on the food system more than on most other industries. As seen in the case study, PCA utilizes only a minimal fraction of water, energy, and land resources, coupled with reduced greenhouse gas emissions. More exactly, it uses only less than ten per cent of all mentioned resources with Solar Foods being the most advanced in resource saving compared to beef and plant protein. If the system were to replace a significant portion of the protein sourced from conventional agriculture and livestock with precision fermentation-derived alternatives, it could potentially address and partially resolve the environmental, social, and governmental challenges outlined in Chapter 2.1.2.

The urgency in addressing these challenges, often labeled as a crisis by journalists and scientists, may serve as a catalyst for the supply-push process elucidated by Markides. Within markets emerging from a supply-push process, startups often play the role of early pioneers, pooling their expertise (Markides 2006). This pattern is evident in the PCA market as well. The role of later entrants is frequently assumed by larger players with sufficient capital and capacity to scale up from the niche market to the mass market (Markides 2006). To make a statement regarding the PCA market in this context, it is important to note that the market is still in an early development stage. As illustrated in the case study, most startups are still in the pilot phases, launching pilot products, often in collaboration with major partners such as Nestlé and Bel Group. For instance, Nestlé has introduced a PCA milk, while Bel Group has launched a PCA cream cheese, expanding their existing line of plant-based cream cheeses in the USA. The success and benefits of these pilot products, particularly in terms of supply chain efficiency and cost-effectiveness, may prompt well-capitalized corporations within the food industry to invest in PCA, playing a pivotal role in its scaling process (Bushnell et al. a) 2022). A broader examination of the entire Precision Cellular Agriculture (PCA) market landscape reveals that many other existing players in the conventional food sector are involved in PCA developments. Figure 3 illustrates the involvement of conventional food players in the PCA sector compared to the plant-based sector. When comparing their involvement in PCA with their involvement in plant-based solutions, it can be observed that plant-based solutions are significantly more prevalent, even though the market for plant-based alternative proteins is still growing (Bushnell et al. 2022 b)). This suggests that the involvement of well-capitalized conventional companies in PCA-derived alternative proteins will likely increase in the coming years. By attracting more capital through investors and establishing collaborations with well-established companies, the industry can overcome its most significant challenge, scaling, and achieve cost optimization. These investments and partnerships empower industry participants to fund research and development projects, expand their production capabilities, and improve overall efficiency. Involvement of established companies can therefore be viewed as a force multiplication for the industry (Bushnell et al. a), p.27, 2022).

Figure 3. CONVENTIONAL COMPANIES WITH INVOLVEMENT IN PCA-DERIVED AND PLANT-BASED ALTERNATIVE PROTEIN (Bushnell et al. 2022)



[1]Consumer packaged Goods
Own illustration based on Bushnell et al. (2022)

5.4 Other Considerations

The case study reveals that currently, primarily luxury products are being nutritionally enriched, and to date, only western, capital-rich markets are being targeted. The question arises whether this focus is sufficient to sustainably transform such a significant sector as the agricultural sector.

From an environmental standpoint, this approach makes sense because the richest 10% of the world are responsible for almost 50% of total lifestyle consumption emissions (Oxfam 2023). Simultaneously, LI and LMI countries are the most vulnerable to excessive greenhouse gas emission consequences. Considering the UN SDG to "end world hunger" (United Nations 2024), Solar Foods presents a promising approach. Extreme hunger and poverty are predominantly rural and often in drought-sensitive areas, hence areas with significant sun exposure (United Nations 2024). Solar Foods' main resources to produce nutritionally valuable protein are air and solar energy. Their solution can therefore be an extraordinarily promising approach to producing nutritious protein, independently from weather conditions in the areas most vulnerable to drought and lack of nutrition and therefore an approach to providing food security within a food system that becomes more vulnerable every day.

This aspect is also immensely important considering the study by Kinnunen et al. (2020) mentioned in chapter 2.1.2. It has been found that 26%-64% of the world's population cannot cover their needs of special crops within a distance of 1.000 km and is therefore largely dependent on functioning trade within the food system.

6 Conclusions

The present work outlines an analysis of Precision Fermentation Agriculture (PCA) as a potential disruptive innovation in the food system.

