



Derleme Makalesi – Review Article

Geliş Tarihi / Received: 20/08/2025

Kabul Tarihi / Accepted: 19/10/2025

Yayın Tarihi / Published: 30/11/2025

Developments in Calcium Propionate Production for Sustainability

Sürdürülebilirlik İçin Kalsiyum Propiyonat Üretimindeki Gelişmeler

Muhammed Bora Akın^{1*}

^{1*} Çankırı Karatekin University/ Faculty of Engineering/ Department of Chemical Engineering/ Çankırı, Türkiye, mboraakin@gmail.com/ mbakin@karatekin.edu.tr/ <https://orcid.org/0000-0003-3841-1633>

Ethical Statement: It is declared that scientific and ethical principles were followed during the preparation of this study and that all studies used are stated in the bibliography.

Artificial Intelligence Ethical Statement: The author(s) declares that artificial intelligence was used solely for translation and language editing purposes in the preparation of this manuscript, and that full responsibility for the content rests with the author.

Conflicts of Interest: The author(s) has no conflict of interest to declare.

Grant Support: The author(s) acknowledge that they received no external funding to support this research.

License: CC BY-NC 4.0

Etik Beyan: Bu çalışmanın hazırlanma sürecinde bilimsel ve etik ilkelere uyulduğu ve yararlanılan tüm çalışmaların kaynakçada belirtildiği beyan olunur.

Yapay Zeka Etik Beyanı: Yazar bu makalenin hazırlanmasında yapay zekânın yalnızca çeviri ve dil düzenleme amaçlı kullanıldığını ve içeriğin tüm sorumluluğunun yazara ait olduğunu beyan etmektedir.

Çıkar Çatışması: Çıkar çatışması beyan edilmemiştir.

Finansman: Bu araştırmayı desteklemek için dış fon kullanılmamıştır.

Lisans: CC BY-NC 4.0

Developments in Calcium Propionate Production for Sustainability

ABSTRACT

Calcium propionate is widely used as a preservative in both the food and feed industries due to its antifungal effectiveness, safety, and nutritional properties. Traditionally, it is produced through the neutralization of propionic acid with calcium hydroxide. This method is economically advantageous and technically straightforward. However, growing concerns regarding sustainability and environmental performance have led to the search for greener production approaches. Current research focuses on methods such as chemical synthesis, direct neutralization, biotechnological fermentation, electrochemical synthesis, waste valorization, and enzymatic conversion. This review compiles data from scientific and technical literature and examines these methods by considering key criteria, such as scalability, economic feasibility, environmental impact, process complexity, and product quality. The findings reveal that chemical synthesis and direct neutralization remain the most practical and cost-effective methods. However, biotechnological fermentation and waste valorization approaches clearly demonstrate the highest levels of sustainability and environmental performance, indicating significant progress toward green manufacturing. Nevertheless, although fermentation and enzymatic conversion processes reduce environmental impact and support low-carbon, circular production models, they still face challenges in terms of efficiency and scalability. Additionally, electrochemical synthesis and waste valorization methods are promising due to their energy efficiency and potential for resource recovery, while enzymatic methods stand out for their high product selectivity and mild reaction conditions. Overall, this study has been written as a literature-based decision support tool for anyone interested in calcium propionate production, aiming to identify or develop more sustainable, resource-efficient, and environmentally responsible calcium propionate production technologies.

Keywords- *Calcium Propionate, Sustainable Production, Green Chemistry, Fermentation, Enzymatic Conversion, Waste Valorization*

Highlights

- This study claims that a comparative evaluation of calcium propionate production methods can provide a decision-support framework for selecting sustainable and feasible strategies.
- Six production routes—chemical synthesis, direct neutralization, biotechnological fermentation, electrochemical synthesis, waste valorization, and enzymatic conversion—were systematically compared.
- The evaluation criteria included scalability, cost-effectiveness, environmental impact, process complexity, and product purity.
- Chemical synthesis was identified as the most scalable and economical option, but it showed major environmental shortcomings.
- Biologically driven approaches, such as fermentation and enzymatic conversion, emerged as promising alternatives for future low-carbon and circular production models.

Sürdürülebilirlik İçin Kalsiyum Propiyonat Üretimindeki Gelişmeler

ÖZ

Kalsiyum propiyonat, antifungal etkinliği, güvenliği ve besleyici özellikleri sayesinde koruyucu olarak hem gıda hem de yem endüstrilerinde yaygın olarak kullanılır. Geleneksel olarak, propiyonik asidin kalsiyum hidroksit ile nötralizasyonu yoluyla üretilir. Söz konusu yöntem ekonomik ve teknik açıdan basittir. Ancak, sürdürülebilirlik ve çevresel performans endişeleri, daha çevreci üretim arayışlarına neden olmaktadır. Araştırmalar kimyasal sentez, doğrudan nötralizasyon, biyoteknolojik fermantasyon, elektrokimyasal sentez, atık değerlendirme ve

enzimatik dönüşüm yöntemleri üzerine yoğunlaşmaktadır. Bu derleme, bilimsel ve teknik literatürdeki verileri bir araya getirmekte ve üzerine yoğunlaşılacak yöntemleri ölçeklenebilirlik, ekonomik uygulanabilirlik, çevresel etki, süreç karmaşıklığı ve ürün kalitesi kriterlerini göz önüne alarak incelemektedir. Yapılan çalışma sonucunda, kimyasal sentez ve doğrudan nötralizasyonun hâlâ en uygulanabilir ve maliyet açısından en uygun yöntemler olduğunu ortaya koymaktadır. Bununla birlikte biyoteknolojik fermantasyon ve atık değerlendirme yaklaşımlarının en yüksek sürdürülebilirlik ve çevresel performansı sergilemekte olduğu aşikardır. Bu durum yeşil üretim yönünde önemli ilerlemeler olduğunu göstermektedir. Ancak, fermantasyon ve enzimatik dönüşüm süreçleri, çevresel yükü azaltıp, düşük karbonlu, döngüsel üretim modellerini desteklese de, verimlilik ve ölçeklenme açısından zorluklarla karşılaşmaktadır. Ayrıca, elektrokimyasal sentez ve atık değerlendirme yöntemleri, enerji verimliliği ve kaynak geri kazanımı sayesinde umut verici proseslerdir. Enzimatik yöntemler, ise yüksek ürün seçiciliği ve yumuşak reaksiyon koşulları ile öne çıkmaktadır. Genel olarak, bu çalışma kalsiyum propiyonat üretimi ile ilgilenen herkes için daha sürdürülebilir, kaynak verimli ve çevresel açıdan sorumlu kalsiyum propiyonat üretim teknolojilerinin belirlenmesi veya geliştirilmesi amacıyla literatür temelli bir karar destek aracı olarak hazırlanmıştır.

Anahtar Kelimeler- *Kalsiyum Propiyonat, Sürdürülebilir Üretim, Yeşil Kimya, Fermantasyon, Enzimatik Dönüşüm, Atık Değerlendirme*

Öne Çıkanlar

- Bu çalışma, kalsiyum propiyonat üretim yöntemlerinin karşılaştırmalı değerlendirilmesinin, sürdürülebilir ve uygulanabilir stratejilerin seçimi için bir karar destek çerçevesi sunabileceğini ileri sürmektedir.
- Altı üretim yolu—kimyasal sentez, doğrudan nötralizasyon, biyoteknolojik fermantasyon, elektrokimyasal sentez, atık değerlendirme ve enzimatik dönüşüm—sistemik olarak karşılaştırılmıştır.
- Değerlendirme kriterleri arasında ölçeklenebilirlik, maliyet etkinliği, çevresel etki, süreç karmaşıklığı ve ürün saflığı yer almıştır.
- Kimyasal sentez en ölçeklenebilir ve ekonomik seçenek olarak belirlenmiş, ancak önemli çevresel eksiklikler göstermiştir.
- Fermantasyon ve enzimatik dönüşüm gibi biyolojik tabanlı yaklaşımlar, gelecekte düşük karbonlu ve döngüsel üretim modelleri için umut verici alternatifler olarak öne çıkmıştır.

I. INTRODUCTION

Calcium propionate, a salt of propionic acid ($\text{CH}_3\text{CH}_2\text{COOH}$), is a versatile compound with a broad spectrum of applications, particularly in food preservation and animal nutrition (Figure 1). As a food additive, calcium propionate, widely recognized under the code E282, is highly effective in inhibiting mold and certain bacterial growth, which is vital in extending the shelf life of perishable products such as bread, pastries, and dairy items. Its antimicrobial action is primarily attributed to the dissociation of propionic acid under acidic conditions, which disrupts microbial cell metabolism [1-3].

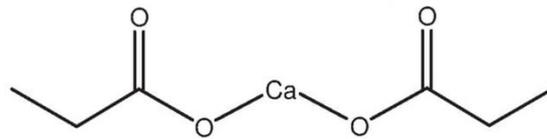


Figure 1. Chemical structure of calcium propionate

According to data from maximizemarketresearch.com [4], the global market outlook clearly indicates that the Global Calcium Propionate Market is expected to experience significant growth during the 2024–2030 forecast period, with a compound annual growth rate (CAGR) of 6.6%. The market was valued at USD 377.61 million in 2023, and the same data suggest that it is projected to reach USD 590.68 million by 2030. These indicators clearly reflect the rising demand for calcium propionate. The increasing demand for calcium propionate largely stems from its extensive use in the food industry, supported by its strong antimicrobial activity [5]. Its proven effectiveness in bakery, dairy, meat, and seafood products has made it one of the most preferred additives for extending shelf life and preventing microbial spoilage [3, 5]. Beyond its role as a food preservative, calcium propionate also enhances feed stability and safety, thereby contributing to animal nutrition. As demonstrated by

dos Santos et al. (2022) and Zhang et al. (2020), this role also helps improve livestock performance [6, 7]. In addition, in pharmaceutical formulations, its antimicrobial properties and chemical stability ensure high compatibility with certain active ingredients [5]. Consumer preferences have increasingly shifted toward clean-label and health-oriented product development approaches [4, 5, 7]. This trend has further strengthened the position of calcium propionate as a versatile and commercially valuable compound across various industries.

Recent research has demonstrated that calcium propionate suppresses microbial growth by interfering with fungal cell wall formation, showing particular efficacy against mold genera such as *Aspergillus* and *Penicillium* [8]. Supporting this, Black et al. (2013) [1] revealed that propionate derivatives compromise fungal membrane integrity during sourdough fermentation. Similarly, Sequeira et al. (2017) reported that calcium propionate maintains prolonged antifungal activity against *Penicillium* and *Aspergillus* species in cellulose-based substrates [9]. Taken together, these studies confirm the broad-spectrum and adaptable antimicrobial potential of calcium propionate across various biological systems [2].

