

Review

Microwave-Assisted Enzymatic Ring-Opening Polymerization: Toward Green Synthesis of Medical and Pharmaceutical Polymers

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Abstract

Microwave-assisted enzymatic ring-opening polymerization (eROP) has emerged as a promising green approach for the synthesis of biomedical polymers with potential applications in drug delivery systems and implantable biomaterials. This review provides a critical overview of the current state of microwave-assisted eROP, with particular emphasis on systems catalyzed by *Candida antarctica* lipase B (CALB), the most widely used biocatalyst in this field. The fundamental aspects of CALB-catalyzed polymerization, including its catalytic mechanism and key parameters influencing reaction efficiency, are discussed under both conventional and microwave-assisted conditions. Microwave irradiation can offer significant advantages, such as reduced reaction times, improved energy efficiency, and, in some cases, enhanced polymer properties, including higher molecular weight and narrower dispersity. However, its effects are strongly dependent on reaction conditions, including solvent properties, temperature, and enzyme stability, with both accelerating and inhibiting effects reported. The review summarizes the current literature on microwave-assisted eROP of representative cyclic monomers, including ϵ -caprolactone, ω -pentadecalactone, and L-lactide, highlighting the influence of microwave parameters on polymerization outcomes and material properties. Despite promising results, microwave-assisted eROP remains relatively underexplored, with limited monomer scope and incomplete understanding of microwave–enzyme interactions. Challenges such as enzyme deactivation, lack of standardized methodologies, and scalability issues are also addressed. Overall, microwave-assisted eROP of cyclic monomers represents a sustainable and efficient strategy for producing high-quality pharmaceutical polymers. However, further research is required to fully realize its potential in industrial and biomedical applications.



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1. Introduction

The growing demand for safer and more effective drug delivery systems (DDSs) has accelerated interest in polymer-based pharmaceutical materials. Although specific strategies vary, they predominantly focus on developing advanced systems, such as micro- and nanoparticles, polymer–drug conjugates (macromolecular prodrugs), hydrogels, and other

innovative polymeric delivery platforms. Polymers intended for use as carriers must be fully biocompatible, non-toxic, easily obtainable, and cost-effective. For implantable formulations, they should also be biodegradable or bioresorbable. Moreover, the polymer must not compromise the stability of the active pharmaceutical ingredient [1–3]. One of the most important and promising classes of biomedical polymers used in pharmaceutical formulations includes aliphatic polyesters, polycarbonates, and their co- or terpolymers derived from cyclic ester and cyclic carbonate monomers. The most commonly used monomers are ϵ -caprolactone (ϵ -CL), glycolide (GG), trimethylene carbonate (TMC), ω -pentadecalactone (ω -PDL) and lactide (LA). LA is particularly interesting due to its stereochemistry, which allows tuning the crystallinity and degradation rate of the resulting polymers, properties highly relevant for drug delivery and implantable systems [2]. One of the key methods for producing biomedical polymers is ring-opening polymerization (ROP) [4,5]. ROP can provide polymers with high purity, controlled molecular characteristics, and relatively low dispersity ($\bar{M}_w/\bar{M}_n$) under appropriately optimized conditions. These materials can be synthesized using coordination catalysts, cationic or anionic initiators, as well as enzymatic catalysts. The use of enzymes in ROP offers significant advantages, as they are environmentally friendly and non-toxic to living organisms. Moreover, enzymatic catalysis simplifies the production of biomedical polymers by eliminating the need for purification from toxic residues of traditional initiators or catalysts. Because of these advantages, enzymatic ring-opening polymerization (eROP) is especially appealing for the synthesis of polymers intended for medical and pharmaceutical applications. To date, the activity of numerous biocatalysts in the ROP process of cyclic monomers has been studied (including *Candida antarctica* lipase B (CALB)/Novozym 435, *Pseudomonas cepacia* lipase/PS 30, *Pseudomonas fluorescens* lipase, porcine pancreatic lipase, and esterases from *Archaeoglobus fulgidus* [6,7].

An emerging and promising approach to producing polymers for pharmaceutical applications is microwave-assisted synthesis. Numerous studies have demonstrated that microwave-assisted polymerization can accelerate reaction rates, enhance selectivity, and in particular systems, advancements in yield or material qualities have also been observed. Beyond improving synthesis efficiency, microwave irradiation also aligns with green chemistry principles by enabling rapid, energy-efficient heating and reducing solvent and energy consumption [8–12].

In recent years, increasing attention has been given to combining eROP with microwave irradiation, a strategy that shows considerable promise for medical and pharmaceutical applications. In this review, we focus specifically on microwave-assisted eROP with use of CALB, discussing its current state, advantages and disadvantages, and its potential to produce polymers relevant to the pharmaceutical field. It should be emphasized that the focus of this review on CALB reflects the current state of the primary literature rather than a restriction imposed by the authors. To the best of our knowledge, all microwave-assisted enzymatic ROP studies reported to date have employed CALB, almost exclusively as the immobilized preparation Novozym 435. This is notable given that, under conventional heating, non-CALB biocatalysts such as lipase PS and porcine pancreatic lipase exhibit markedly higher activity than CALB toward LAs and certain other monomers that are poorly polymerized by CALB [13]. The absence of microwave-assisted ROP studies employing these alternative enzymes therefore represents not merely a gap but also a specific and promising research opportunity, particularly for the enzymatic synthesis of polylactide (PLA), which remains challenging for CALB.

2. *Candida antarctica* Lipase B as a Biocatalyst in Microwave-Assisted Ring-Opening Polymerization

Lipases are an important class of biocatalysts that facilitate a broad range of reactions, including esterification, transesterification, and enzymatic polyester synthesis. Owing to their high selectivity, metal-free nature, and ability to operate under mild reaction conditions, lipases have become key enzymes employed in eROP. Among them, CALB derived from the psychrotolerant Antarctic yeast *Moesziomyces antarcticus* (formerly *Candida antarctica* [14]) is by far the most extensively studied and widely applied enzyme in both conventional and microwave-assisted eROP. The widespread adoption of CALB in polymer chemistry arises from its high enantio-, regio-, and chemo-selectivity, broad monomer scope, especially with respect to lactones and certain cyclic esters, and excellent operational stability, particularly in immobilized forms. In this section, the catalytic mechanism of CALB in eROP and the key determinants of CALB-catalyzed polymerization efficiency are discussed [15–18].

2.1. Catalytic Mechanism of *Candida antarctica* Lipase B in Enzymatic Ring-Opening Polymerization

CALB is a member of the α/β -hydrolase-fold superfamily. Its active site is defined by a catalytic triad comprising Ser105, His224, and Asp187, a motif common to serine hydrolases, which works in concert with two hydrophobic substrate-binding pockets. Above the triad lies the oxyanion hole, formed by hydrogen-bond donors from Gln106 and Thr40, which stabilizes the tetrahedral transition state and the oxyanion of the reaction intermediate. Together, these features enable efficient eROP under appropriate reaction conditions [15,16,19].