The food system, as widely recognized, is vulnerable to a variety of external and internal pressures, including disruptions in supply chains, political instability, price fluctuations, and trading complexities. However, climate change with droughts, soil degradation, and crop failures stands out as a primary concern, amplifying existing vulnerabilities. Within the system, agriculture and livestock farming most strongly contribute to climate change. Therefore, the food system can indeed be described as a self-destructive organism. Environmental degradation, including greenhouse gas emissions, deforestation, biodiversity loss, soil erosion, and water pollution are only some of the most impactful consequences of agriculture and livestock farming. These issues directly affect food security, particularly in LI and LMI countries. Livestock farming in particular consumes substantial resources in terms of water, land, and energy legitimated by the reason of meeting the global demand for protein, which is expected to increase exponentially with the rapidly growing world population. However, upon closer examination, livestock-derived protein with regard to total calorie provision is highly inefficient.

PCA offers an alternative to livestock farming for protein production. PCA-derived proteins, which are structurally identical to their animal counterparts, are produced entirely without livestock and land. They are cultivated in large fermentation tanks, using only a fraction of the resources water, energy, and land, compared to animal- or plant-derived proteins. This process can also be applied to fats, enzymes, and carbohydrates.

Precision Fermentation, the technology behind PCA, is a well-known method in the pharmaceutical industry. However, its application in the food industry, where PCA-derived food ingredients are used as additives or ingredients in a wide variety of food and beverages, has only been implemented in recent years. Various researchers and columnists regard PCA as one of the most promising solutions for the current vulnerability of our food system and for ensuring food security.

Since existing literature predominantly focuses on various technical aspects of PCA, it overlooks its potential as a disruptive innovation in the food system. To explore this potential, a case study of six relevant companies in the sector was conducted. The companies were analyzed based on 13 criteria regarding their business models and environmental impact. The findings were then used to assess the disruptive potential of the PCA companies in the food sector.

From an industrial perspective, the various PCA companies cannot all be equally classified as the same kind of disruptive innovation. The different facets of the offered products, channels of distribution, and targeted customer segments of the examined companies result in the disruptive potential being perceived as a blend of the three categories of disruptive innovation: innovative technology, innovative business models, and innovative new-to-the-market products.

Regarding PCA as an innovative technology, it is plausible that the technology itself may not inherently be classified as disruptive. Nevertheless, in its new application within the food sector, serving as an alternative protein or food additive for nutritional enhancement, it could potentially exert a disruptive influence.

PCA as an innovative business model, can be found in the areas of dairy, meat and fish substitutes. Here, the potential for disruption lies primarily in the value proposition of the PCA-derived substitutes compared to conventional plant-based substitutes. Particularly noteworthy is the superiority of PCA-derived substitutional products in terms of taste, texture, and nutrition over plant-based substitutional products. Another central value proposition is the independence of PCA-derived food ingredient production from nearly all external factors such as weather conditions and resource availability, thereby significantly reducing supply chain and price volatility risks. Given the increasing vulnerability of the food system to external and internal shocks, this differentiation in the business model is a promising indicator for a potential disruptive process in the dairy, meat, and fish substitute product sector.

In the area of new-to-the-market product innovation, PCA-derived food ingredients are considered as end products in their pure form. In this form, the products primarily target business customers. Here, the potential for a disruptive process based on the findings from the case study can be considered high. On the one hand, this is due to the superior value propositions as mentioned above. However, a far more decisive factor may be the typical supply-push process identified by Markides (2006).

From a sustainability and ethical point of view, the PCA method surpasses protein extracted from livestock or plants in numerous factors such as resource consumption, risk exposure, and greenhouse gas emissions. Especially compared to livestock, the ethical aspect related to animal welfare favors PCA-protein over animal-derived protein. Should the food system indeed reach a point in its vulnerability where conventional farming can no longer meet the needs of a rapidly growing world, PCA may be one of the few known options to ensure food security for the entire world population.

Chapter 2.1.2 of this work contains a series of enumerations of significant environmental and social damage caused by the conventional food system totaling around 700 words. Nevertheless, this chapter outlines only a very small fraction of the actual significant and negative impacts of our current food system and provides only an idea of the significance of the food crisis we may face in the near future. In order to tackle this major societal challenge, PCA is a more than promising option.