While its antimicrobial activity is well recognized, calcium propionate also offers notable nutritional advantages as a valuable source of calcium. Calcium is an essential mineral required for key physiological processes, including bone development, muscle contraction, blood coagulation, and nerve signal transmission [10, 11]. Thus, the inclusion of calcium-based additives such as calcium propionate in food fortification programs enhances both food safety and nutritional value, particularly benefiting populations susceptible to calcium deficiency [2, 5, 10]. Pampaloni and Brandi (2022) noted that calcium-containing compounds can lower osteoporosis risk and play a vital role in maintaining bone health in calcium-deficient diets [10]. Likewise, Huey et al. (2021) reported that calcium compounds, including calcium propionate, improve calcium absorption and bioavailability [11]. In this regard, Yang et al. (2023) pointed out that the environmentally sustainable production of calcium propionate provides a safe, multifunctional additive that combines antimicrobial effectiveness with nutritional fortification potential [5].

Compared to conventional calcium sources such as calcium carbonate and calcium citrate, calcium propionate demonstrates superior bioavailability. Its excellent solubility and chemical stability enhance gastrointestinal absorption, making it effective in both acidic and neutral food environments. Huey et al. (2021) reported that highly soluble calcium salts significantly enhance calcium absorption, and Sorathiya et al. (2025) emphasized the dual function of calcium propionate in food systems as both a preservative and a nutritional fortifier. These complementary and beneficial characteristics have promoted its inclusion in diverse dietary formulations aimed at improving bone health, particularly for children and older adults who are more prone to calcium deficiency [2, 11].

Multiple experimental studies have explored the antifungal activity of calcium propionate in depth. One investigation assessed its inhibitory effects on several mold species, including *Aspergillus flavus*, *A. versicolor*, *A. niger*, *Penicillium citrinum*, *P. verrucosum*, *Cladosporium macrocarpum*, *Fusarium semitectum*, *Mucor racemosus*, and *Rhizopus oligosporus*, cultivated on Potato Dextrose Agar at pH values of 5, 6, and 7. The results showed that calcium propionate exhibited the strongest antifungal activity at pH 5. Moreover, increasing its concentration from 1 g/L to 2 g/L further improved mold inhibition. These observations align with those of Black et al. (2013), who reported similar antifungal behavior in sourdough fermentation systems, and Sequeira et al. (2017), who demonstrated the long-term inhibition of *Penicillium* and *Aspergillus* species in cellulose-based matrices [1, 9]. Another study investigated the influence of calcium propionate on mold growth in real feed materials. In this experiment, sterilized corn samples with 14% moisture were supplemented with calcium propionate at concentrations of 1 g/L, 2.5 g/L, and 4 g/L, and stored at 25 °C. The results indicated that calcium propionate delayed mold development during storage, though complete inhibition was not achieved at the tested concentrations over extended periods [5, 12]. Similarly, Yang et al. (2023) reported that the antifungal effectiveness of calcium propionate tends to decrease with prolonged storage [5]. Despite these promising outcomes, the use of E282 in human food remains relatively limited. Although its preservative function is well documented, its application in food products is less widespread than in animal feed. This restriction largely results from regulatory limitations and a growing consumer preference for products containing fewer additives. Regulatory bodies such as the European Food Safety Authority (EFSA) have confirmed the safety of calcium propionate and established acceptable daily intake levels; however, consumer perception continues to be a determining factor in its limited dietary use [13, 14]. Furthermore, as the food industry increasingly adopts natural preservation methods and ingredients, the reliance on synthetic preservatives such as E282 has diminished. With consumer demand shifting toward “clean-label” products that minimize artificial additives, manufacturers are progressively adopting more natural and sustainable preservation approaches [5, 13]. Table 1 provides a summary of the principal functions of E282 in the food industry.

Table 1. Overview of calcium propionate applications in food products

Food Type	Purpose	Notes
Bread and Baked Goods	Prevents mold growth and extends shelf life	Commonly found in sliced and packaged bread, as well as tortillas, flatbreads, and cakes.
Certain Cheese Varieties Pastry Products	Contains propionic acid as a natural preservative Preservative for chemically leavened products, preventing mold and spoilage	Naturally present in aged cheeses. Includes items like cakes, cookies, and pastries.
Dairy Products & Processed Meats	Prevents mold growth, spoilage, and microbial contamination in milk-based and meat products	Used in processed cheeses, yogurts, sausages, smoked meats, and deli products.

A. Applications in Animal Nutrition

Calcium propionate is predominantly associated with animal feed because of its remarkable effectiveness in controlling mold and bacteria, which is particularly critical in large-scale feed production systems. This compound acts as a preservative, inhibiting the growth of spoilage microorganisms and thereby extending the shelf life of animal feed while preserving its nutritional value. Numerous studies have consistently demonstrated that its inclusion in ruminant diets improves both feed stability and overall animal performance [15, 16]. The importance of maintaining microbial control in feed cannot be overstated, since contamination by mold and bacteria poses serious risks to livestock health and productivity; in fact, such contamination can lead to substantial economic losses and animal health disorders [8, 15].

Research has shown that beyond its well-known preservative function, the inclusion of calcium propionate in animal feed formulations enhances product stability, reduces spoilage, improves nutrient efficiency, and minimizes losses [6, 17]. Beyond its preservative role, its dietary supplementation has been found to improve metabolic responses and enhance growth performance, particularly under stressful or nutrient-deficient conditions [18]. Such applications represent a biotechnology-based approach that supports sustainable production while promoting animal development [19]. In ruminant species (e.g., cattle and sheep), calcium propionate plays a central role in metabolism as the direct precursor of propionate, one of the main volatile fatty acids (VFAs) produced during ruminal fermentation. After absorption through the rumen epithelium, propionate is transported to the liver, where it serves as a key substrate in gluconeogenesis, the metabolic pathway responsible for endogenous glucose synthesis. This process is particularly crucial for lactating and rapidly growing animals, whose high glucose requirements are essential for milk production and tissue development [7, 20, 21].

Several studies have confirmed that calcium propionate supplementation increases the energy density of the diet, improves feed efficiency, and maintains rumen pH balance and fermentation stability without causing carbohydrate overload. Zhang et al. (2022) reported that in early-lactation dairy cows, dietary supplementation with calcium propionate not only increased milk yield but also reduced the risk of metabolic disorders such as ketosis during the postpartum period [15]. Ketosis remains a major metabolic disorder in high-producing dairy cows. This condition occurs when the energy demands of lactation exceed dietary intake, leading to excessive mobilization of body fat and accumulation of ketone bodies in the bloodstream. Calcium propionate plays a dual role in this context: it both supports hepatic glucose synthesis and helps regulate calcium homeostasis. Wang et al. (2022) reported that calcium propionate reduces fatty acid-induced mitochondrial stress and apoptosis in liver cells, indicating its therapeutic potential in preventing ketosis [22]. During microbial fermentation in the rumen, enteric methane emissions represent one of the largest sources of greenhouse gases in livestock production systems. These emissions primarily originate from methanogenic archaea, which utilize hydrogen to convert carbon dioxide into methane. Calcium propionate has the potential to mitigate this process by acting as an alternative hydrogen sink. By promoting propionate formation, it redirects ruminal fermentation away from acetate production, which favors methane generation, and toward propionate production, which suppresses methanogenesis. This metabolic shift reduces the hydrogen available for methane synthesis, thereby lowering methane emissions in ruminants [7, 23]. In a notable study, Roskam et al. (2024) reported that dietary supplementation with calcium-based additives in beef cattle increased propionate concentrations while decreasing methane emissions, demonstrating a favorable shift in rumen fermentation dynamics [24]. Taken together, these results indicate that calcium propionate is an integral component of sustainable livestock production strategies, playing a key role in balancing productivity, animal health, and environmental responsibility. Alam et al. (2014) reported that calcium propionate significantly reduced mold formation and aflatoxin production in broiler starter feed, emphasizing the value of this compound as a natural preservative [25]. Similarly, the study by Zhang et al. (2020) demonstrated that calcium propionate can be effectively used in dairy cattle feed to reduce mycotoxin exposure and nutrient loss during storage [7]. In another study, Whitlow and Hagler (2005) confirmed the strong antifungal properties of organic acids such as calcium propionate, highlighting their role in maintaining feed hygiene by preventing the growth of spoilage microorganisms [26]. Furthermore, calcium propionate helps reduce the amount of hydrogen required for methanogenesis by shifting rumen fermentation toward propionate production, thereby lowering enteric methane emissions and reducing the overall carbon footprint [27]. Despite the growing number of studies supporting these benefits, most existing research has primarily focused on the functional performance and conventional chemical synthesis routes of calcium propionate, while the

environmental impacts of its production processes have received comparatively little attention. Only a few studies have compared different production pathways in terms of sustainability, scalability, and process efficiency, and even fewer have employed comprehensive analytical frameworks such as Life Cycle Assessment (LCA) or Techno-Economic Analysis (TEA) to evaluate their overall environmental impact. In particular, renewable-resource-based and waste-valorization production approaches remain largely unexplored in the scientific literature, despite their potential to enhance environmental performance and reduce production costs. To address these knowledge gaps, this review presents a comparative evaluation of six distinct calcium propionate production routes, including chemical synthesis, direct neutralization, biotechnological fermentation, electrochemical synthesis, waste valorization, and enzymatic conversion, with a particular emphasis on their environmental performance, technological feasibility, and alignment with green manufacturing and circular economy principles. Figure 2 summarizes the multifaceted roles of calcium propionate in livestock management.



Figure 2. Key benefits of calcium propionate in animal husbandry

II. METHODS FOR THE PRODUCTION OF CALCIUM PROPIONATE

The production of calcium propionate can be achieved through several distinct methods, each tailored to specific industrial, economic, and environmental needs [5]. While the majority of calcium propionate is produced via traditional chemical synthesis, alternative methods are gaining attention for their sustainability and potential economic benefits.

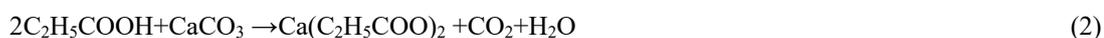
A. Direct Neutralization

Direct neutralization involves a single-step reaction between propionic acid and a calcium base, typically calcium hydroxide ($\text{Ca}(\text{OH})_2$) or calcium carbonate (CaCO_3), to produce calcium propionate under mild conditions (40–80 °C) [28–30]. This method is widely used in industrial settings due to its operational simplicity, absence of complex catalysts, and minimal equipment requirements. It is also economically advantageous, relying on low-cost, abundant raw materials such as limestone or eggshell-derived CaCO_3 , and requiring relatively low energy input. Environmentally, the process is favorable, as it generates only water or carbon dioxide as by-products, depending on the base employed [28–30]. However, its dependence on externally sourced propionic acid, which is mainly produced from petrochemical feedstocks, raises sustainability concerns [31].