CALB-catalyzed eROP proceeds in two main steps, illustrated here using lactones as representative substrates (Figure 1). First, nucleophilic attack by the catalytic Ser105 opens the lactone ring, forming an active acyl–enzyme complex (AEC). Second, a nucleophile, typically an added alcohol initiator, or, alternatively, residual water or hydroxyl-containing impurities, attacks the acyl carbon of the AEC, regenerating the enzyme and yielding a ring-opened ω -hydroxycarboxylic acid; added alcohol initiators afford better control over initiation and end-group structure, whereas water promotes hydrolytic chain transfer that lowers molecular weight. Chain growth then proceeds by nucleophilic attack of the terminal hydroxyl group of the growing chain on a newly formed AEC, leaving a hydroxyl group at one terminus and the initiator-derived functionality at the other. Kinetic studies have shown that both the formation of the lipase–lactone complex and the reactivity of the AEC are critical determinants of polymerization efficiency and achievable molecular weight [15].

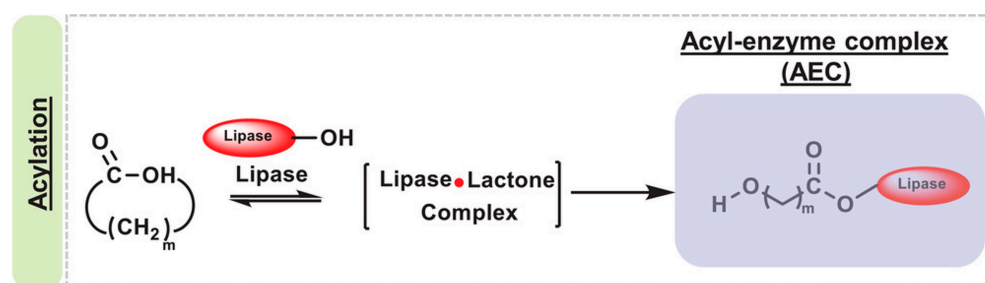


Figure 1. Cont.

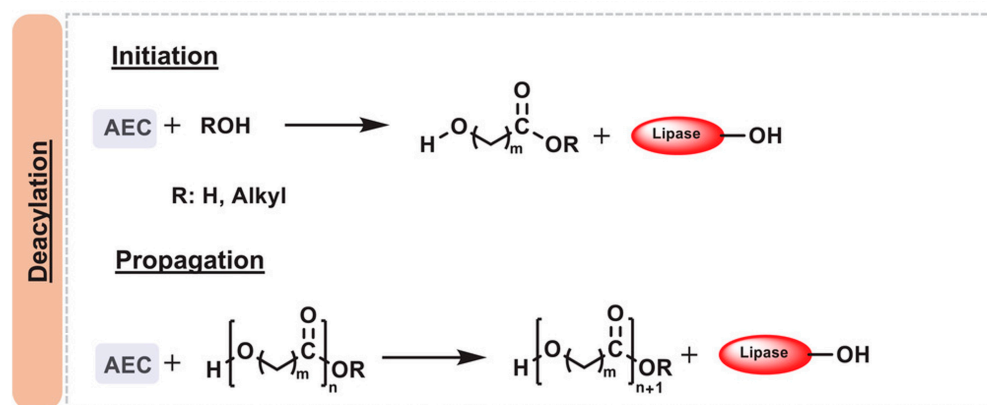


Figure 1. Lipase-catalyzed ring-opening polymerization to form polyesters from cyclic esters. Reproduced from Hevilla et al. [15] under a CC BY 4.0 license.

2.2. Determinants of *Candida antarctica* Lipase B-Catalyzed Polymerization Efficiency

Several studies have focused on identifying key reaction parameters that influence polymerization efficiency in systems where CALB serves as the catalyst [15,16,19–22]. Although these reactions were conducted under conventional heating conditions and include both ROP and polycondensation, the determinants of catalytic efficiency discussed below are intrinsic to the enzyme and therefore directly relevant to microwave-assisted eROP systems.

The first consideration when using CALB as a catalyst is whether the enzyme is employed in its free or immobilized form. Immobilized CALB preparations, such as Novozym 435, are generally preferred, as they consistently exhibit enhanced activity and operational stability compared to the free enzyme, particularly at elevated temperatures, variable pH, and mechanical stirring. Reaction temperature and time are additional key parameters affecting CALB performance. In general, provided that enzyme denaturation or reduced monomer affinity does not occur, increasing reaction temperature and extending reaction time promote higher conversions and facilitate chain growth, leading to increased weight-average molecular weight (M_w) of the obtained polymers. Another critical determinant is the presence of water. Limited amounts of bound or residual water can support catalytic activity and may also play a role in chain initiation. However, an overabundance of water fosters hydrolytic side reactions, often resulting in products with lower number-average molecular weight (M_n) and a decrease in the conversion. Therefore, careful control of water content is essential. The presence and type of solvent also play a crucial role in CALB-catalyzed polymerizations. The choice of solvent strongly influences the achievable molar mass in CALB-catalyzed eROP, primarily through its polarity and enzyme compatibility. Kumar and Gross [23] demonstrated this systematically for Novozym 435-catalyzed ϵ -CL polymerization: solvents with low log P values (log P -1.1 to 0.49) gave low conversions ($\leq 30\%$ in 4 h) and short chains ($M_n \leq 5200 \text{ g}\cdot\text{mol}^{-1}$), whereas solvents with higher log P values (log P 1.9 – 4.5) afforded markedly higher molar masses ($M_n = 11,500$ – $17,000 \text{ g}\cdot\text{mol}^{-1}$), with toluene reaching $M_n \approx 44,800 \text{ g}\cdot\text{mol}^{-1}$ on a larger scale. However, the solvent's physical properties, such as polarity, dielectric constant, and log P, must be carefully considered, as they can either promote or hinder polymerization. Highly polar solvents may deactivate the enzyme by inducing conformational changes or by stripping essential water molecules from the enzyme, thereby favoring hydrolysis over polymerization. Consequently, low-polarity solvents are generally preferred. In addition, strong enzyme-solvent affinity is required to preserve the optimal three-dimensional structure of the active site, guaranteeing accessibility to reactive groups of polymerized monomers. Other solvent characteristics, including chemical stability under the reaction

conditions and boiling point, must also be considered. These considerations are particularly important in microwave-assisted eROP, where solvent dielectric properties directly influence energy absorption and heating efficiency, thereby affecting enzyme performance. Monomer structure strongly influences eROP efficiency, and ring size affects enzymatic and chemical ROP in opposite ways. In conventional ROP, reactivity is governed by ring strain and decreases sharply as the ring expands, with propagation rates spanning several orders of magnitude between the strained six-membered lactone and the essentially strain-free sixteen- and seventeen-membered macrolactones. In CALB-catalyzed eROP, this dependence is inverted: the macrolactones, despite their low ring strain, polymerize fastest, with the sixteen- and seventeen-membered rings reacting roughly an order of magnitude faster than ϵ -CL [24,25]. Finally, the ratio of cyclic monomer to enzyme, as well as the presence of initiators, strongly influences the Mw and end-group fidelity of the resulting polymers.