Of course, to carry out a truly disruptive process and advancement in the industry, PCA companies must address various dependencies and barriers, as found in the conducted case study. Since the PCA movement is largely pioneered by the start-up scene, scaling up production to reach price parity heavily depends on investors.

Another key factor in conquering the market is consumer acceptance. However, this aspect is out of the scope of this work and therefore presents a limitation of the work and a possible future field of study. Another important possible future field of study is the implication of a possible disruptive process of PCA companies in the food industry, especially in protein production.

Declaration of Use of Generative Artificial Intelligence Tools in the Bachelor's Thesis

I, Tamara Henle, a student of Business Administration and Management with International Mention (E4) at Universidad Pontificia Comillas, hereby submit my Bachelor's Thesis titled "Is Applied Precision Cellular Agriculture in the Food Industry a Potential Disruptive Innovation for the Food System?". I declare that I have utilized the generative artificial intelligence tool ChatGPT or similar AI tools solely within the context of the activities described below:

1. Brainstorming research ideas: Used to brainstorm and outline potential research areas.
2. Literary and language style corrector: To enhance the linguistic and stylistic quality of the text.
3. Translator: For translating texts from one language to another.

I affirm that all information and content presented in this thesis are the result of my individual research and effort, except where otherwise indicated and appropriate credits have been given (I have included proper references in the thesis and have explicitly stated the use of ChatGPT or other similar tools). I am aware of the academic and ethical implications of presenting non-original work and accept the consequences of any violation of this declaration.

Date: 03.20.2024 Signature:

Tamara Henle

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Appendix

Appendix 1: Results Obtained from the Case Study

	Micro Description	Mission	Main Innovation Driver	Product Portfolio	Channels and Customer Segments
Perfect Day	HQ: USA Protein(s) produced: ProFerm (whey protein) Segment: Dairy	build a more equitable, resilient, and diverse food system for all of us.'	Predominantly ethical concerns about sustainability in conventional farming Ethical concerns about animal welfare in conventional farming	ProFerm™ (highly functional whey protein, lactose-, cholesterol-, hormone- and pesticide-free).	B2B: dairy food manufacturers, dairy-substitute manufacturers, other food and beverage manufacturers
Formo	HQ: Germany Protein(s) produced: Casein, whey, new protein Segment: Dairy	we want to massively reduce the impact of protein consumption on our home (planet earth) and those we share it with.'	Predominantly ethical concerns about sustainability in conventional farming Ethical concerns about animal welfare in conventional farming	selection of PCA-cheeses	B2C/B2B -> unkown; cheese-alternative consumers, cheese consumers
Impossible Foods	HQ: USA Protein(s) produced: plant-based heme protein Segment: Meat	to make our global food system truly sustainable'	Predominantly ethical concerns about sustainability in conventional farming, Ethical concerns about animal welfare in conventional farming	a variety of ready-to-eat meat substitute products (beef burger patties, sausages, pork, meatballs, chicken and bowls)	B2B: supermarkets, restaurants, online delivery providers
Paleo	HQ: Belgium Protein(s) produced: animal heme protein Segment: Meat & Fish	we want to make meat and fish, but not kill animals to do it.'	Predominantly ethical concerns about animal welfare in conventional farming, Ethical concerns about sustainability in conventional farming	chicken heme protein beef heme protein pork heme protein tuna heme protein (mammoth heme protein)	B2B: meat related food manufacturers, meat-substitute manufacturers, other food maufacturers
The EVERY Company	HQ: USA Protein(s) produced: Egg protein Segment: Eggs	unlock powerful proteins designed for the future of every human, every animal, everywhere.'	Predominantly ethical concerns about sustainability in conventional farming, Ethical concerns about animal welfare in conventional farming	EVERY Protein (nature equivalent additive protein) EVERY Egg white (functional egg white substitute) EVERY Pepsin (enzyme 1-1 applicable to porcine pepsine (pork-derived) pepsine)	B2B: animal-food and beverage manufacturers, plant-based food and beverage manufacturers, blant-based substitutional product manufacturers
Solar Foods	HQ: Finland Protein(s) produced: Solein® (new protein) Segment: Others	disconnecting food production from agriculture to produce the world's most sustainable protein. Protein that will never run out.'	Predominantly ethical concerns about sustainability in conventional farming Ethical concerns about animal welfare in conventional farming	Solein® (natural protein originated from a natural, non-modified single cell organism)	B2B: animal-food and beverage manufacturers, plant-based food and beverage manufacturers, plant-based substitutional product manufacturers