The choice of neutralizing agent plays a decisive role in determining the reaction kinetics, product yield, and environmental impact. $\text{Ca}(\text{OH})_2$ is generally preferred for high-efficiency production because of its higher solubility and stronger basicity, which promote rapid and complete neutralization with propionic acid [29, 30]. The reaction is exothermic, allowing operation at lower external energy inputs:



In contrast, CaCO_3 reacts more slowly due to its lower solubility in water, making the reaction less efficient in terms of time [30, 32]. The neutralization mechanism involves the decomposition of CaCO_3 into calcium ions (Ca^{2+}) in acidic conditions, producing CO_2 as a side-product:



The evolution of CO₂ can make process control more difficult, particularly in continuous or large-scale systems, as it may cause foaming or pressure build up, which requires proper venting or controlled acid addition [29, 30].

From a process standpoint, Ca(OH)₂ offers faster reaction rates, higher product purity, and minimal by-products, which simplifies downstream purification. However, excessive dosing may lead to precipitation or unwanted alkalinity, requiring pH adjustment [13]. On the other hand, CaCO₃ offers milder buffering behavior, helping maintain stable reaction pH and minimizing the risk of over-neutralization [33]. Although it is less caustic and safer to handle, its low reactivity demands longer processing times and mild heating (50–80 °C) to enhance dissolution and reaction completion [27, 30, 34].

In terms of sustainability, CaCO₃ is more environmentally benign and naturally abundant, making it attractive where raw material cost and availability are priorities [33, 35]. Nevertheless, CO₂ emissions generated during neutralization can offset some of these advantages in large-scale systems [31]. Conversely, Ca(OH)₂ provides superior kinetics but has a higher carbon footprint in its production, as it is obtained through CaCO₃ calcination at elevated temperatures, releasing CO₂ [36, 37].

Operationally, Ca(OH)₂-based neutralization typically occurs at ambient to moderate temperatures (25–50 °C) and pH 8–10, with near-instantaneous neutralization and high yield [30]. The CaCO₃ route, while slower, can still be practical under optimized conditions, producing yields up to 86% depending on temperature, acid concentration, and particle size [29, 30]. Industrially, both batch and continuous stirred-tank reactors (CSTRs) are used, with Ca(OH)₂ favored for high-throughput operations requiring rapid conversion, while CaCO₃ is applied where sustainability and raw material availability are prioritized [28, 38, 39].

In summary, Ca(OH)₂ provides faster kinetics, higher purity, and reduced downstream processing, which makes it suitable for large-scale, efficiency-oriented production. CaCO₃, in contrast, provides a safer and more sustainable alternative, though at the cost of slower reactions and additional CO₂ handling requirements. The selection between the two depends on specific industrial goals, balancing reaction efficiency, environmental performance, and economic feasibility [31].

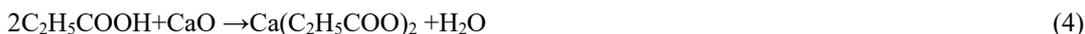
B. Chemical Synthesis

Chemical synthesis of calcium propionate typically involves the production of propionic acid from petrochemical or renewable feedstocks, followed by its reaction with a calcium source. A common route for propionic acid synthesis is hydrocarboxylation of ethylene:



The synthesized propionic acid is subsequently neutralized with a calcium base, following a process similar to direct neutralization [31]. This chemical synthesis route offers strong integration potential with other industrial processes, enabling the in-house production of propionic acid from either petrochemical or renewable sources. Such flexibility allows for better control over feedstock selection and process optimization [40]. However, this approach is more complex, as it involves multiple reaction steps and the formation of intermediate compounds. It also demands higher energy input, often requiring elevated temperatures, pressures, and the use of specialized catalysts [33]. Moreover, the environmental footprint of chemical synthesis can vary considerably, as it may lead to waste generation or emissions depending on the chosen feedstock and overall process configuration [41].

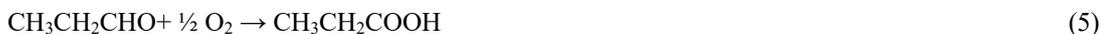
Some methods outside of petrochemical alternatives include propionaldehyde oxidation or the use of CaO as examples. The use of CaO in calcium propionate production provides an alternative and sustainable approach. CaO, at high temperatures, forms Ca(OH)₂ or CaCO₃, which later reacts with propionic acid in an acidic environment, facilitating the synthesis of calcium propionate [30]. The strong basic properties of CaO allow it to function effectively as a catalyst in transesterification reactions, where it interacts with alcohol-derived intermediates to support the synthesis of calcium propionate [42].



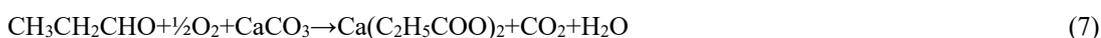
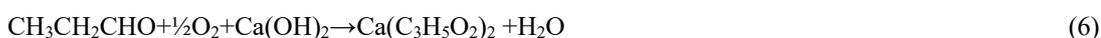
Also, in the literature, solid catalysts based on CaO-MgO derived from waste dolomite have been reported to be effective in the hydrolysis of PET, thereby contributing significantly to both PET waste recycling and environmental sustainability [32].

Furthermore, CaO plays a crucial role in the recycling of organic and inorganic waste; for example, CaO can be obtained from calcium-rich compounds derived from the processing of agricultural waste [42]. In this context, utilizing calcium sources acquired from agricultural sectors offers potential for enhancing the economic and environmental efficiency of calcium propionate synthesis. One of the key advantages of CaO is its ease of reuse, which reduces production costs and promotes sustainable manufacturing methods [43].

The oxidation of propionaldehyde in calcium propionate production is a critical process for synthesizing propionic acid, an essential compound in this field. Propionaldehyde is commonly used to obtain propionic acid through air oxidation [31]. This process occurs in several steps; initially, propionaldehyde reacts with oxygen gas, converting into propionic acid. During the oxidation reaction, the use of appropriate catalysts can enhance yield and product quality [41]. Additionally, optimizing reactor conditions, including careful control of pressure and temperature, has the potential to reduce the formation of undesired side-products [31]. The reaction for the first step is given in Equation 5.



The catalysts employed in propionaldehyde oxidation are typically based on metal oxides or metal carbides, which are engineered with specific structural properties to enhance reaction efficiency [44]. Research has shown that these catalysts can promote the oxidation of propionaldehyde with remarkably high effectiveness [37]. However, precise control over by-product formation remains essential, as it directly influences the purity and overall quality of the resulting propionic acid [45]. Consequently, additional purification or by-product removal strategies must be implemented to optimize the process. Depending on the calcium source utilized, the overall reactions proceed as represented in Equations 6 and 7 [9].



The production of propionic acid can be achieved through two primary reaction pathways involving the oxidation of propionaldehyde: neutralization with $\text{Ca}(\text{OH})_2$ (Equation 6) and neutralization with CaCO_3 (Equation 7). Both methods rely on the oxidation of propionaldehyde with oxygen to form propionic acid; however, the process varies depending on the calcium source used [3, 46, 47].

In the $\text{Ca}(\text{OH})_2$ method (Equation 6), the reaction occurs rapidly, where propionic acid is directly neutralized with $\text{Ca}(\text{OH})_2$ to produce calcium propionate and water. Due to its high reactivity, this process is considered more efficient in industrial applications, as it generates fewer by-products, reducing the need for post-processing purification [3, 48, 49].

On the other hand, in the CaCO_3 method (Equation 7), propionic acid reacts with CaCO_3 to produce calcium propionate along with CO_2 and water. This method is considered a more environmentally friendly approach, as natural CaCO_3 sources are abundant and result in lower chemical waste production [42, 50]. However, the low solubility of CaCO_3 and the slower reaction rate make this method a more time-intensive process [47, 51].

In conclusion, $\text{Ca}(\text{OH})_2$ provides a faster and more efficient reaction pathway, while CaCO_3 contributes to greater environmental sustainability by offering an alternative, eco-friendly route [52]. When selecting the most suitable method for industrial-scale production, several factors, including reaction kinetics, secondary product formation, and environmental impact, must be considered, since the optimal choice ultimately depends on overall process efficiency and cost factors [41].

When comparing the two approaches, direct neutralization operates through a simple acid–base reaction between propionic acid and calcium base, whereas chemical synthesis involves multiple stages with intermediate products (Table 2). Direct neutralization functions under mild conditions, exhibiting low energy requirements and high scalability, while chemical synthesis generally requires elevated temperatures and pressures. Owing to its straightforward raw materials, direct neutralization is typically more cost-efficient, whereas chemical synthesis may become more expensive depending on feedstock selection. In environmental terms, direct neutralization generates minimal by-products (mainly water and CO_2), while chemical synthesis may result in additional emissions or chemical residues.

Overall, the choice between these two methods should balance simplicity, scalability, cost, and environmental performance. Direct neutralization is advantageous for industries seeking low-cost, easily implemented routes, whereas chemical synthesis offers broader flexibility for feedstock integration and process customization. Future work should aim to enhance the sustainability of both approaches through renewable feedstocks and improved reaction efficiency [53–59].

Table 2. Comparative Analysis of Direct Neutralization and Chemical Synthesis

Feature	Direct Neutralization	Chemical Synthesis
Mechanism	Single-step acid-base reaction.	Multistep processes with intermediates.
Reactants	Propionic acid and calcium base.	Ethylene, CO, H ₂ O, calcium base.
Energy Requirements	Low, operates at mild conditions.	High, often involves elevated temperatures and pressures.
Scalability	Easily scalable to industrial applications.	Requires more complex setups.
Cost Efficiency	High, using simple raw materials.	Moderate to low, depending on feedstock.
Environmental Impact	Minimal, water/ CO_2 by-products only.	Varies, can generate waste or emissions.

C. Biotechnological Production

Although biotechnological production is based on the microbial fermentation of carbon-rich substrates to obtain propionic acid, a subsequent neutralization step is applied to produce calcium propionate. Microorganisms belonging to genera such as *Propionibacterium* are used to ferment carbohydrates such as glucose or lactose [60]. This method is more environmentally sustainable compared to conventional chemical synthesis; however, the control of fermentation parameters increases production costs [61].

In recent years, biotechnological production has attracted increasing attention as a sustainable and renewable alternative to chemical synthesis in the production of calcium propionate. This method employs microbial fermentation processes involving *Propionibacterium* spp., *Clostridium* spp., and genetically engineered yeast strains capable of producing propionic acid, which serves as the key precursor for calcium propionate synthesis [60]. The fermentative pathway primarily proceeds through the Wood–Werkman cycle, during which substrates such as glycerol, glucose, lactose, or agro-industrial by-products are converted into propionic acid as the main end product [62]. The resulting fermentation product is then neutralized with $\text{Ca}(\text{OH})_2$ to produce calcium propionate [63].