2.3. Microwave-Assisted Enzymatic Ring-Opening Polymerization

In recent years, microwave heating has attracted increasing attention as an alternative heat source in green chemistry, offering a rapid, energy-efficient, and potentially more selective means of driving chemical reactions. Microwave heating is based on the interaction of materials with electromagnetic irradiation at frequencies between 300 MHz and 300 GHz, corresponding to wavelengths ranging from 1 mm to 1 m. In polymerization processes, microwave heating has been shown to significantly shorten reaction times, improve yields and selectivity, and reduce overall heating energy requirements. Although many of these enhancements can be attributed to purely thermal effects, in some cases, they are not always readily reproduced under conventional heating conditions. Such effects are often associated with characteristics of dielectric heating, including inverted temperature profiles, solvent superheating under ambient pressure, and the selective heating of highly microwave-absorbing species in less polar reaction media [22,26,27].

Microwave heating is therefore considered a promising tool for more sustainable chemistry, given the abovementioned properties. The application of microwave heating for the polymerization process has been studied for numerous reactions, e.g., ROP, controlled radical polymerizations, and metal-catalyzed cross-coupling polymerization [9].

In this context, microwave heating has also emerged as a promising energy source for eROP, particularly in systems catalyzed by CALB. The following sections focus on the application of microwave irradiation to eROP, with emphasis on the CALB forms employed and the monomer scope explored to date.

2.4. Enzyme Forms and Monomer Scope in Microwave-Assisted eROP

Compared to conventional studies on eROP, microwave-assisted eROP remains a relatively underexplored area, with only a limited number of reports available in the literature. To date, the catalytic systems employed almost exclusively involve immobilized forms of CALB, most commonly in its commercial preparation, Novozym 435 [26,28–31], although laboratory-immobilized variants have also been reported [32]. Regarding monomer scope, ϵ -CL is by far the most frequently investigated substrate. In contrast, larger lactones, such as ω -PDL, and cyclic diesters, such as L-lactide (LLA), have received considerably less attention (Table 1). The literature discussed in this review was identified through searches of the Scopus, Web of Science, and PubMed databases, complemented by Google Scholar, using combinations of the terms “microwave,” “enzymatic,” “lipase,” “*Candida antarctica* lipase B,” “Novozym 435,” and “ring-opening polymerization,” with no date restrictions and covering publications available up to 1 March 2026. Reference lists of the retrieved articles were manually screened for additional sources. This search revealed that the body of primary experimental work dedicated specifically

to microwave-assisted eROP is remarkably small, comprising only a handful of peer-reviewed studies, despite the substantial independent literature on enzymatic ROP and on microwave-assisted polymerization considered separately. Rather than reflecting a restricted search, this scarcity is itself one of the central observations of the present review and motivates the critical, study-by-study treatment adopted here. Notably, recent methodological advances in enzymatic ROP have concentrated on continuous-flow processing and bio-derived green solvents rather than on microwave heating, which may partly explain why the microwave-assisted eROP literature has not expanded substantially in recent years [33,34]. Several cyclic monomers of clear biomedical relevance, as discussed above, have not been reported under microwave-assisted eROP conditions. To the best of our knowledge, no peer-reviewed study describes the microwave-assisted enzymatic ROP of TMC, GG, or their copolymers. This gap is striking because microwave heating and enzymatic ROP have each been applied to these monomers separately, but never in combination. TMC, for example, has been successfully polymerized under microwave irradiation using metal-free initiators [35] and has independently been polymerized enzymatically with various lipases under conventional heating [36]; yet microwave-assisted enzymatic ROP of TMC remains unreported. GG has also been successfully copolymerized using several enzymes [37], but no studies have reported the combination of eROP with microwave heating in these reactions. Several factors likely explain why TMC, GG, and their copolymers have not yet been examined under microwave-assisted eROP conditions. First, CALB exhibits distinct substrate specificity: it efficiently polymerizes ϵ -CL and macrolactones [24,25] but shows limited activity toward six-membered cyclic diesters [13] and carbonates like TMC, which are being polymerized more readily by other lipases than by CALB [38]. Because essentially all microwave-assisted eROP studies reported to date have employed CALB, these monomers fall outside its most productive substrate range of the currently used biocatalyst. Second, CALB exhibits clearly solvent-dependent behavior under microwave conditions [28], which introduces an additional factor to consider when selecting reaction conditions: when a solvent is used, monomer solubility and crystallinity behavior must also be taken into account to achieve optimal polymerization. Third, the dielectric heating that makes microwave processing attractive may also increase the risk of local overheating and thermal deactivation of the biocatalyst [26], precisely under the more forcing conditions required by higher-melting monomers such as GG. Taken together, substrate specificity, monomer solubility and crystallization behavior, and susceptibility to enzyme deactivation may plausibly account for the current absence of microwave-assisted enzymatic ROP data for TMC, GG, and their copolymers. These gaps represent clear opportunities for future work, particularly given the relevance of TMC-based polycarbonates and GG-containing copolymers to resorbable biomedical devices.

As noted above, the most commonly used immobilized form of CALB in microwave-assisted eROP is Novozym 435, an immobilized preparation of CALB supplied by Novone-sis (formerly Novozymes). The first report describing its use in polymerization dates back to 1992. Novozym 435 consists of CALB immobilized on Lewatit[®] VP OC 1600, a macroporous acrylic resin support based on poly(methyl methacrylate) crosslinked with divinylbenzene. The enzyme is immobilized by adsorption via interfacial activation; however, this method has also been reported to cause partial aggregation of enzyme molecules. To date, Novozym 435 remains the most widely used lipase preparation in the eROP literature, including studies that employ microwave heating. An alternative immobilized CALB system reported in the discussed studies [32] involves CALB immobilized on nanopolystyrene, using the photoreactive reagent 1-fluoro-2-nitro-4-azidobenzene (FNAB) as a coupling agent.

Table 1. Conditions of the enzymatic ring-opening polymerization process assisted by microwave irradiation of cyclic esters and properties of the obtained products.

Monomer	Enzyme Catalyst	Temp. (°C)	Solvent	Microwave Power (W)	Time (min)	Key Outcomes	Ref.
ϵ -CL	Novozym 435	reflux	toluene, benzene, THF, dioxane, diethyl ether	100–300	90	The microwave effect was strongly solvent-dependent. In boiling diethyl ether the polymerization rate increased under microwave irradiation, whereas in boiling toluene or benzene it was lower than under conventional heating. Yield and molecular-weight have shown solvent-dependent behavior.	[28]
ϵ -CL initiated with 2-mercaptoethanol	Novozym 435	reflux	diethyl ether	200	90	Microwave-assisted enzymatic polymerization produced thiol-terminated PCL with higher yield and improved chemoselectivity compared to conventional heating. The obtained polyester was characterized by SEC ($M_n \sim 3600 \text{ g} \cdot \text{mol}^{-1}$) and was used as a macro chain transfer reagent for the synthesis of PCL-block-polystyrene.	[29]
ϵ -CL	Novozym 435	20–90	in bulk	50–250	30–240	The study showed that microwave irradiation can enhance lipase-catalyzed, solvent-free synthesis of PCL, but the effect is not linear. Excessive power or the temperature may reduce enzyme stability due to microenvironmental heating and water-content sensitivity. The authors calculated the optimal microwave heating conditions (90 °C, 50 W and 240 min), that allow them to obtain PCL with $M_n = 20,624 \text{ g} \cdot \text{mol}^{-1}$ measured by GPC with $\bar{D} = 1.2$	[26]

Table 1. Cont.