	Protein Application	Environmental Impact	Key Resources
Perfect Day	Ingredient for PCA-dairy substitute products Nutritional boost in non-substitutional products Application possible in a wide range of products: PCA-cream cheese, PCA-sour cream, PCA-whipped topping, PCA-ice cream, PCA-barista milk, protein snacks, protein bars, ready to drink (rtd) beverages, ready to mix (rtm), PCA-yogurt, confectionary, and PCA-egg replacer)	% of respective resource required compared to the production of 1kg of whey protein by cow's milk water: 1% ghg: 3% non renewable energy use: 40%	Physical: fungal multicellular microflora, water, sugar, nutrients, energy, machinery and infrastructure
Formo	Ingredient exclusively for PCA-cheeses by Formo	% of respective resource required compared to the production of dairy cheese water: <10% land use: <1% ghg: 3-16%	Physical: microorganisms, plant-based fats, enzymes, water, energy, machinery and infrastructure
Impossible Foods	Ingredient exclusively for PCA-meat substitites by Impossible Foods	% of respective resource required to produce Impossible Beef compared to the production of conventional animal-derived beef: water: 8% land use: 4% ghg: 9%	heme production: Physical: energy, water, yeast, sugar, nutrients, machinery and infrastructure substitutional products production: respective additional plant based ingredients (predominantly soy
Paleo	Ingredient for chicken/beef/pork/tuna substitute products	no detailed indication; 'Precision fermentation uses only a fraction of the land, feedstock, energy and water required for animal farming, while emitting far less greenhouse gases. No need to use toxins, antibiotics or hormones.'	no indications, process applied: Precision Fermentation
The EVERY Company	Ingredient for egg substitute products, nutritional boost in non-substitutional products	no detailed indication, validation in process	Physical: Yeast, sugar, water, energy, machinery and infrastructure
Solar Foods	Ingredient for meat/dairy/fish substitute products nutritional boost in non-substitutional products	% of respective resource required compared to the production of 1kg of protein by beef and plants water: beef: 0,16 plants: 1% land use: beef: 0,5% plants: 5% CO2 emisisons: beef: 0,5% plants: 20% possible CO2-negative production of Solein	Physical: Air (carbon, nitrogen, oxygen, hydrogen), nutrients (phosphorus, calcium), renewable energy, machinery and infrastructure