Three main fermentation strategies are commonly employed in the biological production of calcium propionate: batch, fed-batch, and continuous fermentation. In batch fermentation, all substrates are added at the beginning of the process, and fermentation continues until the nutrients are depleted. This method is suitable for small-scale or experimental production due to its operational simplicity [60]. Fed-batch fermentation, on the other hand, involves the gradual addition of substrates throughout the process, thereby preventing substrate inhibition and improving yield. This approach is particularly effective when high substrate concentrations could otherwise inhibit microbial activity [61]. Continuous fermentation represents the most advanced technique, in which substrates and nutrients are continuously supplied while the products are simultaneously withdrawn from the system. Although this method ensures high productivity and consistent output, it requires complex equipment and precise control systems [64].

Advancements in metabolic engineering have enhanced the efficiency and resilience of microbial strains that are crucial for these systems. For example, genetic modifications in *Propionibacterium freudenreichii* have improved both propionic acid yield and tolerance to acid accumulation [60]. Similarly, recombinant *Escherichia coli* strains engineered to express propionate biosynthetic pathways have shown promising potential for utilizing non-conventional feedstocks such as lignocellulosic biomass [65]. In addition, co-culture systems based on the synergistic interaction of microbial consortia aim to enhance substrate conversion efficiency and minimize by-product formation [66].

To eliminate factors that hinder purification processes due to the formation of unwanted by-products such as acetic acid and lactic acid, various separation and purification techniques are applied. Methods such as membrane filtration, ion-exchange resins, and solvent extraction can enhance both the purity and yield of calcium propionate [67]. These innovations improve the feasibility of biotechnological production while reducing dependence on petrochemical raw materials [68]. Considering the increasing global demand for calcium propionate in food preservation and animal feed, such bio-based production methods align with the principles of green chemistry and circular bioeconomy, representing a viable alternative capable of meeting industrial-scale requirements [69].

The overall efficiency of calcium propionate production is closely related to the performance of the upstream microbial fermentation process responsible for propionic acid generation. Fundamental operational parameters such as pH, temperature, substrate concentration, and microbial community composition directly influence not only acid yield but also the subsequent conversion efficiency to calcium propionate. Therefore, a clear understanding and careful optimization of these factors are critical for improving overall process performance and ensuring consistent product quality. Calcium propionate production is a multifactorial process governed by the interaction of these variables [60]. Optimizing these parameters is essential to achieve higher efficiency, cost-effectiveness, and sustainability. Future research must focus on exploring alternative substrate sources, enhancing microbial consortia through metabolic and genetic engineering, and improving fermentation conditions to maximize propionate yield while maintaining economic feasibility [58].

Table 3 systematically summarizes the key parameters influencing the biotechnological production of calcium propionate. These parameters are presented with their operational ranges, associated challenges, and relevant literature references, providing a structured overview for process optimization.

Table 3. Critical parameters for calcium propionate production by biotechnological production

pH	Temp. °C	Substrate Conc. g/L	Yield g/g	Co-products	Inhibitory Effect	Conversion to Calcium Propionate	Continuous Fermentation Productivity g/L/h	Reference
6.5–7.0	30–37	50–100	0.4–0.6	Acetic acid, CO ₂	Acetate and low pH	Neutralization with Ca(OH) ₂	2–3	[60]
6.5	30	70	0.44	CO ₂ , Acetate	Substrate inhibition	Ca(OH) ₂ addition	2.0–3.0	[70]
6.2–6.7	37	55	0.43	Minimal acetic acid	pH below 6.0 inhibits growth	Neutralization directly in broth	2.5	[71]
6.8	36	50–60	0.6	Acetate, lactate	Acetate accumulation	Continuous Ca supply	2.8	[57]
6.3–6.6	32	80–100	0.5	Acetic acid, Succinic acid	Product inhibition (PA > 32 g/L)	Neutralization with NH ₄ OH	0.3–1.4	[72]
6.4–6.6	32	100	0.54	Acetic acid, Succinic acid	Product inhibition (PA > 30 g/L)	Neutralization with NH ₄ OH	0.18–0.23	[73]
6.5–7.0	30–37	70–80	0.50–0.56	Minimal CO ₂ , acetate	Low substrate tolerance	CaCO ₃ for pH control	2.0–2.7	[74]
6.8	37	51.4–64.5	0.38–0.79	-	Acid inhibition of growth	Addition of NaOH / HCl	0.98–1.82	[75]
6.5–6.8	35	85–90	0.5	Acetic acid, CO ₂	PA > 30 g/L inhibits	Intermittent Ca(OH) ₂	1.5–2.2	[76]

The efficiency of biotechnological calcium propionate production depends strongly on the precise regulation of operational parameters, including substrate selection, substrate concentration, temperature, pH level, and microbial community dynamics. For example, Liu et al. demonstrated that maintaining a moderate temperature range (30–37 °C) and a near-neutral pH (6.5–7.0) allows *Propionibacterium* species to achieve propionic acid yields of 0.4–0.6 g/g, with the co-production of acetic acid and CO₂. Moreover, Ca(OH)₂ effectively neutralized the medium's acidity, sustaining continuous productivity levels between 2–3 g/L/h. These findings underscore the necessity of maintaining stable, near-neutral conditions to support microbial metabolism and optimize propionate synthesis [60]. In a similar temperature range but with a fixed pH of 6.5, Wang et al. reported comparable results using 70 g/L substrate, achieving 0.44 g/g yield. However, substrate inhibition became prominent, necessitating direct Ca(OH)₂ supplementation to achieve 2.0–3.0 g/L/h productivity. This emphasizes the role of substrate levels in modulating metabolic throughput [70]. Contrastingly, Antone et al. found that slightly lower pH levels (6.2–6.7) and 37 °C were sufficient for fermentation using 55 g/L substrate. Although the yield was slightly reduced (0.43 g/g), minimal acetic acid was observed, and productivity (2.5 g/L/h) remained high when pH was directly controlled within the broth. These findings indicate that minor shifts in pH can significantly affect microbial growth and by-product formation [71]. Piwozarek et al. explored a higher pH (6.8) and observed the highest yield (0.6 g/g) using 50–60 g/L substrate. However, acetate and lactate accumulation emerged as limiting factors. They circumvented this inhibition using a continuous calcium supply, maintaining a stable productivity of 2.8 g/L/h, which is among the highest reported. This approach demonstrates that even with inhibitory co-products, tailored pH stabilization can preserve system efficiency [57]. When focusing on inhibition due to product accumulation, both Farhadi et al. [72] and Wang et al. [73] showed that pH in the range of 6.3–6.6 and a temperature of 32 °C, with substrate concentrations between 80–100 g/L, resulted in moderate to high yields (0.5–0.54 g/g). However, yields declined due to propionic acid levels exceeding 30 g/L. Neutralization with NH₄OH improved stability, although productivity ranged lower (0.18–1.4 g/L/h), suggesting that while ammonium hydroxide is effective, it may not fully counteract the toxicity of accumulated acids. Himmi et al. achieved promising results using CaCO₃ for pH control, with minimal CO₂ and acetate formation. With substrate concentrations of 70–80 g/L at 30–37 °C, yields ranged between 0.50–0.56 g/g, and productivity reached up to 2.7 g/L/h. This points to the effectiveness of buffered systems in supporting metabolic balance during mid-scale operations [74]. The study by Cavero-Olguin et al. presents a broader productivity spectrum (0.98–1.82 g/L/h) using NaOH and HCl for direct acid-base control at pH 6.8. Despite the wide yield range (0.38–0.79 g/g) across 51.4–64.5 g/L substrate, this system reflects the inherent variability introduced by aggressive pH corrections, often necessary when working with sensitive

microbial consortia [75]. Finally, Dishisha et al. provide insight into high substrate regimes (85–90 g/L) at pH 6.5–6.8, where propionic acid concentrations above 30 g/L caused inhibition. Intermittent $\text{Ca}(\text{OH})_2$ addition mitigated this effect and maintained a productivity of 1.5–2.2 g/L/h. Compared to continuous systems; intermittent control offers a balance between pH stability and cost efficiency [76]. Taken together, these studies illustrate that while optimal temperature and pH ranges are generally consistent, variations in substrate concentration and pH control strategy significantly affect yield and productivity. Continuous or intermittent calcium-based buffering appears most robust under high-yield conditions, while ammonium-based systems may be more suitable for moderate-scale or cost-sensitive operations.

Effect of the Parameters on the Biotechnological Production Process

The efficiency of biotechnological calcium propionate production strongly depends on key operational parameters such as substrate selection, substrate concentration, temperature, pH level, and microbial community dynamics. Figure 3 illustrates these critical factors and their interrelations in the fermentation process.

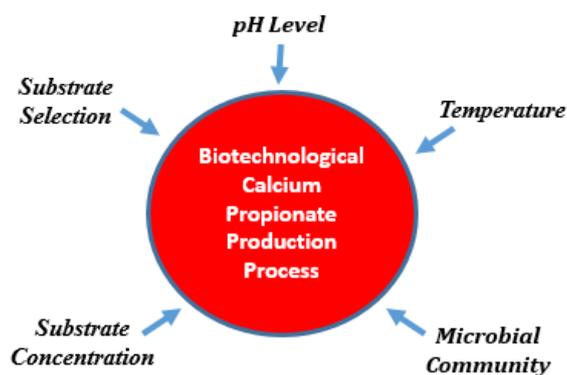


Figure 3. Parameters affecting biotechnological calcium propionate production

The fermentation of organic substrates, particularly agricultural and vegetable biowaste, has become a promising strategy for sustainable propionate production. Schmidt et al. demonstrated that propionate can be generated through anode-assisted anoxic conversion of vegetable biowaste, serving as a valuable platform chemical for a range of downstream biotechnological applications [77]. This finding highlights the potential of agricultural waste utilization as a renewable substrate for propionate synthesis, aligning with the increasing global emphasis on environmentally friendly and resource-efficient bioprocessing methods. A wide range of organic materials can be employed as substrates for propionate production. Elghandour et al. investigated the combined use of organic acid salts with unconventional carbon sources such as glycerol and propylene glycol to enhance propionate formation in ruminant systems [78]. Their results indicate that diverse feedstocks can be effectively leveraged for calcium propionate synthesis, thereby improving process adaptability and contributing to its environmental sustainability. However, competition among microbial pathways remains a critical factor influencing propionate yield. Brand et al. reported that the presence of acetate can modify the activity of sulfate-reducing bacteria, which may compete with propionate-producing microorganisms under anaerobic conditions [79]. Such microbial interactions can impact both yield and selectivity, underscoring the importance of optimizing fermentation parameters to ensure maximum production efficiency.