Monomer	Enzyme Catalyst	Temp. (°C)	Solvent	Microwave Power (W)	Time (min)	Key Outcomes	Ref.
ω -PDL	Novozym 435	70	in bulk	200	30–240	Maximum Mn achieved with microwave-assisted eROP equaled 24,997 g·mol ^{−1} with Đ = 1.93 after 240 min. Conventional heating yielded polymer with Mn = 8060 g·mol ^{−1} ; Đ = 2.17 within the same reaction time. Microwave irradiation accelerated polymerization without adverse effects on thermal properties.	[30]
ϵ -CL/ ω -PDL	Novozym 435	85	toluene	240	60	High conversions of 91–95% were obtained within 60 min. The products were semicrystalline polyesters/copolyesters. The melting temperature increased from about 57 °C to 95 °C with increasing ω -PDL content; thermal stability also increased with higher ω -PDL fraction.	[31]
L-LA	Covalently immobilized CALB	90	toluene	200	240–960	Optimum conditions: 8 wt% biocatalyst relative to monomer and 8 h reaction time. Monomer conversion ~98%; viscosity-average molar mass M_{η} ~56,125 g·mol ^{−1} ; crystallinity 50.3%; specific rotation 145 deg dm ^{−1} g ^{−1} cm ³ . Simultaneous cooling increased molar mass by improving microwave penetration and biocatalyst stability.	[32]

Immobilization of CALB offers several well-recognized advantages, including improved thermal stability, enhanced operational stability, and catalyst reusability. However, the use of solid supports can also introduce limitations. The observed decrease in activity is primarily attributed to enzyme leaching, adsorption of oligomers or polymer chains onto the catalyst surface, mechanical damage to the support during repeated handling, and gradual thermal or solvent-induced enzyme deactivation. At the same time, the extent of biocatalyst deactivation strongly depends on the reaction medium, temperature, monomer type, water activity, and the immobilization strategy employed. Immobilization on hydrophobic supports not only facilitates catalyst recovery but also enhances thermal stability and preserves the enzyme's active conformation, making repeated use feasible across a broad range of reaction conditions.

Despite numerous reports demonstrating successful biocatalyst recycling, systematic comparative studies remain relatively limited, and the methodologies used to evaluate catalyst reusability vary considerably among publications. Consequently, direct comparison of operational stability across different biocatalytic systems is often challenging. We emphasize that standardized protocols for catalyst recovery and long-term reuse testing would greatly facilitate the comparison of different immobilized enzyme systems and accelerate their industrial implementation.

3. Studies on Microwave-Assisted eROP by Monomer Class

3.1. ϵ -Caprolactone

ϵ -CL is a seven-membered lactone widely used as a monomer for the synthesis of poly(ϵ -caprolactone) (PCL), a semicrystalline aliphatic polyester characterized by excellent biocompatibility, slow hydrolytic degradation, minimal acidic byproduct formation, and a relatively low melting temperature. These properties make PCL particularly attractive for the design of DDSs and implantable biomedical devices.

PCL is commonly synthesized via ROP, including eROP under mild reaction conditions (Figure 2). From a synthetic standpoint, ϵ -CL readily undergoes ROP due to the ring strain and the reactivity of its ester bond. The presence of a polar carbonyl group within the lactone ring enables efficient dipolar polarization under microwave irradiation, facilitating rapid dielectric heating. Consequently, microwave-assisted polymerization of ϵ -CL has been reported in selected systems to reduce reaction times, improve process efficiency, and potentially enhance control over molecular weight, an essential parameter for tailoring degradation kinetics in pharmaceutical and biomedical applications [27,39].

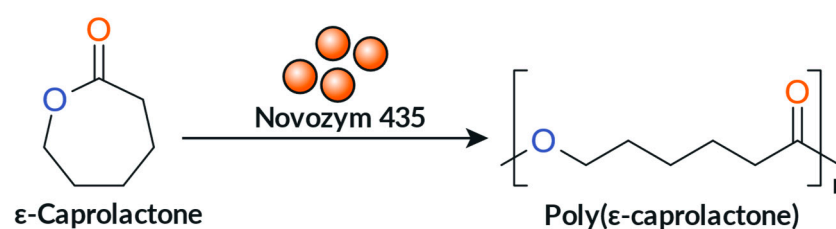


Figure 2. Enzymatic ring-opening polymerization of ϵ -caprolactone catalyzed by Novozym 435, yielding poly(ϵ -caprolactone). Oxygen atoms indicate the bond cleavage and structural transformation occurring during the ring-opening process.

In the first study to address the influence of microwave irradiation on eROP of ϵ -CL, Kerep and Ritter systematically compared microwave-assisted polymerization with conventional oil bath heating in various boiling solvents. Since Novozym 435 catalyzed eROP of ϵ -CL is known to strongly depend on both temperature and solvent polarity, five solvents with different dielectric properties were selected: tetrahydrofuran (THF)

and dioxane as polar solvents; toluene, benzene, and diethyl ether as less polar solvents. To ensure reliable comparison between heating methods, a monomer stock solution was prepared by dissolving 5 g of ϵ -CL in 20 g of solvent, which was subsequently divided into two equal portions. Novozym 435 (125 mg) was added to each portion, and the mixtures were polymerized under reflux for 90 min either under constant microwave irradiation (100–300 W) in a microwave reactor or in an oil bath at the respective boiling temperature. After reaction, the enzyme was removed by filtration, and the polymer was isolated by precipitation in cold methanol. Yields were determined gravimetrically, monomer conversion was analyzed by ^1H NMR spectroscopy, and molecular weights were determined by size exclusion chromatography (SEC) using polystyrene standards. No polymerization occurred in the polar solvents (THF and dioxane) under either heating method. Therefore, further investigations focused on the less polar solvents. When toluene or benzene was used as a boiling solvent, microwave irradiation resulted in significantly lower monomer conversion than conventional heating. In toluene, microwave irradiation led to a maximum conversion of approximately 30% after 60 min, after which the reaction plateaued, whereas thermal heating produced continuous conversion increases up to ~60% after 90 min. Similar deceleration was observed in benzene. The authors attributed this behavior to possible microwave-induced denaturation of the enzyme. However, enzyme stability under microwave irradiation was not independently evaluated. In contrast, when diethyl ether was used, the opposite trend was observed. Under microwave irradiation, the reaction proceeded faster and reached higher conversions (~60%) than under conventional heating (~50%). The authors suggested that microwave irradiation might promote a more favorable spatial fit between the enzyme active site and the substrate under these conditions. Gravimetrically determined yields and SEC-derived molecular weights followed the same solvent-dependent trend. In toluene and benzene, microwave-assisted reactions yielded lower M_n values than those obtained with thermal heating. Conversely, in diethyl ether, microwave irradiation yielded higher M_n values, up to $\sim 5800\text{ g}\cdot\text{mol}^{-1}$ at 200 W, compared to $\sim 4900\text{ g}\cdot\text{mol}^{-1}$ with oil bath heating. MALDI-TOF analysis further confirmed a shift toward higher-molecular-weight species under microwave irradiation in diethyl ether and revealed a higher ratio of linear chains to macrocyclic species. Importantly, variation in irradiation power (100–300 W) did not significantly affect conversion or yield. To exclude microwave-induced superheating, reaction temperatures were monitored with a fiber-optic temperature probe. The maximum deviation between oil bath and microwave heating was only 1–1.5 °C, within experimental error. The authors therefore concluded that the small variations in temperature noted between the two heating modes support the argument that the behavior influenced by the solvent cannot be explained merely by differences in bulk temperature, although the specific origin of the effect is still not fully understood. This study demonstrated, for the first time, that microwave irradiation can produce both accelerating and decelerating effects on eROP, depending strongly on the dielectric properties of the reaction medium. Careful temperature monitoring using a fiber-optic probe strengthened the discussion of potential thermal versus microwave-specific effects [28].