	Value Proposition	Dependencies	Barriers	Investments, Key Partners and Scale-Up
Perfect Day	ProFerm™: superiority of nutrients compared to animal whey protein, superiority in taste and texture to plant-based alternative protein, highest BCAAs in the market, blends clearly in solutions, more stable and therefore less risk-prone supply chain, reach of new audiences, integration of ESG considerations	energy availability, energy price development, large-scale investments for scale up, consumer acceptance	economies of scale, client education	Investment since 2015: >840MM$ key partners: Nestlé (PCA-milk), Bel Group (PCA-cream cheese), Mars (PCA-milk chocolate), MyProtein (PCA-whey protein powder), Coolhaus (PCA-ice cream), Renewal Mill (PCA-baking mixes and cookies), Bored Cow (PCA-milk), Brave Robot (PCA-ice cream), juice land (protein fruit smoothie), Nick's (PCA-ice cream), striev nutrition (PCA-milk hybrids), Member of the Precision Fermentation Alliance
Formo	Experience of consuming animal free dairy identical in taste and texture to animal-derived dairy lactose, hormone, antibiotic free as opposed to conventionally produced animal-derived cheese	energy availability, energy price development, large-scale investments for scale up, consumer acceptance	regulatory approvals to emerge in non-EU markets, economies of scale, client education	Investment: 54MM$ Investors: EQT, Agronomics, Good Seed Ventures, Grazia Equity, M Ventures, Elevat3 Capital, Stray Dog Capital, CPT Capital, Lionheart Ventures, Happiness Capital, and Albert Wenger.
Impossible Foods	firsts to apply heme protein in plant-based substitutional products; savory, 'meaty' flavour; Experience of consuming animal free meat similar in taste and texture to animal-derived meat and at the same time more healthy; antibiotic-free, hormone-free, cholesterol-free, comparable nutritional values to meat protein	energy availability, energy price development, consumer acceptance	regulatory approvals in key markets like EU pending, economies of scale, client education	total investment of 2 billion $; key partnerships: Amazon fresh and Amazon buy now (delivery services), several restaurants and stores in up to 11 countries
Paleo	most advanced heme platform on the market, only extracellular heme platform on the market (pure protein without yeast), nutritional values equal to meat and superior to plant-protein in iron	energy availability, energy price development, large-scale investments for scale up, consumer acceptance	regulatory approvals in key markets like USA (GRAS-Status), EU and UK pending, acceptance as supplier by leading brands = client education, economies of scale	recently closed a 12M funding series A venture round
The EVERY Company	superior performance in texture, unction and taste compared to plant-based protein alternatives, identical performance compared to animal-derived proteins, gluten free, cholesterol free, kosher, halal pioneers in animal-ree pepsin identical to pig-derived pepsin (superior effectiveness and less prone to risk)	energy availability, energy price development, large-scale investments for scale up, consumer acceptance	regulatory approvals in key markets like EU and UK pending, acceptance as supplier by leading brands=client education, economies of scale	233 MM$ by investprs to make worlds first animal free liquid egg (Grupo Bimbo and AB inBev (worlds largest brewer), member of the Precision Food Alliance, Partnership with Bakery (Chantal Guilon) to commercially use EVERY Eggwhite in their vegan macarons; Key Partenrs: Ingredion (global ingredient solutions provider): Distribution, AB Inbev (world's largest brewer) & BioBrew (precision fermentation company by AB Ibvev) :scale up development, Grupo Nutresa (leading processed food company in colombia): Collaboration Agreement
Solar Foods	Solein*: carbon-neutralpossibly carbon-negative, growth is possible independently from weather conditions, superior nutritional profile, functional versatility, stable price due to non-dependency of external factors, cost competitive, unlimited possibility to local production	energy availability, energy price development, large-scale investments for scale up, consumer acceptance	regulatory approvals in key markets like USA (GRAS-Status), EU and UK pending, acceptance as supplier by leading brands=client education, economies of scale	first factory opening in Vantaa, Finland in H1, 2024 for first commercial scale-up, large investors: Fazer, EU (IPCEI), oversubscribed funding rounds, clients: total:20; most important clients: Fazer, Ajinomoto

	Level of Commercialization	Non-GMO	Price Parity
Perfect Day	active markets: 3 (USA; Hong Kong, Singapore), phase: partner products launched, GRAS- and 'no-objections'-letter in USA, permits in Hong Kong and Singapore	YES	Krogers: Bel Brands Nurishh Incredible Dairy: 0,69$/oz ; Krogers cream cheese 0,25$/oz ; Bel Brands Laughing Cow cream cheese: 0,79$/oz Whey protein powder by MyProtein: WheyForward by Perfectday: 14,3$/lb ; regular whey protein by MyProtein: 14,2$/lb
Formo	active markets: 0, phase: pilot phase	YES	no information available
Impossible Foods	active markets: various several product launches made; commercially available for custoemrs in several restaurants in USA + 5 countries including Canada and UK, several stores in USA + 11 countries (excluding Canada and UK)	NO	Kroger: Impossible Ground Beef: 0,75$/oz ; Private Selecton Angus Ground Beef: 0,5$/oz ; Kroger store brand: 0,4$/oz
Paleo	active markets: 0 phase: pilot	YES	no information available
The EVERY Company	active markets: 1 (USA), partner product launches are partially available, EVERY Pepsin is available and distributed through Ingredion	YES	no information available
Solar Foods	active markets: 1 (singapore) phase: pilot phase	YES	no information available