From an economic standpoint, the feasibility of calcium propionate production is strongly dependent on substrate selection and fermentation efficiency. Ekman and Börjesson highlighted that propionic acid, most commonly used as calcium propionate, holds a significant economic importance as a preservative in both the food and feed industries [80]. Developing integrated biorefinery systems that combine propionate production with other value-added bioproducts could therefore enhance overall profitability and advance the transition toward sustainable industrial biomanufacturing.

Temperature is a key parameter influencing the efficiency of the fermentation process, particularly in determining the metabolic activity of propionic acid-producing bacteria. Liu et al. reported that the optimal temperature for propionate production is approximately 30 °C, noting that higher temperatures lead to a marked decline in propionic acid yield [60]. This observation is supported by Watanabe et al., who found that specific plant extracts can enhance propionate formation in ruminants, further emphasizing that careful temperature regulation is essential to maintain optimal microbial activity and maximize propionate production in fermentation systems [81].

The pH of the fermentation medium is crucial in determining the efficiency of propionate production. Studies have shown that neutral or slightly acidic conditions enhance the growth and metabolic activity of

propionic acid-producing bacteria, whereas alkaline environments suppress this function [66]. Moreover, Zhou et al. reported that high calcium concentrations in anaerobic reactors can reduce hydrolysis rates, negatively affecting both overall digestion performance and propionate synthesis [51]. These findings emphasize the importance of considering not only balanced pH but also calcium levels to ensure optimal fermentation efficiency and product yield.

The composition of the microbial community is another factor influencing calcium propionate production. McIlroy et al. identified novel anaerobic bacterial strains that play important roles in propionate fermentation and demonstrated that microbial diversity is key to achieving high yields [63]. In addition, the presence of specific genera such as *Propionibacterium* is also critical, as these microorganisms are uniquely capable of converting certain substrates into propionic acid [34]. The dynamic interactions among different microbial populations can also affect the degradation of volatile fatty acids (VFAs), including propionate, which is important for maintaining stability in anaerobic digestion systems [79].

Substrate concentration affects both the yield and productivity of propionic acid fermentation. Insufficient substrate levels may lead to incomplete metabolism and low product output, whereas excessively high concentrations can cause substrate inhibition, reducing microbial activity and overall efficiency. Optimal substrate concentrations, typically in the range of 50–80 g/L, promote balanced microbial growth and prevent the accumulation of inhibitory intermediates. Adjusting the substrate concentration in conjunction with pH control and calcium levels has been shown to significantly improve propionate production efficiency [70, 71].

Sustainability and Biorefinery Integration

The production of calcium propionate through fermentation processes showcases a paradigm where industrial biochemistry aligns with sustainability principles [31, 64]. This integration is particularly significant in the context of addressing environmental challenges while promoting efficient resource utilization. By employing agricultural residues such as crop straw, corn stover, or other lignocellulosic biomass as feedstock, the synthesis of calcium propionate serves as an exemplary model for the circular economy [65,70]. In such systems, waste streams are transformed into high-value additives, reducing landfill pressures and contributing to a more sustainable production cycle [64, 67].

The circular economy paradigm aims to minimize waste while promoting the reintegration of materials into production systems through reuse and recycling. In calcium propionate production, the use of large amounts of agricultural residues that are often underutilized exemplifies this approach [64, 65]. The fermentation processes employed in production can adapt to various feedstocks, facilitating the valorization of regionally available biomass. For instance, Shi et al. (2022) demonstrated that sweet sorghum bagasse hydrolysates could effectively serve as a carbon source for the growth of *Propionibacterium freudenreichii*, enabling efficient bio-based calcium propionate production [36]. This approach not only converts agricultural waste into value-added products but also sets an example for sustainable industrial practices. Similarly, Zhang et al. (2018) investigated the production of propionic acid from agro-industrial effluents and demonstrated the potential for integrating different feedstocks into fermentation processes [65]. Taken together, these studies emphasize the importance of using waste materials in bioprocesses, clearly aligning with the principles of the circular economy, which aim to maximize resource efficiency and minimize environmental impact.

Optimizing the fermentation process in calcium propionate synthesis means reducing energy consumption and greenhouse gas emissions [17, 38]. Technological advancements such as immobilized microbial cultures, adaptive consortia, and controlled bioreactor systems have enhanced fermentation process efficiency [80]. Dishisha et al. (2024) reported that the use of adaptive microbial consortia can improve the conversion efficiency of agricultural residues to calcium propionate while achieving a 30% reduction in energy consumption compared to conventional fermentation methods [76]. An important aspect is that by integrating renewable energy sources such as biogas obtained from the anaerobic digestion of residual biomass, these systems can operate with an almost zero carbon footprint [77, 80].

The biorefinery concept enables the simultaneous production of multiple value-added products from the same feedstock. This concept expands the potential of calcium propionate production. Ekman and Börjesson (2011) proposed biorefinery systems capable of producing bioethanol, bioplastics, and biofertilizers together with calcium propionate. In this way, overall economic viability is improved while waste generation is reduced [80]. This integration ensures the efficient utilization of every component of the biomass feedstock, making it fully compatible with sustainability goals. Figure 4 presents a schematic representation of this biorefinery concept as described by Ekman and Börjesson [80].

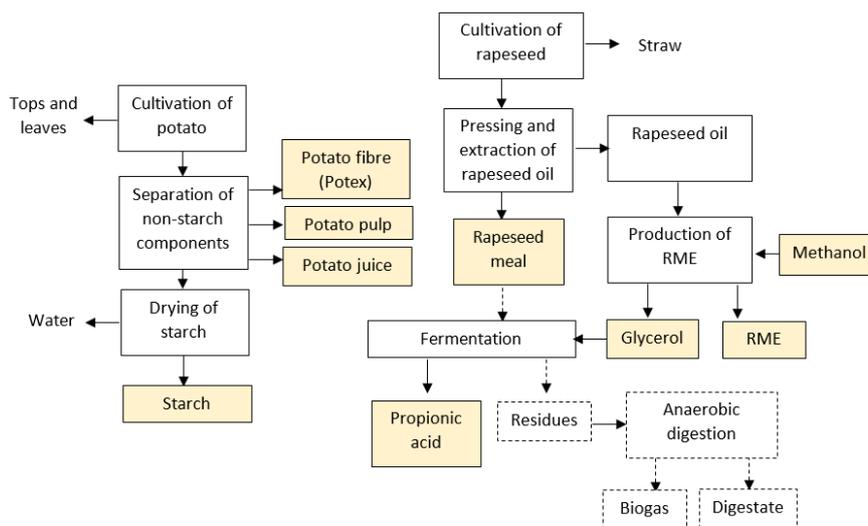


Figure 4. Flowchart of a biorefinery concept [73]

Recent studies in biorefinery design focus on combining enzymatic hydrolysis with microbial fermentation to increase the efficiency of calcium propionate production. Schmidt et al. (2018) found that the use of enzymatically pretreated corn stover enhanced substrate availability for microbial fermentation [77]. In their study, dilute acid and alkaline sodium sulphite pretreatments were combined, effectively fractionating the main components of corn stover and improving both enzymatic hydrolysis and subsequent ethanol production. These findings indicate that synergistic technologies in integrated biorefinery systems can reduce operational costs, enhance substrate utilization, and improve overall process efficiency [77].

According to the LCA studies conducted by Ekman and Börjesson (2011), biobased calcium propionate production can reduce carbon emissions by up to 40% compared to petrochemical processes [80]. Above all, the use of agricultural residues as fermentation feedstock provides significant cost advantages, especially in regions where such raw materials are abundant and inexpensive. However, several challenges remain before calcium propionate production through biorefinery applications can be fully adopted on an industrial scale. The main limitation is the variability in feedstock composition, followed by the costs of pretreatment and the scalability of fermentation systems [60]. Traditional fermentation approaches, such as batch and fed-batch processes, are not economically preferred due to their complexity, long processing times, and high purification costs [70]. Ongoing research aims to overcome these bottlenecks through metabolic and genetic engineering strategies, particularly targeting strains of *Propionibacterium*. These efforts focus on improving substrate specificity, enhancing propionic acid yield, and reducing production costs [71]. For example, novel genetically engineered strains of *Propionibacterium* have demonstrated improved ability to metabolize lignocellulosic sugars, thereby expanding the range of viable feedstocks for calcium propionate production [36]. Such advancements are expected to enhance both the economic feasibility and environmental sustainability of biotechnological calcium propionate production in the near future.

The integration of calcium propionate production into biorefinery systems exemplifies a transformative approach to sustainable industrial biochemistry [31, 80]. By utilizing agricultural residues as feedstock, these systems not only reduce environmental burdens but also enhance economic viability through waste valorization and multi-product outputs [64, 65]. Advances in fermentation technologies and biorefinery designs continue to drive the feasibility of large-scale implementation, making calcium propionate production a model for future sustainable manufacturing practices [31, 64].

Calcium propionate exemplifies a multifunctional compound with critical roles spanning food safety, public health, animal nutrition, and sustainability [1, 5, 7]. Its ability to inhibit spoilage organisms ensures the longevity and quality of food products, while its nutritional contribution addresses dietary calcium deficiencies [15]. In animal agriculture, calcium propionate supports both productivity and environmental goals by enhancing feed efficiency and reducing methane emissions [7, 17]. Furthermore, its sustainable production from renewable resources underscores its importance in the advancement of circular bioeconomy models [5, 31]. The integration of calcium propionate into food and feed systems highlights its value as a cornerstone in contemporary food science and agricultural practices, promising enhanced human and animal health alongside environmental conservation.

D. Electrochemical Synthesis

In calcium propionate production, the electrochemical method is based on the oxidation of propane to obtain propionic acid. In the subsequent step, neutralization is carried out with calcium hydroxide. Although still

in the developmental stage, it is promising due to its high potential for reducing environmental impact, especially when powered by renewable energy sources [54]. Electrochemical synthesis performs reactions using electrical energy with minimal by-product formation, making it more sustainable compared to traditional chemical methods [53]. This process also provides significant advantages in terms of energy efficiency, reaction control, and operational safety.

Recent studies on the electrochemical synthesis of calcium propionate have evaluated the fundamental reaction mechanisms, optimization parameters, and scalability potential [54]. These studies emphasize reaction efficiencies and environmental benefits, highlighting the industrial significance of electrochemical synthesis. The ability to design electrochemical systems that operate under mild temperature and pressure conditions further enhances their environmental compatibility and energy efficiency [50].