Kerep and Ritter investigated microwave-assisted eROP of ϵ -CL using 2-mercaptoethanol as the initiator to synthesize a thiol-terminated PCL that functions as a macro chain transfer reagent (MCTR). The resulting MCTR was subsequently evaluated in combination with 2,2'-azobis(2-methylpropionitrile) (AIBN) for the radical polymerization of styrene to form block copolymers. As in their previous work, polymerizations performed under conventional oil bath heating and microwave irradiation were directly compared. For the eROP, ϵ -CL was dried over CaH_2 and distilled prior to use, while Novozym 435 was dried over phosphorus pentoxide under vacuum for 24 h. To ensure a reliable comparison of heating methods, a stock solution of ϵ -CL and 2-mercaptoethanol was prepared. A

mixture of 5 g (44 mmol) of ϵ -CL and 160 mg (2 mmol) of 2-mercaptoethanol was dissolved in 20 g of diethyl ether, divided into two equal portions, and 125 mg of Novozym 435 was added to each. The reactions were conducted for 90 min under reflux, either at constant microwave irradiation power (200 W) or in an oil bath at the corresponding reflux temperature. After polymerization, the enzyme was removed by filtration, and the polymer was isolated by precipitation at 5 °C in diethyl ether/hexane (2:1 *w/w*). M_n and $\bar{D}$ were determined by SEC (THF, polystyrene standards). The ratio of ester to thioester structures (i.e., polymers with and without terminal –SH groups) was calculated from ^1H NMR spectra, and yields were determined gravimetrically after precipitation. Both heating methods yielded polymers with comparable molecular weights ($M_n = 3600 \text{ g}\cdot\text{mol}^{-1}$ under microwave heating and $3400 \text{ g}\cdot\text{mol}^{-1}$ under oil bath heating) and identical dispersities ($\bar{D} = 1.5$). However, the yield was higher under microwave irradiation (29%) than under conventional heating (18%). Thermodynamic considerations suggest that the formation of standard ester linkages is favored over thioesters, as thioesters are more reactive and prone to transesterification. Consistent with this expectation, ^1H NMR analysis confirmed that the predominant product in both cases was polyester bearing a terminal –SH group. Importantly, microwave irradiation enhanced chemoselectivity: the ratio of –SH-terminated polyester to non-thiol-terminated species was 86:14 under microwave irradiation, compared to 78:22 under oil bath conditions. This indicates a beneficial influence of microwave irradiation on the selectivity of initiation. MALDI-TOF MS analysis further confirmed the formation of predominantly thiol-terminated PCL and showed good agreement between calculated and experimental *m/z* values. No significant macrocyclic species or disulfide dimers were detected, indicating that oxidation of –SH groups did not occur under the applied conditions. The synthesized thiol-terminated PCL was subsequently used as a macromolecular chain transfer reagent in the radical polymerization of styrene. (Further discussion of the radical copolymerization is omitted here, as it is beyond the scope of this review) [29].

Matos et al. investigated microwave-assisted, lipase-catalyzed ROP of ϵ -CL under solvent-free conditions. In contrast to Kerep and Ritter, no boiling solvents were used, allowing evaluation of microwave effects in bulk polymerization. To optimize reaction conditions, a modified mixture design (monomer-biocatalyst) was employed. The independent variables were temperature (20–90 °C), microwave power (50–250 W), and reaction time (30–240 min), while the response variables were M_n and $\bar{D}$. Linear, quadratic, and cubic regression models were developed to analyze primary and interaction effects. Ternary contour plots and 3D visualizations were generated to map the design space and identify optimal conditions. Novozym 435 (10 wt % relative to monomer) was reacted with ϵ -CL in a microwave reactor with simultaneous air cooling to control bulk temperature. After the reaction, the polymers were dissolved in THF, filtered to remove the enzyme, and characterized by gel permeation chromatography (GPC) to determine their M_n and $\bar{D}$ values. Ternary plots showed that M_n increased toward the boundary between the temperature and time vertices, whereas high microwave power reduced M_n . $\bar{D}$ decreased in regions where M_n was highest, consistent with eROP mechanisms in which chain propagation at higher conversion leads to higher M_n and narrower distributions. A cubic regression model ($R^2 = 0.94$, adjusted $R^2 = 0.84$; F-value = $3.49 \cdot 10^{-7}$) indicated that temperature had the strongest positive effect on M_n , followed by time, while microwave power had the least positive influence. The only statistically significant interaction was between power and time ($p < 0.05$). Model optimization using Solver within Microsoft Excel® predicted optimal reaction conditions at 90 °C, 240 min, and 50 W. Under these conditions, PCL with $M_n = 20,624 \text{ g}\cdot\text{mol}^{-1}$ and $\bar{D} = 1.2$ was obtained, exceeding values observed within the experimental matrix and representing a substantial improvement over prior solvent-based

microwave studies. Reducing power to 10 W at the same temperature and time decreased M_n to $7644 \text{ g}\cdot\text{mol}^{-1}$ and increased $\bar{D}$ to 1.6, confirming that microwave irradiation contributes positively but nonlinearly to the process. The study concludes that microwave irradiation can enhance lipase-catalyzed, solvent-free PCL synthesis, but the effect is not linear. Excessive power or temperature may reduce enzyme stability due to microenvironmental heating and water-content sensitivity. Optimal microwave heating conditions, therefore, balance enhanced chain propagation with preservation of enzymatic activity [26].

3.2. ω -Pentadecalactone

ω -PDL is a 15-membered macrolactone that yields poly(ω -pentadecalactone) (PPDL) upon ROP (Figure 3). The synthesized homo- and copolymers exhibit favorable mechanical properties, while the presence of hydrolyzable ester linkages along the polymer backbone enables biodegradability. These characteristics have generated significant interest in PPDL as a biodegradable material for diverse biomedical engineering applications. Consequently, PPDL is considered a promising candidate for long-term biomedical implants and sustained drug delivery matrices, where prolonged structural integrity and controlled degradation are essential, as in DDSs and contraceptive implants [30,40–42].