A review of the literature shows that studies have been conducted on the effects of electrolytic cell design and electrode material selection on process performance. In a typical setup using a two-compartment electrolytic cell separated by an ion-exchange membrane to prevent product cross-contamination, the anode compartment contains an aqueous propionic acid solution, while calcium ions are introduced into the cathode compartment in the form of calcium chloride [54]. Titanium-coated electrodes are preferred due to their high corrosion resistance under both oxidative and reductive conditions [53]. In addition, the cathode is specially designed to enhance the reduction of propionate anions, thereby increasing conversion efficiency and selectivity [50]. In another study, the electrolyte was prepared with 1 M calcium chloride and 0.5 M propionic acid to ensure high ionic conductivity and maintain sufficient availability of reactants [54]. In addition, buffering agents were used to keep the pH stable within the range of 6 to 8, which is considered optimal for propionate formation [50]. Equation (8) represents the reaction between propionate anions ($C_2H_5COO^-$), formed by the dissociation of propionic acid, and Ca^{2+} ions [46].



This reaction occurs at the cathode under the applied electric potential. Parameters such as current density, electrode spacing, and electrolyte temperature were systematically varied to maximize yield and minimize side reactions [54]. The operating conditions effectively prevent $CaCO_3$ precipitation. Studies have shown that when the conditions are optimized, selectivity for calcium propionate increases and yields exceed 85% [53]. Product purity is enhanced through effective pH control and electrode design [54]. Energy consumption can be reduced by using efficient electrodes and maintaining moderate cell voltages. The process has demonstrated scalability in batch-type experiments, revealing its potential for industrial application. Compared to conventional methods, electrochemical synthesis eliminates the use of hazardous reagents and reduces chemical waste generation [50, 54]. It is evident that the electrochemical synthesis of calcium propionate is a promising alternative to conventional methods. This process is environmentally friendly, efficient, and scalable, allowing for sustainable production [54]. In future research, if renewable energy sources can be integrated into this process, reaction efficiency could be further enhanced, thereby paving the way for broader industrial applications [50, 53].

E. Waste Valorization Processes

Agricultural and industrial wastes (such as glycerol and lignocellulosic biomass) are potential raw materials for propionic acid production through microbial fermentation. In this process, the propionic acid produced can then be neutralized with $Ca(OH)_2$ or $CaCO_3$ to obtain calcium propionate [61, 64]. Since renewable raw materials are used, this method both reduces the amount of waste materials and enables the production of value-added products from them. It is clear that this process, which fully aligns with the principles of the circular economy, will be preferred in the future [65].

A wide range of organic wastes represent a valuable resource for the sustainable production of calcium propionate. Agricultural residues rich in fermentable carbohydrates and lignocellulosic biomass are suitable for propionic acid production through hydrolysis and fermentation. This acid serves as a precursor for many calcium propionate synthesis methods [64, 65]. Similarly, food wastes containing high levels of simple sugars are also suitable for propionic acid production. As can be understood, this approach reduces waste generation from various processes and increases resource efficiency [67, 77]. Another potential source is industrial by-products obtained from bioethanol and biodiesel production. In particular, glycerol and other carbon-rich compounds can be used in propionate synthesis. When this process is adopted, it not only supports the circular economy but also ensures both environmental and economic sustainability [61, 65].

In the microbial fermentation of organic waste, *Propionibacterium* species are highly effective in anaerobically converting sugars and glycerol into propionic acid [60, 61]. Laboratory-scale experiments have shown that optimizing key parameters can achieve yields exceeding 85% [70]. The resulting propionic acid is neutralized using a calcium source, thereby converting it into calcium propionate. When this method is applied near waste generation sites, transportation costs can be significantly reduced [65]. Such integrated approaches not only lower dependency on fossil fuels and reduce greenhouse gas emissions but also enhance overall process

efficiency [31]. Moreover, integration with existing industrial production systems further improves the economic feasibility and environmental sustainability of calcium propionate production [31, 65].

Looking ahead, advancements in microbial strain engineering, fermentation optimization, and process integration are essential to fully unlock the potential of waste-derived calcium propionate [60, 65]. Additionally, conducting comprehensive LCAs will be critical for quantifying environmental benefits, identifying key areas for improvement, and guiding the transition toward a more sustainable and circular bioeconomy [31, 80].

F. Enzymatic Synthesis

Emerging enzymatic synthesis techniques utilize biocatalysts to produce propionic acid and subsequently calcium propionate under mild and environmentally friendly conditions. Although these approaches are still largely experimental and not yet widely implemented at an industrial scale, they show strong potential for achieving high reaction specificity and minimal by-product formation [5, 55]. Enzymatic synthesis represents an innovative, eco-conscious alternative to traditional chemical routes, relying on enzyme-mediated transformations that align with the principles of green chemistry and sustainable manufacturing [5, 31, 54].

In this method, enzymes such as lipases or esterases catalyze the reaction between $\text{Ca}(\text{OH})_2$ or CaCO_3 and propionic acid, resulting in the formation of calcium propionate [5, 55]. Since these reactions are typically carried out in aqueous environments, the generation of chemical waste is minimized [50]. Studies focusing on recombinant enzyme engineering aim to enhance catalytic activity and substrate selectivity, thereby improving overall yield [55]. One of the main advantages of this approach is its ability to significantly reduce the formation of unwanted by-products while increasing product purity [5, 50].

Moreover, the enzymatic process typically operates at ambient temperature and near-neutral pH, requiring less energy compared to conventional chemical synthesis methods [31]. The newly developed immobilized enzyme systems allow for enzyme recovery and reuse, thereby enhancing scalability while reducing costs [56]. As research in this field progresses, enzymatic synthesis is expected to enable the sustainable and low-energy production of calcium propionate, further enhancing its industrial applicability within the framework of environmental responsibility.

Of course, despite its advantages, there are certain limitations related to enzyme stability and activity. The high cost of enzyme production and the potential deactivation during use raise concerns regarding its industrial-scale applicability [55]. Moreover, optimizing the operating conditions of enzymes to achieve maximum yield requires comprehensive and detailed research [5]. The greatest advantage of enzymatic synthesis lies in its alignment with green chemistry principles, achieved by reducing dependence on hazardous chemicals and lowering the carbon footprint [50]. Furthermore, the utilization of renewable substrates, such as agricultural wastes, for propionic acid production contributes to supporting a circular economy [64]. However, the economic feasibility of this method remains strongly dependent on advancements in enzyme production technologies and the optimization of these processes [31, 55].

Future research should focus on improving enzyme robustness and reducing costs through genetic engineering and large-scale production techniques [55]. Additionally, integrating enzymatic synthesis with renewable energy sources and waste valorization processes could further enhance its environmental and economic sustainability [5, 31, 64].

Comparative Overview of Production Methods

Each production method for calcium propionate offers distinct advantages and limitations that determine its suitability under various industrial, economic, and environmental contexts. As summarized in Table 4, chemical synthesis remains the conventional industrial route due to its scalability and cost efficiency, although its dependence on petrochemical feedstocks limits sustainability. Direct neutralization, while simple and low-cost, faces quality control challenges that restrict product consistency. In contrast, biotechnological production provides an eco-friendly and renewable alternative, relying on microbial fermentation of sustainable feedstocks. However, its high operational cost and complex fermentation control currently limit large-scale commercialization. Electrochemical synthesis offers high conversion efficiency and process controllability, yet the initial equipment cost and emerging technological maturity pose significant barriers to industrial adoption. Waste valorization stands out as a promising sustainable approach that transforms industrial by-products into valuable products, thereby reducing waste and supporting circular economy principles. Nonetheless, variability in feedstock composition and supply can affect process stability. Finally, enzymatic synthesis provides high product specificity and minimal side-products, though it remains at an experimental stage with high enzyme costs limiting industrial viability. The comparative assessment indicates that while chemical synthesis and direct neutralization are currently the most feasible methods for large-scale production, biotechnological, electrochemical, waste valorization, and enzymatic routes represent the future direction of sustainable calcium propionate production. Further research should focus

on process integration, cost reduction, and renewable raw material utilization to enhance both environmental and economic performance across all methods.

Table 4. Comparison of Methods for Calcium Propionate Production: Advantages and Challenges.

Method	Advantages	Challenges	Reference
Chemical Synthesis	Scalable, cost-effective	Reliant on petrochemical feedstocks	[30, 31, 37]
Direct Neutralization	Simple, low-cost	Quality control issues	[30, 37]
Biotechnological	Eco-friendly, renewable feedstocks	Expensive, complex fermentation conditions	[71, 75, 76]
Electrochemical	High efficiency potential	High initial costs, emerging technology	[53, 54]
Waste Valorization	Reduces waste, sustainable	Variable feedstock availability	[64, 65]
Enzymatic	Specific, low side-products	Experimental, high cost	[5, 55]

Note: The comparative data in this table have been updated based on recent studies published between 2020 and 2024 to reflect the latest advancements in calcium propionate production technologies.

III.CONCLUSION

Calcium propionate production represents a dynamic and evolving field that seeks to balance process efficiency, cost, and sustainability. This review has comparatively analyzed six production methods (chemical synthesis, direct neutralization, biotechnological fermentation, electrochemical synthesis, waste valorization, and enzymatic conversion) highlighting their respective advantages and challenges. Chemical synthesis remains the most scalable and cost-effective approach but relies heavily on petrochemical feedstocks, limiting its environmental compatibility. Direct neutralization offers operational simplicity and low cost, though it requires quality control improvements and sustainable acid sourcing.

Biotechnological and waste valorization methods exhibit strong potential to align with green chemistry and circular bioeconomy principles by utilizing renewable substrates and minimizing waste. However, these processes face challenges related to high operational costs, fermentation control, and downstream purification. Meanwhile, electrochemical and enzymatic approaches emerge as innovative alternatives that could substantially lower carbon footprints once issues of scalability, enzyme stability, and energy integration are resolved.

Looking forward, future research should prioritize the integration of renewable energy systems and the development of hybrid processes combining biotechnological, electrochemical, and enzymatic principles. LCAs and TEAs must accompany process innovations to ensure both environmental and industrial viability. Moreover, the application of advanced modeling, artificial intelligence, and process intensification techniques could accelerate optimization and scale-up. By addressing these emerging directions, the sustainable production of calcium propionate may evolve toward fully circular and carbon-neutral manufacturing platforms, enhancing both industrial competitiveness and environmental stewardship.