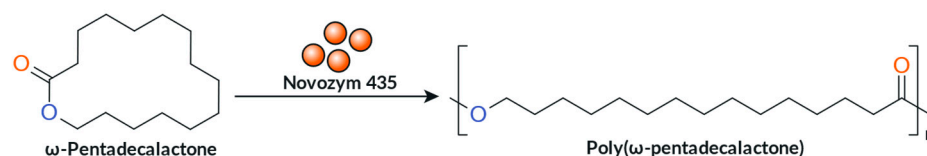


Figure 3. Enzymatic ring-opening polymerization of ω -pentadecalactone catalyzed by Novozym 435, yielding poly(ω -pentadecalactone). Oxygen atoms indicate the bond cleavage and structural transformation during the ring-opening process.

The laboratory responsible for the study in which they investigated the effects of microwave process parameters (microwave power, irradiation time, and temperature) on lipase-catalyzed polymerization of ϵ -CL, described in the previous subchapter, conducted a follow-up study focused on the microwave-assisted eROP of ω -PDL. Mahapatro and Matos synthesized PPDL using ω -PDL monomers with Novozym 435 as the catalyst. Reactions were performed in a solvent-free environment. An enzyme-to-monomer ratio of 1:10 (wt.%/wt.%) was used. The reactions were carried out in a microwave reactor at 70°C , monitored by an in situ optical probe, with a constant power of 200 W and predetermined reaction times of 30, 60, 120, and 240 min. The control reaction was performed with the same reagents for 240 min using a conventional oil bath. The reactions were terminated by dissolving the residual monomer and polymer in chloroform and separating the insoluble enzyme by filtration through glass-fritted filters. The polymer was then dissolved in chloroform and precipitated with methanol. The precipitated material was filtered and washed three times with fresh methanol. The polymer was subsequently dried in a vacuum oven and characterized. The obtained products were analyzed by NMR to confirm the presence of PPDL, by GPC to determine molecular weight, and by thermogravimetric analysis (TGA) to study the thermal properties of the polymers. Microwave-assisted polymerization of PPDL resulted in approximately three times higher M_n and lower $\bar{D}$ (1.93 for microwave heating compared to 2.17 for oil bath heating) than polymers synthesized using conventional heating within the same reaction time. Notably, a relatively high M_n ($13,342 \text{ g}\cdot\text{mol}^{-1}$) with $\bar{D} = 1.94$ was achieved after only 30 min of microwave-assisted polymerization. Polymer yields were also significantly higher, with only about 20% obtained using the oil bath method compared to 41–62% using microwave heating. The higher M_n and lower $\bar{D}$ values were also confirmed compared with literature results obtained using conventional heating over significantly longer reaction times (24–72 h).

Thermal properties of enzyme-catalyzed PPDL in bulk, studied by TGA, showed no significant differences between polymers synthesized using microwave irradiation and those obtained using conventional heating [30].

Herrera-Kao et al. employed microwave-assisted eROP to synthesize poly(ϵ -caprolactone-co- ω -pentadecanolactone) across the full compositional range (ϵ -CL/ ω -PDL feed ratios from 100/0 to 0/100), using Novozym 435 at a constant 1:10 enzyme-to-monomer ratio in toluene under nitrogen, with molecular sieves to control water content. High monomer conversions of 91–95% were achieved within 60 min, as determined gravimetrically. Differential scanning calorimetry (DSC) revealed a single composition-dependent melting transition that increased linearly from 57 °C (PCL) to 95 °C (PPDL), along with a corresponding increase in melting enthalpy (ΔH_m), which the authors interpreted as evidence of random rather than block copolymer formation. TGA showed a single mass-loss step with degradation temperature increasing with ω -PDL content (from 408 to 424 °C), indicating improved thermal stability with increasing content of the longer-methylene-chain ω -PDL units [31].

3.3. Lactide

PLA is a biodegradable aliphatic polyester synthesized primarily via ROP (Figure 4), of the lactic acid dimer (LA). PLA undergoes hydrolytic degradation via bulk erosion, leading to chain scission and a gradual reduction in molecular weight. The degradation products include lactic acid (LAc), a naturally occurring metabolite in human physiology, which contributes to PLA's excellent biocompatibility and supports its widespread use in biomedical and pharmaceutical applications.

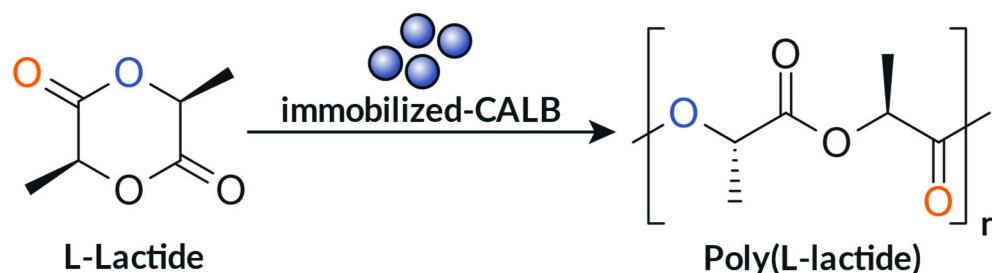


Figure 4. Enzymatic ring-opening polymerization of L-lactide catalyzed by immobilized *Candida antarctica* lipase B (immobilized-CALB), yielding poly(L-lactide). Oxygen atoms indicate the bond cleavage associated with the ring-opening process.

Due to the presence of chiral centers in the LAc or LA repeating units (Figure 5), PLA exists in several stereochemical forms, most commonly poly(L-lactide) (PLLA), poly(D-lactide) (PDLA), and poly(D,L-lactide) (PDLLA). Among these, PLLA is a semicrystalline polymer whose degree of crystallinity depends on M_n and processing conditions. PLLA exhibits high tensile strength, low elongation at break, and a relatively high elastic modulus. Its high crystallinity contributes to increased hydrophobicity, which in turn reduces water uptake and slows hydrolytic degradation [43].

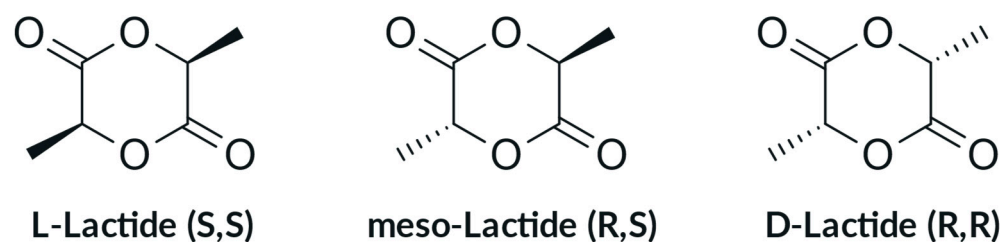


Figure 5. Stereoisomers of lactide: L-lactide (S,S), meso-lactide (R,S), and D-lactide (R,R).

Bukhari et al. investigated the effect of microwave irradiation on the eROP of LLA. The reaction mixture was prepared in a humidity-free glove box under vacuum. Polymerizations were conducted at 90 °C using a covalently immobilized CALB (prepared according to Bukhari et al., 2014 [20]) at concentrations of 4, 8, and 12% (*w/w*) relative to LLA, and reaction times of 4, 8, 12, and 16 h. Toluene was added prior to the reaction, and all experiments were carried out under a dry nitrogen atmosphere with magnetic stirring. Microwave power was initially set at 200 W. After the predetermined reaction time, DMSO was added to reduce viscosity, and the mixture was centrifuged (20–30 min, 3000 rpm) to separate the biocatalyst. The polymer was precipitated with cold methanol and vacuum dried at 40–50 °C. Control experiments without immobilized CALB were also performed. At optimal conditions, bulk polymerization (without solvent) was conducted to assess solvent effects. Additionally, simultaneous cooling was applied using a jacketed flask connected to a chiller. The obtained PLLA was characterized by intrinsic-viscosity-based viscosity-average molecular weight (M_{η} , Ubbelohde viscometer), optical rotation (polarimetry), monomer conversion (^1H NMR), thermal properties (DSC: T_m , ΔH_m , crystallinity), and chemical structure (FTIR). M_{η} increased with increasing biocatalyst concentration up to an optimum of 8% (*w/w*), at which PLLA with a molar mass of 44,651 g/mol, T_m of 157.37 °C, and optical rotation of -148° was obtained. At 4% catalyst loading, only ~20% monomer conversion was achieved after 12 h, whereas 8% catalyst loading yielded ~98% conversion under the same conditions. Increasing the catalyst concentration beyond 8% did not improve conversion and led to reduced yield (36%) and molar mass (41,099 g/mol), likely due to the enzyme's enhanced hydrolytic activity. At the optimal catalyst concentration (8%), increasing microwave irradiation time from 4 to 16 h resulted in higher conversion and yield, with ~20% conversion after 4 h and complete conversion (99–100%) after ≥ 8 h, as confirmed by the disappearance of monomer signals in ^1H NMR spectra. The highest molar mass (50,482 g/mol) and crystallinity (~50.3%) were obtained after 8 h of microwave heating, indicating this as the optimal reaction time. Simultaneous cooling under optimal conditions (8% enzyme, 8 h of microwave heating) significantly enhanced the process. The microwave power decreased from 200 W to 100 W upon reaching 90 °C but increased to ~140 W under cooling to maintain the temperature, indicating enhanced microwave penetration. Under these conditions, monomer conversion was maintained (99–100%), while yield increased from 50.5% to 55.3% and molar mass reached 56,125 g/mol. In bulk polymerization, lower yield (32.4%) and molar mass (34,269 g/mol) were obtained. Optical rotation analysis indicated that PLLA synthesized under microwave irradiation was optically active and relatively pure (-155° to -145°). However, prolonged microwave exposure or simultaneous cooling led to a decrease in optical rotation (to approximately -145°), suggesting partial racemization and formation of PDLLA. Thus, 8 h of microwave irradiation was identified as optimal for balancing high conversion, molar mass, and optical purity [32].

3.4. Biomedical and Pharmaceutical Applications of the Resulting Polymers

The polymer families accessible by microwave-assisted eROP are already well established in pharmaceutical and biomedical practice, and their application profiles are governed by key physicochemical properties, including molar mass, $\bar{D}$, crystallinity, and degradation rate, which microwave-assisted eROP is able to tune. PCL is a versatile and extensively studied material for pharmaceutical drug delivery and other biomedical applications. Its biocompatibility, non-toxicity, and customizable mechanical properties enable its processing into several structures, including microspheres, nanoparticles, scaffolds, fibers, films, micelles, and hydrogels. PCL's slow degradation process, initiated by non-enzymatic hydrolysis and followed by enzymatic surface erosion, can take months, making

it well-suited for sustained, long-term drug release. Due to its inherent hydrophobicity, PCL is often blended or co-polymerized with hydrophilic polymers such as polyethylene glycol to optimize degradation rate, mechanical strength, and drug-loading behavior for specific applications. PCL has been extensively studied in tissue engineering, where its scaffolds support bone, cartilage, and vascular regeneration, and it has also been used as a carrier for chemotherapeutics, antibiotics, hormones, and proteins. Despite this extensive experimental success, PCL-based formulations remain largely confined to research and preclinical/clinical trials rather than widespread commercial pharmaceutical products [44]. PPDL and its copolymers offer prolonged structural integrity and tunable degradation arising from a lower ester density along the backbone, and have accordingly been investigated as matrices for sustained drug release in cancer therapy [41,45,46], as long-acting implant materials for HIV treatment [47], and as biodegradable microsphere-forming materials for drug-carrier systems [48]. The ability, demonstrated under microwave-assisted eROP, to raise molar mass and narrow $\bar{M}$ relative to conventional heating is directly relevant to controlling the mechanical persistence and release kinetics of such matrices and implants. PLA and its copolymers provide the mechanical strength and resorbability required for bioresorbable stents and sutures, orthopedic implants, and controlled-release systems, with degradation profiles that depend strongly on stereochemical purity and crystallinity [49,50]. The optical purity and crystallinity achievable under microwave-assisted eROP are therefore of direct pharmaceutical relevance [32].

4. Conclusions

Microwave-assisted eROP represents a promising combination of biocatalysis and energy-efficient heating for the synthesis of pharmaceutical polymers. As demonstrated throughout this review, immobilized CALB is the most effective and widely applied biocatalyst for eROP, offering high selectivity, broad monomer scope, and compatibility with mild reaction conditions. The reviewed studies consistently demonstrate that Novozym 435 exhibits excellent operational stability under optimized conditions. In contrast, elevated temperatures, prolonged microwave exposure, or unsuitable reaction media accelerate catalyst deactivation, leading to reduced monomer conversion and lower polymer molecular weights. In contrast, mild reaction conditions combined with appropriate immobilization strategies enable repeated catalyst reuse while maintaining high catalytic activity and satisfactory polymerization performance, highlighting the importance of balancing reaction rate with long-term catalyst durability. Microwave irradiation has been shown to significantly influence eROP by accelerating reaction rates, enhancing monomer conversion, and, in some systems, improving molecular weight and lowering $\bar{M}$ of the resulting polymers. These effects are primarily attributed to rapid dielectric/volumetric heating and to interactions between microwave fields and polar reaction components. However, the observed outcomes remain strongly system-dependent. Both accelerating and decelerating effects have been reported, particularly in relation to solvent dielectric properties and enzyme stability, highlighting the complexity of microwave-assisted enzymatic systems.