REFERENCES

- [1] Black, B. A., Zannini, E., Curtis, J. M., & Gänzle, M. G. (2013). Antifungal hydroxy fatty acids produced during sourdough fermentation: Microbial and enzymatic pathways, and antifungal activity in bread. *Applied and Environmental Microbiology*, 79(6), 1866–73.
- [2] Sorathiya, K. B., Melo, A., Hogg, M. C., & Pintado, M. (2025). Organic acids in food preservation: Exploring synergies, molecular insights, and sustainable applications. *Sustainability*, 17(8), 3434.
- [3] Mirshekari, A., Madani, B., & Golding, J. B. (2017). Suitability of combination of calcium propionate and chitosan for preserving minimally processed banana quality. *Journal of the Science of Food and Agriculture*, 97(11), 3706–3711.
- [4] Maximize Market Research. (2024). Global calcium propionate market. India, <https://www.maximizemarketresearch.com/market-report/global-calcium-propionate-market/25135/>, (November 12, 2025).
- [5] Yang, X., Zhang, S., Lei, Y., Wei, M., Liu, X., Yu, H., Xie, P., & Sun, B. (2023). Preservation of stewed beef chunks by using calcium propionate and tea polyphenols. *LWT*, 176, 114491.
- [6] dos Santos, F. F., Brochine, L., Nascimento, R. A., Moreira, F. M., Gameiro, A. H., & Gallo, S. B. (2022). Economic performance of high-energy diets and supplementation with chromium propionate or calcium salts of palm oil in ewes' production. *Revista Brasileira de Zootecnia*, 51, e20210063.
- [7] Zhang, F., Nan, X., Wang, H., Guo, Y., & Xiong, B. (2020). Research on the applications of calcium propionate in dairy cows: A review. *Animals*, 10(8), 1336.
- [8] Birbir, M., & Çakırlı Doğu, N. (2003). The evaluation of antifungal effect of calcium propionate on different mold species. *Biotechnology & Biotechnological Equipment*, 17(1), 74–80.
- [9] Sequeira, S. O., Phillips, A. J. L., Cabrita, E. J., Macedo, M. F. (2017). Antifungal treatment of paper with calcium propionate and parabens: Short-term and long-term effects. *International Biodeterioration and Biodegradation*, 120, 203–215.
- [10] Pampaloni, B., & Brandi, M. (2022). Mineral water as food for bone: an overview. *International Journal of Bone Fragility*, 2(2), 48–55.

- [11] Huey, Y. W., Zulkipli, A. S., Tajarudin, H. A., & Salleh, R. M. (2021). Physicochemical properties of pre-treated cuttlebone powder and its potential as an alternative calcium source. *Journal of Food Processing and Preservation*, 45, e15831.
- [12] Paster, N., Bartov, I., & Perelman, A. (1985). Studies of the fungistatic activity of antifungal compounds in mash and pelleted feeds. *Poultry Science*, 64(9), 1673–1677.
- [13] EFSA Panel on Food Additives and Nutrient Sources. (2014). Scientific opinion on the re-evaluation of propionic acid (E280), sodium propionate (E281), calcium propionate (E282), and potassium propionate (E283) as food additives. *EFSA Journal*, 12(7), 3779.
- [14] Vidra, A., & Németh, Á. (2018). Bio-produced propionic acid: A review. *Periodica Polytechnica Chemical Engineering*, 62(1), 57–67.
- [15] Zhang, F., Zhao, Y., Wang, Y., Wang, H., Guo, Y., & Xiong, B. (2022). Effects of calcium propionate on milk performance and serum metabolome of dairy cows in early lactation. *Animal Feed Science and Technology*, 283, 115185.
- [16] Carrillo-Muro, O., Rivera-Villegas, A., Hernández-Briano, P., López-Carlos, M. A., Aguilera-Soto, J. I., Estrada-Angulo, A., Medina-Flores, C. A., & Mendez-Llorente, F. (2022). Effect of calcium propionate level on the growth performance, carcass characteristics, and meat quality of feedlot ram lambs. *Small Ruminant Research*, 207, 106618.
- [17] Liu, Z., & Liu, Y. (2018). Mitigation of greenhouse gas emissions from animal production. *Greenhouse Gases: Science and Technology*, 8(4), 627–638.
- [18] Rivera-Villegas, A., Carrillo-Muro, O., Rodríguez-Cordero, D., Hernández-Briano, P., Sánchez-Barbosa, O.Y., Lazalde-Cruz, R., Castro-Pérez, B.I., & Plascencia, A. (2024). Effects of supplemental calcium propionate and concentrate level: Growth performance, body fat reserves, and health of high-risk beef calves. *Veterinary Sciences*, 11(8), 336.
- [19] Okon, B., Ibom, L. A., Anlade, Y. D. R., & Dauda, A. (2023). A biotechnology perspective of livestock nutrition on feed additives: a mini review. *Nigerian Journal of Animal Production*, 49(5), 47–58.
- [20] Rodríguez-Cordero, D., Carrillo-Muro, O., Hernandez-Briano, P., Rivera-Villegas, A., & Estrada-Angulo, A. (2023). Effect of dietary calcium propionate inclusion level and duration in high-risk newly received stocker calves: Growth performance, body fat reserves, and health. *Agriculture*, 13(11), 2062.
- [21] Zhang, F., Tang, X., & Xiong, B. (2025). Optimal Calcium Propionate Supplementation in Early-Lactation Dairy Cows Improves Milk Yield and Alters Milk Composition. *Animals*, 15(20), 2995.
- [22] Wang, X., Zhu, M., Loo, J.J., Jiang, Q., Zhu, Y., Li, W., Du, X., Song, Y., Gao, W., Lei, L., Wang, J., Liu, G., & Li, X. (2022). Propionate alleviates fatty acid-induced mitochondrial dysfunction, oxidative stress, and apoptosis by upregulating PPAR γ coactivator 1 α in hepatocytes. *Journal of Dairy Science*, 105(5), 4581–4592.
- [23] Osorio-Terán, A. I., Mendoza, G. D., Miranda-Romero, L. A., Martínez-Gomez, D., Hernández-García, P. A., Rangel-Ramírez, V. V., & Lee-Rangel, H. A. (2025). Role of Calcium Propionate and Monensin on Performance, Rumen Fermentation Patterns, and Ruminal Bacterial Populations in Growing Lambs. *Veterinary Sciences*, 12(4), 298.
- [24] Roskam, E., Kenny, D. A., Kelly, A. K., O'Flaherty, V., & Waters, S. M. (2024). Dietary supplementation with calcium peroxide improves methane mitigation potential of finishing beef cattle. *Animal*, 18(11), 101340.
- [25] Alam, S., Shah, H. U., Afzal, M., & Magan, N. (2014). Influence of calcium propionate, water activity and storage time on mold incidence and aflatoxins production in broiler starter feed. *Animal Feed Science and Technology*, 188, 137–144.
- [26] Whitlow, L. W., & Hagler, W. M. (2005). Molds and mycotoxins in feedstuffs—Prevention and treatment. In *Proceedings—Florida Ruminant Nutrition Symposium*, pp. 123-142
- [27] Ullmann's Encyclopedia of Industrial Chemistry. (2000). *Ullmann's Encyclopedia of Industrial Chemistry*. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA
- [28] Huazhong Agricultural University. (2014, October 22). Preparation method of calcium propionate by egg shell (China Patent No. CN102675082B). Retrieved from <https://patents.google.com/patent/CN102675082B/en>
- [29] BASF Aktiengesellschaft. (1987, October 13). Preparation of calcium propionate (U.S. Patent No. US 4,700,000 A). Retrieved from <https://patents.google.com/patent/US4700000A/en>
- [30] Mahmood, A., Zahra, S., Mahmood, R., & Sheikh, A. (2023). Synthesis of calcium propionate from indigenous limestone from Swat area in Pakistan. *European Journal of Chemistry*, 14(4), 460–465.
- [31] Teles, J. H. (2024). Sustainable production of propionic acid and derivatives on an industrial scale. *ChemSusChem*, 17(9), e202301666.
- [32] Niu, S., Li, Y. J., Han, K., Zhao, J. L., & Lu, C. M. (2012). Thermal decomposition characteristics of calcium-based organic compounds under carbon dioxide enriched atmosphere through thermogravimetric analysis. *Advanced Materials Research*, 516–517, 494–501.

- [33] Tiwari, R., Sathesh-Prabu, C., & Lee, S. K. (2022). Bioproduction of propionic acid using levulinic acid by engineered *Pseudomonas putida*. *Frontiers in Bioengineering and Biotechnology*, 10, 939248
- [34] Bicchieri, M., Valentini, F., Calcaterra, A., & Talamo, M. (2017). Newly developed nano-calcium carbonate and nano-calcium propanoate for the deacidification of library and archival materials. *Journal of Analytical Methods in Chemistry*, 2017, 2372789.
- [35] Piwowarek, K., Lipińska, E., Hać-Szymańczuk, E., Kieliszek, M., & Ścibisz, I. (2018). *Propionibacterium* spp.-source of propionic acid, vitamin B12, and other metabolites important for the industry. *Applied Microbiology and Biotechnology*, 102(12), 515–538.
- [36] Shi, Y., Li, R., Zheng, J., Xue, Y., Tao, Y., & Yu, B. (2022). High-yield production of propionate from 1,2-propanediol by engineered *Pseudomonas putida* KT2440, a robust strain with highly oxidative capacity. *Journal of Agricultural and Food Chemistry*, 70(51), 16263–16272.
- [37] Uğur, M., Durmaz, M., Kocakerim, M. M., & Yartaşı, A. (2024). Dissolution behavior and kinetic investigation of colemanite ore in propionic acid solution. *International Journal of Chemistry and Technology*, 8(2), 143–152.
- [38] Thanahiranya, P., Charoensuppanimit, P., Soottitantawat, A., Arpornwichanop, A., Thongchul, N., & Assabumrungrat, S. (2022). Sustainable process design of propionic acid production from glycerol: A comparative study of bio-based and petroleum-based technologies. *ACS Sustainable Chemistry & Engineering*, 10(45), 14761–14774.
- [39] Kjellin, P., Rajasekharan, A. K., Currie, F., & Handa, P. (2016). Investigation of calcium phosphate formation from calcium propionate and triethyl phosphate. *Ceramics International*, 42(12), 14061–14065.
- [40] Rodriguez, B. A., Stowers, C. C., Pham, V., & Cox, B. M. (2014). The production of propionic acid, propanol, and propylene via sugar fermentation: An industrial perspective on the progress, technical challenges, and future outlook. *Green Chemistry*, 16(4), 1066–1076.
- [41] Eş, I., Khaneghah, A. M., Hashemi, S. M. B., & Koubaa, M. (2017). Current advances in biological production of propionic acid. *Biotechnology Letters*, 39(5), 635–645.
- [42] Yadav, V. K., Yadav, K. K., Tirth, V., Gnanamoorthy, G., Gupta, N., Algahtani, A., Islam, S., Choudhary, N., Modi, S., & Jeon, B.-H. (2021). Extraction of value-added minerals from various agricultural, industrial and domestic wastes. *Materials*, 14(21), 6333.
- [43] Minaria, M., & Mohadi, R. (2016). Preparation and characterization of calcium oxide from crab shells (*Portunus pelagicus*) and its application in biodiesel synthesis of waste cooking oil, palm and coconut oil. *Science and Technology Indonesia*, 1(1), 1–7.
- [44] Zhang, F., Wang, Y., Hui, N., Nan, X., Guo, Y., & Xiong, B. (2022). Calcium propionate supplementation has minor effects on major ruminal bacterial community composition of early lactation dairy cows. *Frontiers in Microbiology*, 13, 847488.
- [45] Velázquez-Cruz, L. A., Hernández-García, P. A., Mendoza-Martínez, G. D., Espinosa-Ayala, E., Lee-Rangel, H. A., Vázquez-Silva, G., Razo-Ortíz, P. B., Díaz-Galván, C., Orzuna-Orzuna, J. F., & de la Torre-Hernández, M. E. (2024). Growth Performance, Rumen Fermentation, and Meat Quality of Finishing Lambs Supplemented with Calcium Propionate or Sodium Propionate. *Veterinary Sciences*, 11(12), 604.
- [46] Gurumurthy, C. V., & Govindarao, V. M. H. (1974). Rate model and mechanism of liquid-phase oxidation of propionaldehyde. *Industrial & Engineering Chemistry Fundamentals*, 13(1), 9–17.
- [47] Valor, A., Reguera, E. & Sánchez-Sinencio, F. (2002). Synthesis and X-ray diffraction study of calcium salts of some carboxylic acids. *Powder Diffraction*, 17(1), 13–18.
- [48] Boz, M. A., Küçük, V. A., & Akın, M. B. (2024). Investigation of rapid chemical recycling of waste polyethylene terephthalate under microwave effect using calcined dolomite as catalyst. *Journal of the Turkish Chemical Society Section A: Chemistry*, 11(3), 1025–1036.
- [49] He, T., Wang, X., Long, S., Li, J., Wu, Z., Guo, Y., Sun, F., & Chen, Z. (2023). Calcium propionate supplementation mitigated adverse effects of incubation temperature shift on in vitro fermentation by modulating microbial composition. *Fermentation*, 9(6), 544.
- [50] Agnihotri, S., Yin, D. M., Mahboubi, A., Sapmaz, T., Varjani, S., Qiao, W., Koseoglu-Imer, D.Y., Taherzadeh, M.J. (2022). A glimpse of the world of volatile fatty acids production and application: A review. *Bioengineered*, 13(1), 1249–1275.
- [51] Zhou, J., Shang, X., Wang, Z., Zhu, C., & Wang, S. (2019). Effects of calcium concentration on up-flow multistage anaerobic reactor performance in treating bagasse spraying wastewater. *Bioresources*, 14(2), 4254–4269.
- [52] Laramore, S., & Scarpa, J. (n.d.). pH and alkalinity management in aquaculture hatcheries. USA, <https://shellfish.ifas.ufl.edu/wp-content/uploads/pH-and-Alkalinity-Fact-Sheet-for-Hatcheries-Final-Draft.pdf>, (November 12, 2025).
- [53] Badsara, S. S., Ucheniya, K., Chouhan, A., & Gurjar, A. (2025). Electrochemical synthesis: An alliance of electrochemistry and organic synthesis for value-added moieties. *The Chemical Record*, 25, e2500092.