Despite these promising advances, microwave-assisted eROP remains a relatively underexplored field. The current literature is dominated by studies on ϵ -CL, with comparatively limited investigation of other industrially and pharmaceutically relevant monomers, such as LLA and macrolactones. Moreover, important challenges persist, including an incomplete understanding of microwave–enzyme interactions, potential enzyme deactivation under localized heating conditions, and a lack of standardized experimental protocols that would enable direct comparison between studies. The available literature indicates that the enhanced polymerization rates observed under microwave irradiation can be explained by well-established thermal phenomena, including rapid and volumetric heating, improved

heat transfer, reduced temperature gradients, and enhanced mass transport. These factors may increase monomer conversion and shorten reaction times without necessarily altering the enzyme's fundamental catalytic mechanism. At the same time, several authors have proposed that non-thermal microwave effects could contribute to changes in enzyme activity through direct interactions of the electromagnetic field with polar molecules, transient modification of enzyme conformation, or altered substrate–enzyme interactions. However, convincing experimental evidence supporting these hypotheses remains limited and is often difficult to disentangle from purely thermal effects, as accurate temperature measurements under microwave irradiation can be challenging. Moreover, differences in reactor geometry, dielectric properties of reaction media, enzyme immobilization, and local temperature distributions frequently complicate direct comparisons between microwave-assisted and conventionally heated systems. Current mechanistic understanding of eROP is based on the well-established formation of an acyl–enzyme intermediate followed by nucleophilic attack on the propagating chain, and there is currently no experimental evidence demonstrating that microwave irradiation fundamentally changes this catalytic pathway. Instead, microwave irradiation appears to primarily influence the process kinetics by modifying heat and mass transfer while preserving the established enzymatic reaction mechanism. Although non-thermal microwave effects cannot be entirely ruled out, their presence in enzymatic polymerization has not yet been conclusively demonstrated. The currently available experimental data are insufficient to distinguish unequivocally between thermal and possible non-thermal contributions. Consequently, claims regarding specific non-thermal microwave effects should be interpreted with caution until supported by rigorously designed experiments employing identical temperature profiles, precise temperature monitoring, and appropriate conventional heating controls.

To date, microwave-assisted eROP studies have focused on polymer families widely exploited in pharmaceutical and biomedical practice. PCL, owing to its slow hydrolytic degradation and excellent biocompatibility, is established as a material for long-acting drug delivery depots, micro- and nanoparticulate carriers, and implantable devices [51]. PPDL and its copolymers, with their prolonged structural integrity and tunable degradation, have been investigated as matrices for sustained drug release and as contraceptive implant materials [40–42]. PLLA and its copolymers serve as the basis for resorbable sutures, orthopedic fixation devices, and controlled-release systems [52]. The ability of microwave-assisted eROP to deliver these polymers rapidly, under mild and metal-free conditions, and with control over molar mass and $\bar{D}$, both of which directly govern degradation kinetics and drug-release profiles, is therefore of direct pharmaceutical significance. The principal outstanding challenge is that this potential has not yet been validated in application-oriented studies, such as drug-loading, release, or degradation testing of polymers obtained via microwave-assisted eROP.

In conclusion, microwave-assisted eROP catalyzed by CALB holds significant potential as a sustainable and efficient platform for the synthesis of pharmaceutical polymers. However, further fundamental and technological developments are required to realize its applicability in scalable, industrially relevant processes fully.

5. Future Perspectives

The microwave-assisted eROP represents a rapidly evolving area at the intersection of green chemistry, polymer science, and biotechnology. Despite the promising results reported to date, several key directions remain to fully unlock this approach's potential for pharmaceutical and biomedical applications.

First, a deeper mechanistic understanding of microwave–enzyme interactions is essential. Although many observed effects are attributed to rapid dielectric heating, the

possibility of non-thermal microwave effects on enzyme structure, activity, and stability remains debated and insufficiently resolved. Advanced analytical techniques and in situ monitoring methods should be employed to distinguish between purely thermal and microwave-specific phenomena, enabling more rational process design.

Second, expanding the scope of monomers and polymer architectures is a critical step forward. Current research is heavily focused on a limited set of monomers, particularly ϵ -CL. Future studies should investigate a broader range of cyclic esters, carbonates, and functionalized monomers to access polymers with tailored physicochemical and biological properties. This includes the development of copolymers, block polymers, and functionalized systems designed for specific drug delivery and biomedical applications.

Another important direction is the engineering and optimization of biocatalysts. While immobilized CALB remains the dominant enzyme in eROP, exploring alternative enzymes, protein engineering approaches, and novel immobilization strategies could improve catalytic efficiency, stability under microwave conditions, and substrate compatibility. Designing enzyme systems specifically adapted to microwave environments represents a particularly promising avenue.

Process scalability and reproducibility also remain major challenges. Most reported studies have been conducted at a laboratory scale, often under highly specific conditions. For industrial translation, it is necessary to develop scalable microwave reactors, ensure uniform energy distribution, and establish standardized protocols that guarantee consistent polymer quality. Although immobilized enzymes are initially more expensive than conventional metal catalysts, their recoverability, reusability, simplified downstream purification, and elimination of costly catalyst-removal procedures can partially compensate for the higher catalyst cost. In addition, the shorter reaction times typically achieved under microwave irradiation may reduce overall energy consumption and improve process productivity. Integration with continuous-flow systems may offer a viable solution for overcoming these limitations. It will also be essential to perform standardized benchmarking relative to conventionally heated systems, underpinned by techno-economic analysis and life-cycle assessment, to establish if microwave-assisted eROP delivers a real advantage at an expanded scale.

Furthermore, future research should emphasize the design of polymers with precise control over molecular weight, $\bar{M}_n$, and architecture, as these parameters are critical for biomedical performance. Particular attention should be given to polymers intended for advanced DDSs, including stimuli-responsive materials, targeted delivery platforms, and long-term, implantable systems.

Finally, sustainability considerations should remain central to further development. The calculation and evaluation of standardized green chemistry metrics represent an important direction for future research. Nevertheless, the available evidence indicates that enzymatic polymerization offers several inherent sustainability advantages, including the replacement of organometallic catalysts, operation under milder reaction conditions, catalyst recyclability, reduced purification requirements, and the potential use of greener solvents, all of which may contribute to lowering the overall environmental footprint provided that these benefits are validated through comprehensive life-cycle assessment and related sustainability analyses.

In summary, microwave-assisted eROP holds significant promise as a versatile and sustainable platform for the synthesis of next-generation biomedical polymers. Continued interdisciplinary efforts in catalysis, reaction engineering, and materials science will be crucial to translating this technology from laboratory research to practical pharmaceutical applications.

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Abbreviations

The following abbreviations are used in this manuscript:

ϵ -CL	ϵ -Caprolactone
ω -PDL	ω -pentadecalactone
$\bar{D}$	Dispersity
M_n	Number-average molecular weight
M_w	Weight-average molecular weight
M_η	Viscosity-average molecular weight
T_m	Melting point
ΔH_m	Enthalpy of melting
AEC	Acyl-Enzyme Complex
AIBN	2,2'-azobis(2-methylpropionitrile)
CALB	<i>Candida antarctica</i> lipase B
DDSs	Drug Delivery Systems
DSC	Differential Scanning Calorimetry
eROP	Enzymatic Ring-Opening Polymerization
FNAB	1-fluoro-2-nitro-4-azidobenzene
FTIR	Fourier transform infrared spectroscopy
GG	Glycolide
GPC	Gel Permeation Chromatography
MCTR	Macro Chain Transfer Reagent
LA	Lactide
LAc	Lactic acid
LLA	L-Lactide
PCL	Poly(ϵ -caprolactone)
PDLA	Poly(D-lactide)
PDLLA	Poly(D,L-lactide)
PLA	Polylactide
PLLA	Poly(L-lactide)
PPDL	Poly(ω -pentadecalactone)
ROP	Ring-Opening Polymerization
SEC	Size Exclusion Chromatography
TGA	Thermogravimetric Analysis
THF	Tetrahydrofuran
TMC	Trimethylene Carbonate

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