- [54] Chaitanya, N. K., Rajpurohit, A., Nair, P. S., & Chatterjee, P. (2023). Electrochemical synthesis of propionic acid from reduction of ethanol and carbon dioxide at various applied potentials. *Biochemical Engineering Journal*, 194, 108896.
- [55] Bayer, T., Wu, S., Snajdrova, R., Baldenius, K., & Bornscheuer, U. T. (2025). An update: Enzymatic synthesis for industrial applications. *Angewandte Chemie International Edition*, 64, e202505976.
- [56] Sun, Y., Zhang, J., Sun, Z., & Zhang, L. (2018). Biodiesel production using calcium-based catalyst from venus shell: Modeling of startup production in an industrial reactor. *Environmental Progress & Sustainable Energy*, 38(3), e13053.
- [57] Piwowarek, K., Lipińska, E., Hać-Szymańczuk, E., Kolotylo, V., & Kieliszek, M. (2022). Use of apple pomace, glycerine, and potato wastewater for the production of propionic acid and vitamin B12. *Applied Microbiology and Biotechnology*, 106(17), 5433–5448.
- [58] Alonso, S., Rendueles, M., & Díaz, M. (2015). Microbial production of specialty organic acids from renewable and waste materials. *Critical Reviews in Biotechnology*, 35(4), 497–513.
- [59] Carrillo-Muro, O., Rivera-Villegas, A., Hernandez-Briano, P., Lopez-Carlos, M. A., & Castro-Perez, B. I. (2023). Effect of dietary calcium propionate inclusion period on the growth performance, carcass characteristics, and meat quality of feedlot ram lambs. *Agriculture*, 13(8), 1–14.
- [60] Liu, L., Zhu, Y., Li, J., Wang, M., Lee, P., Du, G., & Chen, J. (2012). Microbial production of propionic acid from propionibacteria: Current state, challenges and perspectives. *Critical Reviews in Biotechnology*, 32(4), 374–381.
- [61] Dishisha, T., Ståhl, Å., Lundmark, S., & Hatti-Kaul, R. (2013). An economical biorefinery process for propionic acid production from glycerol and potato juice using high cell density fermentation. *Bioresource Technology*, 135, 504–512.
- [62] Soares Santos, I. M. T., Ramirez Brenes, R. G., Figueiredo, F. R., Martínez Prata, D., Bojorge Ramirez, N. I., & Pereira, N., Jr. (2025). Sustainable production of propionic acid from xylose and glycerol by *Acidipropionibacterium acidipropionici* DSM 4900: A biorefinery approach. *Processes*, 13(11), 3556.
- [63] McIlroy, S., Kirkegaard, R., Dueholm, M., Fernando, E., Karst, S., Albertsen, M., & Nielsen, P. (2017). Culture-independent analyses reveal novel Anaerolineaceae as abundant primary fermenters in anaerobic digesters treating waste activated sludge. *Frontiers in Microbiology*, 8, 1134.
- [64] Sarmiento-Vásquez, Z., Vandenberghe, L., Rodrigues, C., Oliveira A. Tanobe, V., Marín, O., Pereira, G. V. de M., Rogez, H. L. G., Góes-Neto, A., & Soccol, C. R. (2021). Cocoa pod husk valorization: Alkaline-enzymatic pre-treatment for propionic acid production. *Cellulose*, 28(6), 4009–4024.
- [65] Zhang, M., Zhang, D., Du, J., Zhou, B., Wang, D., Liu, X., Yan, C., Liang, J., & Zhou, L. (2023). Enhancing propionic acid production in the acidogenic fermentation of food waste facilitated by a fungal mash under neutral pH. *Journal of Environmental Management*, 327, 116901.
- [66] Puengrang, P., Suraraksa, B., Prommeenate, P., Boonapatcharoen, N., Cheevadhanarak, S., Tanticharoen, M., & Kusonmano, K. (2020). Diverse microbial community profiles of propionate-degrading cultures derived from different sludge sources of anaerobic wastewater treatment plants. *Microorganisms*, 8(2), 277.
- [67] Ranaei, V., Pilevar, Z., Mousavi Khaneghah, A., & Hosseini, H. (2020). Propionic acid: Method of production, current state and perspectives. *Food Technology and Biotechnology*, 58(2), 115–127.
- [68] Handojo, L., Wardani, A. K., Regina, D., Bella, C., Kresnowati, M. T. A. P., & Wenten, I. G. (2019). Electro-membrane processes for organic acid recovery. *RSC Advances*, 9, 7854–7869.
- [69] Ahmed, T. A. E., Wu, L., Younes, M., & Hincke, M. (2021). Biotechnological applications of eggshell: Recent advances. *Frontiers in Bioengineering and Biotechnology*, 9, 675364.
- [70] Wang, Z., Jin, Y., & Yang, S.-T. (2015). High cell density propionic acid fermentation with an acid-tolerant strain of *Propionibacterium acidipropionici*. *Biotechnology and Bioengineering*, 112(3), 502–511.
- [71] Antone, U., Ciprova, I., Zolovs, M., Scerbaka, R., & Liepins, J. (2023). Propionic acid fermentation—Study of substrates, strains, and antimicrobial properties. *Fermentation*, 9(1), 26.
- [72] Farhadi, S., Khosravi-Darani, K., Mashayekh, M., Mortazavian, A.M., Mohammadi, A., & Shahraz, F. (2013). Production of propionic acid in a fermented dairy beverage. *International Journal of Dairy Technology*, 66(1), 127–134.
- [73] Wang, Z., & Yang, S.-T. (2013). Propionic acid production in glycerol/glucose co-fermentation by *Propionibacterium freudenreichii* subsp. *shermanii*. *Bioresource Technology*, 137, 116–123.
- [74] Himmi, E. H., Bories, A., Boussaid, A., & Hassani, L. (2000). Propionic acid fermentation of glycerol and glucose by *Propionibacterium acidipropionici* and *Propionibacterium freudenreichii* ssp. *shermanii*. *Applied Microbiology and Biotechnology*, 53(4), 435–440.
- [75] Cavero-Olguin, V.H., Dishisha, T. & Hatti-Kaul, R. (2023) Membrane-based continuous fermentation with cell recycling for propionic acid production from glycerol by *Acidipropionibacterium acidipropionici*. *Microbial Cell Factories*, 22, 43.

- [76] Dishisha, T., Jain, M., & Hatti-Kaul, R. (2024). High cell density sequential batch fermentation for enhanced propionic acid production from glucose and glycerol/glucose mixture using *Acidipropionibacterium acidipropionici*. *Microbial Cell Factories*, 23, 91.
- [77] Schmidt, A., Sturm, G., Lapp, C., Siebert, D., Saravia, F., Horn, H., Ravi, P. P., Lemmer, A., & Gescher, J. (2018). Development of a production chain from vegetable biowaste to platform chemicals. *Microbial Cell Factories*, 17, 90.
- [78] Elghandour, M. M. Y., Kholif, A. E., Salem, A. Z. M., de Oca, R. M., Barbabosa, A., Mariezcurrena, M., & Olafadehan, O. A. (2016). Addressing sustainable ruminal methane and carbon dioxide emissions of soybean hulls by organic acid salts. *Journal of Cleaner Production*, 135, 194–200.
- [79] Brand, T.P.H., Roest, K., Brdjanović, D., Chen, G.H., & Loosdrecht, M.C.M. (2014). Influence of acetate and propionate on sulphate-reducing bacteria activity. *Journal of Applied Microbiology*, 117(6), 1839–1847.
- [80] Ekman, A., & Börjesson, P. (2011). Environmental assessment of propionic acid produced in an agricultural biomass-based biorefinery system. *Journal of Cleaner Production*, 19(11), 1257–1265.
- [81] Watanabe, Y., Suzuki, R., Koike, S., Nagashima, K., Mochizuki, M., Forster, R.J., & Kobayashi, Y. (2010). In vitro evaluation of cashew nut shell liquid as a methane-inhibiting and propionate-enhancing agent for ruminants. *Journal of Dairy Science*, 93(11), 5258–5267.